Soil and Water Assessment Tool (SWAT) Hydrologic/Water Quality Model: Extended Capability and Wider Adoption

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Abstract. *This article introduces a special collection of 16 research articles on new developments and applications of the Soil and Water Assessment Tool (SWAT) to address various environmental issues at a range of geographic and temporal scales. Highlights include addition of a subdaily erosion and sediment transport algorithm, a biozone module, and a new algorithm for shallow water table depth. Model applications include climate change impact assessments, model adaptation to regional environmental conditions, watershed-scale soil erosion assessments, and linkages to other models. A summary of reported model performance indicates that 85% of daily flow calibration statistics reported in this collection were satisfactory or better, with very good performance in four of the 20 calibration results and in three of the 19 validation results. Details of reported model parameters for calibration of flow and water quality constituents are provided for other SWAT modelers. This collection builds upon a previous ASABE 2010 SWAT Special Collection, demonstrating continued developments to enhance SWAT's capabilities and highlighting SWAT's continued expansion in international applications, especially in Asia.*

Keywords. *Hydrologic modeling, Hydrology, SWAT, Water quality, Watershed.*

The Soil and Water Assessment Tool (SWAT), developed by the USDA Agricultural Research Service (USDA-ARS) (Arnold et al., 1998), is a watershed-scale model that simulates hydrology, water quality, and watershed management. It has been continuously updated (currently SWAT version 2009 with ArcGIS3.x interface is available) in response to advancing technology, improving its capabilities for application around the world. SWAT has been widely used for hydrological assessments at various spatial and temporal scales in the U.S. and European countries, as well as in Asia and Africa. In some studies, the model has been used to simulate entire countries (Schuol and Abbaspour, 2006; Faramarzi et al., 2009) or even entire continents (Schuol et al., 2008).

This article introduces and summarizes 16 research articles, many of which were originally presented at the 2010 International SWAT Conference in Ilsan, Korea. This collection includes new SWAT developments, integration with other models to enhance the joint capabilities, and other interesting SWAT model applications. Modeling research from three continents is represented, with an emphasis on watershed applications from Asia (nine studies) in addition to Africa (two studies) and North America (five studies).

The objectives of this article are to categorize, review, and introduce the research presented in this SWAT special collection and to summarize and synthesize the model performance statistics and parameters reported in these articles. Thus, this article is meant to be a succinct guide to complement the SWAT model summaries by Gassman et al. (2007) and Douglas-Mankin et al. (2010).

The SWAT Model

The first publicly available Soil and Water Assessment Tool (SWAT) model was SWAT94.2 (Arnold et al., 1998). Since then, SWAT has evolved in its simulation capability, use of state-of-the-art interfaces, and expanded global user community. SWAT is a non-proprietary model with an active user group and supportive core developmental team. More than 820 peer-reviewed journal articles have been published on applications of SWAT, covering a wide variety of issues and a range of temporal and spatial scales. The current 2009 version uses the ArcGIS-SWAT (ArcSWAT) interface tool (Winchell et al., 2008). A comprehensive review of SWAT, including historic developments and applications, was presented by Gassman et al. (2007). The 2010 ASABE SWAT

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Table 1a. Summary of reported SWAT streamflow calibration and validation statistics.[a]

