IJABE SWAT Special Issue: Innovative modeling solutions for water resource problems

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Abstract: The Soil and Water Assessment Tool (SWAT) ecohydrological model is used worldwide to evaluate hydrological and water quality concerns across a plethora of watershed scales and environmental conditions. The ten studies featured in this special issue confirm the global utility of SWAT, which include applications of the model in Brazil, China, Ethiopia and the United States. The range of applications reported in the special issue mirror broader trends in the extensive existing SWAT literature and provide valuable insights regarding input data sensitivity, testing, scenario analysis, software development and other important SWAT-related advancements. Brief summaries of these ten studies in this SWAT special issue are provided, highlighting key procedures and findings for each application. A brief description of SWAT structure and historical development is also given including a complete listing of key documentation and enhancements for every major release of the model between the early 1990s to the present time. This overview will serve as a guide to better reading and understanding of the ten research papers in this SWAT special issue of IJABE.

Keywords: Soil and Water Assessment Tool (SWAT), SWAT special issue, modeling solutions, water resource, watershed
DOI: 10.3965/j.ijabe.20150803.1763

Citation: Gassman P W, Wang Y K. IJABE SWAT Special Issue: Innovative modeling solutions for water resource problems. Int J Agric & Biol Eng, 2015; 8(3): 1－8.

1 Introduction

The Soil and Water Assessment Tool (SWAT) ecohydrological watershed model was originally developed in the early 1990s as a fusion of pre-existing models and other modeling concepts[1] that were primarily developed at the Texas A&M University and U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) laboratories that are co-located in Temple, Texas[2]. Since that time SWAT has continuously evolved as chronicled in several studies published in the past two decades[2-6]. The use of SWAT has also expanded greatly worldwide during that same time period as evidenced by review studies and/or special issue/section overview articles[4,5,7-13], documentation of the extent of SWAT peer-reviewed literature[14,15] and bibliometric analyses that reveal the impact of SWAT in water resource, geographic information system (GIS) and other disciplines[16-20].

SWAT has been applied to an extensive array of water resource problems as documented in the previously cited literature, such as the impacts of impoundments, best management practices (BMPs), climate change or land use change on streamflow and/or pollutant transport. Numerous studies have also been conducted to examine the sensitivity of SWAT to different resolutions of spatial delineations or input data. A wide range of preprocessing or postprocessing GIS-based and other

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Received date: 2015-06-20 **Accepted date:** 2015-06-28

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software have further been described in the literature that are designed to support various types of SWAT applications. This overarching domain of SWAT literature is embodied in the ten studies[13,21-29] that are part of the Special SWAT Section (Part 1) published in this issue of IJABE (Table 1). The majority of these studies were originally presented at one of the SWAT conferences that occurred in 2013 or 2014 and collectively provide important new insights on SWAT code development, sensitivity analyses of important inputs, supporting software and scenario analyses (Table 1).

Our objectives in this overview of the special section studies are to provide a short synopsis of SWAT historical development and present a brief summary of the ten special section studies including key findings reported in each respective study.

Table 1 Overview of studies published in the IJABE SWAT Special Issue

Study	Country	Watershed/region	Study focus	SWAT Conference[a]
Bressiani et al.(2015)[13]	Brazil	Entire country of Brazil (multiple study sites)	Comprehensive review of SWAT applications in Brazil during 1999 to 2014	2013 France
Panagopoulos et al. (2015)[21]	United States	528 000 km^2 Ohio-Tennessee River Basin	Evaluation of climate change and best management practice (BMP) impacts	2014 Brazil
Yen et al. (2015)[22]	United States	248 km^2 Eagle Creek (state of Indiana)	Comparison of runoff curve number methods	NA
Kalcic et al. (2015)[23]	United States	56 km^2 Little Pine Creek (state of Indiana)	Development of field-based hydrologic response units (HRUs)	2013 Indonesia
Taylor et al. (2015)[24]	NA	NA	SWAT code modularization developments	2013 France
Can et al. (2015)[25]	China	778 km^{2}Fuhe River (Jiangxi Province)	Evaluation of land use change impacts	2013 France
Ziadat et al. (2015)[26]	Ethiopia	54km^{2}subwatershed of the Tana River basin	Description and example application of Soil–Landscape Estimation and Evaluation Program (SLEEP)	2015 Italy
Mittelstet et al. (2015)[27]	United States	5 900 km^2 North Fork of the Red River (state of Oklahoma)	Evaluation of weather variability on crop yields and in-stream salinity levels	2013 France
Bressiani et al. (2015)[28]	Brazil	73 000 km^{2}Jaguaribe Watershed (state of Ceará)	Evaluation of different spatial and temporal weather data resolutions on streamflow	2013 France
Creech et al. (2015)[29]	Brazil	630 000 km^{2}São Francisco River Basin	Evaluation