Reference	Model	Watershed	Drainage Area (km^2)	Warm-up Period (years)	Time Period	Time Scale	C/V	R^2	NSE	PBIAS (%)
Betrie et al. (2011)	SWAT2005	Upper Blue Nile at Diem (Ethiopia-Sudan)	176,000	1	1980-1986	D	C	--	0.91	--
					1987-1996	D	V		0.82	
Chung et al. (2011)	SWAT2005, SWAT-MODFLOW	Pyoseon (Jeju Island, Korea)	207	1	2006	D	C	0.63	0.50	--
						D	C	0.67	0.62	
Joh et al. (2011)	SWAT2000	Seolma-cheon (Korea)	8.54	--	2007-2008	D	C	0.74	0.70	--
					2009	D	V	0.76	0.71	
Kim et al. (2011a)	SWAT2005	Chungju Dam (Korea)	6,648	--	2005-2009	D	C	--	0.72	--
Lee et al. (2011)	SWAT2005	Galveston Bay (Texas)	16,100	2						
		08067650			1991-2000	D	C	0.68	0.64	--
		08070000			1991-2008	D	C	0.50	0.42	
		08070500			1991-2008	D	C	0.67	0.37	
		08070200			1991-2000	D	C	0.63	0.47	
		08068500			1991-2008	D	C	0.64	0.56	
		08068090			1991-2000	D	C	0.65	0.58	
	SWAT2005	Matagorda Bay (Texas)	11,600	2						
		08164300			1991-2000	D	C	0.64	0.58	--
		08164350			1996-2000	D	C	0.74	0.74	
Lee et al. (2011)	SWAT2005	Galveston Bay (Texas)	16,100	2						
		08067650			1977-1990	D	V	0.29	0.02	--
		08070000			1977-1990	D	V	0.29	-0.52	
		08070500			1977-1990	D	V	0.27	-0.12	
		08070200			1984-1990	D	V	0.26	-0.70	
		08068500			1977-1990	D	V	0.34	-0.04	
		08068090			1984-1990	D	V	0.26	-0.74	
	SWAT2005	Matagorda Bay (Texas)	11,600	2						
		08164300			1977-1990	D	V	0.45	0.24	--
		08164350			1981-1989	D	V	0.49	0.31	
Park et al. (2011b)	SWAT2000	Chungju Dam (Korea)	6,642	22	1998-2000	D	C	0.89	0.81	--
		YW1	1,602			D	C	0.76	0.73	
		YW2	2,261			D	C	0.76	0.64	
		Chungju Dam (Korea)	6,642	22	2001-2003	D	V	0.87	0.78	--
		YD1	1,602			D	V	0.71	0.68	
		YD2	2,261			D	V	0.69	0.58	
Ryu et al. (2011)	SWAT-REMM	Bonggok River (Korea)	90.82	--	2005	D	C	0.73	0.69	--
					2006	D	V	0.72	0.67	
Wagner et al. (2011)	SWAT2009	Western Ghats (India)		1						
		G1	498		2001-2007	D	V	0.71	0.68	--
		G2	331		2001-2007	D	V	0.63	0.63	
		G3	680		2002, 2004-2007	D	V	0.34	0.10	
		G4	99		2001-2006	D	V	0.58	0.58	
Xie et al. (2011)	SWAT2005	Banifing River (Mali, west Africa)	19,312	2	1998-2000	D	C	--	0.92	--
					1996-1998	D	V		0.83	

[a] D = daily, W = weekly, M = monthly, C = calibration, V = validation, R^2 = coefficient of determination, NSE = Nash-Sutcliffe efficiency, and PBIAS = percent bias. Values for empty cells were not specified in the reference article.

Special Collection (Douglas-Mankin et al., 2010) expanded upon this review, summarizing additional research on SWAT developments and applications.

SWAT is a distributed parameter, deterministic, continuous watershed model that operates on a daily time step. It subdivides the watershed into a number of subwatersheds based on topography and user-defined threshold drainage area (minimum area required to begin a stream) or predefined subwatershed and reach delineation supplied by the user. Each subwatershed is further divided into hydrologic response units (HRUs), which are unique combinations of soil, land use, slope, and land management. The HRU is the smallest landscape component of SWAT used for simulating hydrologic processes. The size of an HRU depends on the resolution of inputs, including digital elevation model, soils, land use, and slopes, and user-defined thresholds that define and refine the HRU distribution. The typical size of an HRU in SWAT ranges from about 50 to 500 ha. Hydrological process simulation is divided into two phases: (1) the upland phase, in which the model calculates upland flow and loadings of sediment, nutrients, bacteria, and pesticides from each HRU, and then combines area-weighted HRU-level loadings to the subwatershed level; and (2) the channel/floodplain phase, in which the model routes the upland loadings from each subwatershed through the channel/stream network.

SWAT MODEL PERFORMANCE SUMMARY

Modeling studies typically require calibration and/or validation to evaluate model performance. Table 1 summarizes the reported model performance statistics used in this collection: coefficient of determination (R^2), Nash-Sutcliffe model efficiency (NSE), and percent bias (PBIAS). These statistics

Table 1b. Summary of reported SWAT water table calibration and validation statistics.[a]

Reference	Model	Watershed	Drainage Area (km^2)	Warm-up Period (years)	Time Period	Time Scale	C/V	R^2	NSE	PBIAS (%)
Jeong et al. (2011c)	SWAT2009	Hoods Creek (North Carolina)	1.72	48	2000-2001	W	C	0.82	--	-0.8
Moriasi et al. (2011)	SWAT2005 Auto *wt_fctr*	Muscatatuck River (Indiana)	2,952	16	1992-1994	M	C	--	0.72	2
					1995-1996	M	V		0.63	8
	SWAT2005 Auto *wt_fctr*	Muscatatuck River (Indiana)	2,952	16	1992-1994	D	C	--	0.66	4
					1995-1996	D	V		0.58	10
	SWAT2005 Calib *wt_fctr*	Muscatatuck River (Indiana)	2,952	16	1992-1994	M	C	--	0.73	-7
					1995-1996	M	V		0.40	-1
	SWAT2005 Calib *wt_fctr*	Muscatatuck River (Indiana)	2,952	16	1992-1994	D	C	--	0.64	-13
					1995-1996	D	V		0.41	-3

[a] D = daily, W = weekly, M = monthly, C = calibration, V = validation, R^2 = coefficient of determination, NSE = Nash-Sutcliffe efficiency, and PBIAS = percent bias. Values for empty cells were not specified in the reference article.

Table 1c. Summary of reported SWAT sediment calibration and validation statistics.[a]

Reference	Model	Watershed	Drainage Area (km^2)	Warm-up Period (years)	Time Period	Time Scale	C/V	R^2	NSE	PBIAS (%)
Betrie et al. (2011)	SWAT2005	Upper Blue Nile at Diem (Ethiopia-Sudan)	176,000	1	1980-1986	D	C	--	0.72	--
					1990-1996	D	V		0.66	
Jeong et al. (2011b)	SWAT2005 Subdaily	Riesel Y2 (Texas)	53.4	--	2001	D	C	0.37	0.49	2%
					2002	D	V	0.23	0.21	-59%
Jeong et al. (2011b)	SWAT2005 Daily	Riesel Y2 (Texas)	53.4	--	2001	D	C	--	0.75	--
					2002	D	V		0.29	
Kim et al. (2011a)	SWAT2005	Chungju Dam (Korea)	6,648	2	2007-2009	W	C	--	--	-16
Park et al. (2011b)	SWAT2000	Chungju Dam (Korea)	6,642	22	1998-2000	D	C	--	--	--
		YW1	1,602			D	C	0.79		
		YW2	2,261			D	C	0.69		
		Chungju Dam (Korea)	6,642	22	2001-2003	D	V	--	--	--
		YW1	1,602			D	V	0.95		
		YW2	2,261			D	V	0.53		

[a] D = daily, W = weekly, M = monthly, C = calibration, V = validation, R^2 = coefficient of determination, NSE = Nash-Sutcliffe efficiency, and PBIAS = percent bias. Values for empty cells were not specified in the reference article.

provide insight regarding model performance in simulating streamflow, water table depth, sediment load, and N and P loads across a wide spectrum of watershed conditions and add substantially to the previous compilations of model results by Gassman et al. (2007) and Douglas-Mankin et al. (2010).

Table 2 summarizes the combined results of more than 100 model runs or applications calibrated and/or validated for daily streamflow from this collection and from Gassman et al. (2007) and Douglas-Mankin et al. (2010). Adopting the thresholds of NSE $\geq$ 0.50 for satisfactory and NSE $\geq$ 0.75 for very good model performance for monthly flow (Moriasi et al., 2007) and recognizing that monthly model performance statistics are generally better than daily statistics, 85% of the reported daily flow calibration statistics in this collection were reported to be satisfactory or better. Very good performance for daily flow was achieved in four of the 20 calibration results and in three of the 19 validation results. Combined with data from Gassman et al. (2007) and Douglas-Mankin et al. (2010), 72% of 127 calibration results and 55% of 105 validation results were rated as satisfactory or better, and 20% of calibration results and 11% of validation results were rated as very good.

Many studies also reported the parameters used to achieve the stated calibration statistics for streamflow (table 3). The model parameters used in calibration and the values found to produce optimal calibration for each parameter vary substantially among the studies and watersheds. Interpretation of model results is aided by detailed reporting of the model parameterization and calibration procedures, as found in many of the studies in this collection. However, gaps in reported methods and results were evident in many cases. As indicated by Douglas-Mankin et al. (2010) and re-emphasized here: “Improved reporting of calibration and validation procedures and results, perhaps guided by a set of standard reporting guidelines, is essential for adequate interpretation of each study and comparison among studies in the future. This increased information would also form the basis for assigning typical parameters and ranges for use in either manual or automatic calibration and uncertainty processes.” In addition, considering the uncertainty in measured calibration/validation data will enhance evaluation of model results (Harmel et al., 2010).

MODEL DEVELOPMENTS

Subdaily Erosion and Sediment Transport: In continuation of recently developed subhourly flow models (Jeong et al., 2011a), modified physically based erosion models were incorporated into SWAT for simulating stormwater best management practices (e.g., detention basins, wet ponds, sedimentation ponds, and retention irrigation systems) for small

Table 1d. Summary of reported SWAT nitrogen (total N) calibration and validation statistics.[a]

Reference	Model	Watershed	Drainage Area (km^2)	Warm-up Period (years)	Time Period	Time Scale	C/V	R^2	NSE	PBIAS (%)
Kim et al. (2011a)	SWAT2005	Hangang-A (Korea)	6,648	2	2007-2009	W	C	--	--	-17
Park et al. (2011b)	SWAT2000	Chungju Dam (Korea)	6,642	22	1998-2000	M	C	--	--	--
		YW1	1,602			M	C	0.70		
		YW2	2,261			M	C	0.81		
		Chungju Dam (Korea)	6,642	22	2001-2003	M	V	--	--	--
		YW1	1,602			M	V	0.78		
		YW2	2,261			M	V	0.94		
Ryu et al. (2011)	SWAT-REMM	Bonggok River (Korea)	90.82	--	2005	D	C	0.67	0.62	--
					2006	D	V	0.63	0.60	

[a] D = daily, W = weekly, M = monthly, C = calibration, V = validation, R^2 = coefficient of determination, NSE = Nash-Sutcliffe efficiency, and PBIAS = percent bias. Values for empty cells were not specified in the reference article.

Table 1e. Summary of reported SWAT phosphorus (total P) calibration and validation statistics.[a]

Reference	Model	Watershed	Drainage Area (km^2)	Warm-up Period (years)	Time Period	Time Scale	C/V	R^2	NSE	PBIAS (%)
Kim et al. (2011a)	SWAT2005	Hangang-A (Korea)	6,648	2	2007-2009	W	C	--	--	-22
Park et al. (2011b)	SWAT2000	Chungju Dam (Korea)	6,642	22	1998-2000	M	C	--	--	--
		YW1	1,602			M	C	0.82		
		YW2	2,261			M	C	0.35		
		Chungju Dam (Korea)	6,642	22	2001-2003	M	V	--	--	--
		YW1	1,602			M	V	0.88		
		YW2	2,261			M	V	0.88		

[a] D = daily, W = weekly, M = monthly, C = calibration, V = validation, R^2 = coefficient of determination, NSE = Nash-Sutcliffe efficiency, and PBIAS = percent bias. Values for empty cells were not specified in the reference article.

Table 2. Frequency analysis of SWAT daily hydrologic calibration and validation statistics.[a]

	SWAT 2011 Collection				Gassman et al. (2007) and Douglas-Mankin et al. (2010)				Combined			
	Calibration		Validation		Calibration		Validation		Calibration		Validation	
	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE
n	15	20	15	19	47	107	44	86	62	127	59	105
0.90-1.00	0	2	0	0	9	5	3	1	9	7	3	1
0.80-0.89	1	2	0	2	7	7	6	6	8	9	6	8
0.70-0.79	5	5	3	2	10	25	9	9	15	30	12	11
0.60-0.69	8	4	2	4	8	19	12	19	16	23	14	23
0.50-0.59	1	4	1	2	4	18	11	13	5	22	12	15
0.40-0.49	0	2	2	0	4	8	2	11	4	10	4	11
0.30-0.39	0	1	2	1	0	5	1	8	0	6	3	9
0.20-0.29	0	0	5	1	3	5	0	4	3	5	5	5
0.10-0.19	0	0	0	1	1	4	0	1	1	4	0	2
0.00-0.09	0	0	0	1	1	2	0	1	1	2	0	2
<0.00	0	0	0	5	0	9	0	13	0	9	0	18

[a] R^2 = coefficient of determination, NSE = Nash-Sutcliffe efficiency, and *n* = number of models analyzed.

urban watersheds. The Modified Universal Soil Loss Equation (MUSLE) was replaced by new algorithms based on the European Soil Erosion Model to calculate splash erosion and ANSWERS to calculate overland flow erosion (Jeong et al., 2011b). In this study, the sediment transport model was also modified to compute in-stream sediment routing. In testing on small watersheds in Riesel, Texas, Jeong et al. (2011b) found that the new algorithms were able to adequately represent timing, peak, and duration of sediment transport events in addition to improved simulation of sediment yields.

Septic Systems: A new biozone module was incorporated into SWAT, expanding its applicability to simulate septic tanks, which are common onsite wastewater treatment systems in rural and suburban areas. This added feature in SWAT facilitates simulation of septic systems, including conventional, advanced, and failing types, at the HRU level (Jeong et al., 2011c). In the SWAT biozone algorithm adapted from Siegrist et al. (2005), septic tank effluent directly drains to subsurface soil layers, affecting soil moisture content and percolation, which is a function of soil hydraulic conductivity. The algorithm attempts to simulate the complex biological process due to the solids, organics, and nutrients in the incoming effluent and eventual accumulation of solids and plaque, causing clogging and hydraulic failure of the system.

Table 3. Streamflow-related SWAT calibration parameter values or change (Δ) from default values.

Reference	Model	Watershed	CN2	AWC (mm H_2O mm $soil^{-1}$)	ALPHA _BF (d^{-1})	ESCO	SUR LAG	CH_ N2	CH_K2 (mm h^{-1})	GW REVAP	GW DELAY (d)	GW QMN (mm)	Other
Chung et al. (2011)	SWAT 2005	--	Δ-60%	--	--	--	--	--	--	--	--	--	--[a]
Joh et al. (2011)	SWAT 2000	--	Δ+0-4	--	--	0.01	2.4	--	--	0.2	100	0	--[b]
Lee et al. (2011)	SWAT 2000	Galveston Bay	--	0.1	0.1	--	1-5	--	--	0.17	--	1,000	--
		Matagorda Bay		0.6	0.4					0.2		1,000	
Moriasi et al. (2011)	SWAT 2005	--	55-84	--	--	--	4	--	--	--	--	--	--[c]
Park et al. (2011a)	SWAT 2000	CD	Δ+9%	--	0.30	0.4	--	0.01	70	--	110	--	--[d]
		YW1	Δ+9%	5	0.35	0.8		0.01	50		120		
		YW2	Δ+2%	--	0.50	0.8		0.01	70		110		
Xie et al. (2011)	SWAT 2005	--	30.1	Δ3.6×	0.11	0.8	--	0.03	--	0.16	32	32	--[e]

[a] RCHRG_DP = 1.0.

[b] CANMX = 5; EPCO = 1.0.

[c] FFCB = 1.0 (initial soil water storage expressed as a fraction of field capacity water content).

[d] Additional calibration for snowmelt parameters shown in Park et al. (2011a, table 2).

[e] REVAPMN = 145, SOL_K (mm h^{-1}) = Δ1.02×, SOL_Z_X (mm) = Δ2.9×, and MSK_CO2 = 2.6.

Groundwater: A new algorithm for shallow water table depth was incorporated into SWAT, in which the water table depth was estimated as a function of drainage volume and water table factor (*wtf*). Currently, *wtf* is an HRU-level calibration parameter in SWAT, but a further study by Moriasi et al. (2011) attempted to revise the algorithm wherein *wtf* is automatically computed within the model as a function of soil physical properties. This eliminates the laborious exercise of determining the optimum *wtf* for each HRU through the calibration process, especially for large and heterogeneous watersheds. Moriasi et al. (2011) tested this revised algorithm within SWAT for water table depth in three observation wells in the Muscatatuck River basin in southeast Indiana, resulting in daily NSE of 0.66 (calibration) and 0.58 (validation), PBIAS of 4% (calibration) and 10% (validation), and RMSE of 49 m (calibration) and 0.5 m (validation). Further, the model performance with automatic *wtf* computation was not significantly different from the performance obtained when *wtf* was calibrated externally. This latest development in SWAT's groundwater routine provided critical information on shallow water table depth that is especially valuable for irrigation and drainage water management, both in terms of quantity and quality.

CLIMATE CHANGE ASSESSMENTS

Assessing impacts of future climate change on hydrology and water quality is a major issue that has been addressed using SWAT as well as other hydrological models. Improved understanding of future impacts helps toward establishment of watershed management plans and provides a guideline for effectively dealing with climate changes. The General Circulation Model (GCM) MIROC3.2-hires (Model for Interdisciplinary Research on Climate) was used for simulating future weather conditions and downscaled with bias correction and local adaptation in studies by Joh et al. (2011) and Park et al. (2011a, 2011b). RegCM3 (Regional Climate Model) using EH5OM GCM data was used by Lakshmanan et al. (2011). Climate change scenarios such as A1B, B1, or both, set by the Intergovernmental Panel on Climate Change (IPCC), were selected to simulate various levels of future greenhouse gas emissions. The estimated future climates were applied into a calibrated SWAT model to assess impacts of climate change in the watersheds.

Joh et al. (2011) estimated the impacts on soil moisture and evapotranspiration in a small forested watershed in northwestern Korea due to increases in temperature and precipitation in the years 2040 and 2080 based on A1B and B1 scenarios. They concluded that evapotranspiration would increase while streamflow and soil moisture would decrease. Park et al. (2011a) incorporated future land use change in the Chungju Dam watershed in northeastern Korea with future climate and found a gradual increase of streamflow and groundwater recharge in 2020, 2050, and 2080 compared to the baseline in 2000. Also in the Chungju Dam watershed, Park et al. (2011b) investigated the impacts of climate change on water quantity and quality from 1977 to 2100 and found an increase in total N and total P, although some decreases in nutrient losses were noticed in a couple of months due to the changes in runoff. Lakshmanan et al. (2011) estimated the change in hydrology and rice production due to climate change from 1971 to 2100 in the Bhavani basin in south-central India. Their finding was that temperature increase by up to 2°C would increase rice production, but an increase of greater than 2°C would decrease rice production. On the other hand, the increase in rainfall did not lead to noticeable impacts in the study area.

REGIONAL ADAPTATION

The SWAT model has been adapted to represent local environmental conditions. For instance, the QUAL2E in-stream model in SWAT was modified to consider oxygen demand for nitrification and algal respiration, which improved the accuracy of BOD_5 simulation, a target water-quality parameter in the Korean total maximum daily load (TMDL) program (Kim and Shin, 2011). This modification was deemed necessary to simulate intermittent streamflows and the effects of hydraulic structures that enhance the stream re-aeration process but also promote algae proliferation due to the reduced flow upstream of the structure. In addition, the QUAL2E model in SWAT was found to be more appropriate for continuous streamflow conditions rather than intermittent flows, typical of many streams in Korea. The modified

QUAL2E, referred to as QUAL-NIER, was applied over a portion of the South Han River watershed, resulting in improved estimation of BOD.

Default forest phenology (with dormancy as a function of latitude and day length) parameters in SWAT are more appropriate for temperate regions and were therefore modified to be suitable for monsoon-driven tropical climates, such as the Western Ghats catchments in southern India (Wagner et al., 2011). The modification, which mainly included shifting the dormancy period of forest vegetation to the dry season (April to mid-May) and changing the maximum leaf area index (LAI) for deciduous forests, resulted in better simulation of semi-evergreen forest phenology in the region and, in turn, improved ET and surface runoff estimates. Wagner et al. (2011) also describe the application of SWAT to devise dam management scenarios.

LINKAGES TO OTHER MODELS

SWAT-REMM: The HRU is the smallest landscape component in SWAT and has no spatial connectivity. Runoff and pollutants generated from HRUs within a subwatershed are assumed to enter the reach within that subwatershed. Currently, filter strips simulated by SWAT include the edge-of-field type, wherein sediment and nutrient trapping efficiencies are determined by a simple exponential relationship. With the current structure, SWAT cannot simulate riparian buffer zones. SWAT-REMM (Riparian Ecosystem Management Model) (Ryu et al., 2011) addressed this limitation by considering three zones within riparian buffers. Further, in the SWAT-REMM prototype, drainage from subwatersheds was differentiated, if necessary, into concentrated drainage flow that directly entered the channel or riparian buffer drainage flow that was routed through the riparian zone (Liu et al., 2007). The enhanced SWAT-REMM model (Ryu et al., 2011) was enhanced to address the limitations of earlier versions and now allows users to specify riparian buffers individually by subwatershed, extract soil properties individually for each buffer, and use separate weather station data for each buffer. The enhanced SWAT-REMM model applied in the Bonggok watershed in Korea resulted in R^2 of 0.73 and NSE of 0.69 during calibration and R^2 of 0.72 and NSE of 0.67 during validation. Ryu et al. (2011) also evaluated the effects of riparian buffers on water quality. This enhancement for SWAT is valuable for assessing the water quality impacts of buffers for decision making.

SWAT-SOBEK: SWAT uses the kinematic wave approximation to route flow through the channel system. In situations such as backsurge effects due to dams, estuaries, and oceans, kinematic wave assumptions are not valid. The propagation of waves in the upstream direction decreases the stream velocity and, consequently, sediment transport capacity. The modified Bagnold equation used to determine the amount of sediment deposited or reentrained does not account for bed and bank erosion or sediment deposition due to backsurge in flow. In order to overcome these limitations in SWAT, the model was linked with SOBEK, which has the capability to simulate unsteady, non-uniform flow conditions (Betrie et al., 2011). In this integrated modeling approach, using Open Modeling Interface to couple SWAT to SOBEK, the upland hydrologic components and soil erosion were estimated using SWAT, and the flow and sediment routing was simulated in SOBEK. Testing this integrated modeling package over the Blue Nile River basin, Betrie et al. (2011) demonstrated improvement in simulating the effects of backwater on daily streamflow and sediment deposition.

SWAT-SWMM: Kim et al. (2011b) described the strengths of the integrated SWAT and Storm Water Management Model (SWMM) to simulate a mixed urban and rural land use. In their SWAT-SWMM integrated model, the RUNOFF block of SWMM was linked to SWAT. The SWAT-SWMM model was applied to the White Rock Creek watershed in Texas to assess the impacts of urbanization on hydrology due to incremental increase in impervious area.

SWAT-MODFLOW: Chung et al. (2011) demonstrated an application of the integrated SWAT-MODFLOW model to simulate the hydrological impacts of groundwater pumping in the Pyoseon region of Jeju Island, Korea, which has characteristic hydrology of highly permeable volcanic basalt rock with rapid stream percolation to recharge deep aquifers. The SWAT-MODFLOW model was designed to overcome SWAT's limitation in predicting groundwater flow as a result of pumping due to the spatial disconnection between HRUs and inability to simulate groundwater horizontal dynamics. Chung et al. (2011) concluded that SWAT-MODFLOW better simulated the pulse-type hydrographs typical of intermittent streamflow. SWAT-MODFLOW also helped in investigating the relationship between groundwater pumping levels and freshwater savings by simulating aquifer pump operations.

WATERSHED-SCALE SOIL EROSION ASSESSMENT

The SWAT model has been used to assess the risks of soil erosion and reservoir siltation in a tropical river basin in southern Mali in west Africa (Xie et al., 2011). Due to the lack of observed sediment data, this study conducted a water budget analysis to estimate the intensity of surface runoff that influences soil erosion. The researchers emphasized that data-scarce conditions lead to large uncertainties in estimation of soil erosion rates and even more so in estimation of reservoir lifespan. Details on channel cross-sectional geometry, reservoir operations, and bathymetry will improve modeled estimations. The researchers concluded that soil erosion is not substantial in the basin and, therefore, not likely the reason for low soil fertility, and recommend increasing the use of manure and fertilizers to improve soil productivity. Kim et al. (2011a) used SWAT to calculate transmission ratios (ratio of load delivered to the downstream reach to the load discharged into the upstream reach) to understand pollutant transport characteristics as a function of rainfall amounts and to identify critical areas needing greater attention in pollution control strategy implementation. Lee et al. (2011) applied SWAT to estimate the freshwater inflows to coastal bays, including Galveston Bay and Matagorda Bay in Texas, in order to obtain information on water quantity, quality, and temporal variation to help understand estuary hydrology.

SUMMARY AND CONCLUSIONS

This special collection demonstrates a continued increase in the number, breadth, and depth of SWAT applications to address various environmental issues and identifies specific model improvements to better address these issues. This collection reports enhanced model capabilities (e.g., addition of a subdaily erosion and sediment transport algorithm, a biozone module to simulate septic systems, and a new shallow water table depth algorithm) and applications to climate change impacts and soil erosion/sedimentation. In addition, several studies coupled SWAT with other models, which demonstrated improved simulation performance and representation of regional adaptation to local environmental conditions. The results in this collection add to previous syntheses of results (Gassman et al., 2007; Douglas-Mankin et al., 2010), thus providing a comprehensive assessment of current developments and applications of SWAT.

The international use of SWAT in regions other than the U.S. and Europe is rapidly increasing; however, the lack of input data at the required temporal and spatial scales is a typical limitation in these regions. Thus, proper planning of monitoring programs and alternative strategies for using different technology to develop environmental inputs is desirable. Data sharing between various data collection programs will aid researchers in developing sound scientific information through simulation models to help policy change recommendations. Application of SWAT for bacteria fate and transport, water footprint estimation of feedstock for biofuel production, economic implications due to climate change and land use change, and simulation of concentrated flow sources of sediment and nutrients (such as ephemeral gully, streambank, and legacy streambed sources) are some of the important topics that are not addressed in this collection and that require further development and application.

Adding to the knowledge base of previous reviews of the SWAT model, this collection provides further information on the new capabilities added to the model, and its application to investigate new problems and new geographic locations. It is hoped that this collection offers a platform for researchers, scientists, educators, and planners alike in understanding the present and potential scope of SWAT. This special collection in *Transactions of the ASABE* and *Applied Engineering in Agriculture* provides important information for the wider scientific community working in agriculture and water resources management.

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REFERENCES

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

Betrie, G., A. V. Griensven, Y. A. Mohammed, I. Popescu, A. E. Mynett, and S. Hummel. 2011. Linking SWAT and SOBEK using open modeling interface (OPENMI) for sediment transport simulation in the Blue Nile River basin. *Trans. ASABE* 54(5): 1749-1757.

Chung, I.-M., N. W. Kim, H. Na, J. Lee, S. Yoo, and S. Yang. 2011. Integrated surface-groundwater analysis in Pyoseon region, Jeju Island in Korea. *Applied Eng. in Agric.* 27(6): (in press).

Douglas-Mankin, K. R., R. Srinivasan, and J. G. Arnold. 2010. Soil and Water Assessment Tool (SWAT) model: Current developments and applications. *Trans. ASABE* 53(5): 1423-1431.

Faramarzi, M., K. C. Abbaspour, R. Schulin, and H. Yang. 2009. Modelling blue and green water resources availability in Iran. *Hydrol. Proc.* 23(3): 486-501.

Gassman, P. W., M. R. Reyes, C. H. Green, and J. G. Arnold. 2007. The Soil and Water Assessment Tool: Historical development, applications, and future research directions. *Trans. ASABE* 50(4): 1211-1240.

Harmel, R. D., P. K. Smith, and K. W. Migliaccio. 2010. Modifying goodness-of-fit indicators to incorporate both measurement and model uncertainty in model calibration and validation. *Trans. ASABE* 53(1): 55-63.

Jeong, J., N. Kannan, J. Arnold, R. Glick, L. Gosselink, and R. Srinivasan. 2011a. Development and integration of sub-hourly rainfall-runoff modeling capability with a watershed model. *Water Resour. Mgmt.* 24(15): 4505-4527.

Jeong, J., N. Kannan, J. G. Arnold, R. Glick, L. Gosselink, R. Srinivasan, and R. D. Harmel. 2011b. Development of subdaily erosion and sediment transport models in SWAT. *Trans. ASABE* 54(5): 1685-1691.

Jeong, J., C. Santhi, J. G. Arnold, and R. Srinivasan. 2011c. Development of algorithms for onsite wastewater systems in SWAT. *Trans. ASABE* 54(5): 1693-1704.

Joh, H.-K., J.-W. Lee, M.-J. Park, H.-J. Shin, R. Srinivasan, and S.-J. Kim. 2011. Assessing climate change impact on hydrological components of a small forest watershed through SWAT calibration of evapotranspiration and soil moisture. *Trans. ASABE* 54(5): 1773-1781.

Kim, N. W., and A. H. Shin. 2011. Modification of the SWAT model in the channel BOD simulation scheme for Korean TMDL application. *Trans. ASABE* 54(5): 1739-1747.

Kim, C.-G., S.-W. Park, and N.-W. Kim. 2011a. Analyzing hydrological transmission characteristics of nonpoint-source pollutants using SWAT. *Applied Eng. in Agric.* 27(6): (in press).

Kim, N. W., Y. S. Wong, J. Lee, J. E. Lee, and J. Jeong. 2011b. Hydrological impacts of urban imperviousness in White Rock Creek watershed. *Trans. ASABE* 54(5): 1759-1771.

Lakshmanan, A., V. Geethalakshmi, D. Rajalakshmi, R. Srinivasan, N. U. Sekhar, and H. Annamalai. 2011. Climate change adaptation strategies in Bhavani basin using SWAT model. *Applied Eng. in Agric.* 27(6): (in press).

Lee, T., R. Srinivasan, J. Moon, and N. Omani. 2011. Estimation of freshwater inflow to bays from gauged and ungauged watersheds. *Applied Eng. in Agric.* 27(6): (in press).

Liu, Y., W. Yang, and X. Wang. 2007. GIS-based integration of SWAT and REMM for estimating water quality benefits of riparian buffer in agricultural watersheds. *Trans. ASABE* 50(5): 1549-1563.

Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Binger, R. D. Harmel, and T. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* 50(3): 885-900.

Moriasi, D., J. G. Arnold, G. G. Vazquez-Amabile, and B. A. Engel. 2011. New shallow water table depth algorithm in SWAT2005: Recent developments. *Trans. ASABE* 54(5): 1705-1711.

Park, J.-Y., M.-J. Park, H.-K. Joh, H.-J. Shin, H.-J. Kwon, R. Srinivasan, and S.-J. Kim. 2011a. Assessment of MIROC3.2 hires climate and CLUE-s land use change impacts on watershed hydrology using SWAT. *Trans. ASABE* 54(5): 1713-1724.

Park, J.-Y., M.-J. Park, S.-R. Ahn, G.-A. Park, J.-E. Yi, G.-S. Kim, R. Srinivasan, and S.-J. Kim. 2011b. Assessment of future climate change impacts on water quantity and quality for a mountainous dam watershed using SWAT. *Trans. ASABE* 54(5): 1725-1737.

Ryu, J., J. Cho, I. J. Kim, Y. Mun, J. P. Moon, N. W. Kim, S. J. Kim, D. S. Kong, and K. Y. Lim. 2011. Enhancement of

SWAT-REMM to simulate reduction of total nitrogen with riparian buffer. *Trans. ASABE* 54(5): 1791–1798.

Schuol, J., and K. C. Abbaspour. 2006. Calibration and uncertainty issues of a hydrological model (SWAT) applied to west Africa. *Adv. Geosciences* 9: 137-143.

Schuol, J., K. C. Abbaspour, H. Yang, R. Srinivasan, and A. J. B. Zehnder. 2008. Modeling blue and green water availability in Africa. *Water Resour. Res.* 44: W07406.

Siegrist, R. L., J. McCray, L. Weintraub, C. Chen, J. Bagdol, P. Lemonds, S. Van Cuyk, K. Lowe, R. Goldstein, and J. Rada. 2005. Quantifying site-scale processes and watershed-scale cumulative effects of decentralized wastewater systems. Project No. WU-HT-00-27. Prepared for the National Decentralized Water Resources Capacity Development Project, Washington University, St. Louis, Missouri, by the Colorado School of Mines.

Wagner, P., S. Kumar, P. Fiener, and K. Schneider. 2011. Hydrological modeling with SWAT in a monsoon-driven environment: Experience from the Western Ghats, India. *Trans. ASABE* 54(5): 1783–1790.

Winchell, M., R. Srinivasan, M. Di Luzio, and J. Arnold. 2008. *ArcSWAT 2.1 Interface for SWAT2005, User's Guide.* Temple, Tex.: Texas A&M Agricultural Experiment Station, Blackland Research and Extension Center.

Xie, H., E. Nkonya, and B. Wielgosz. 2011. Assessing the risks of soil erosion and small reservoir siltation in a tropical river basin in Mali using the SWAT model under limited data condition. *Applied Eng. in Agric.* 27(6): (in press).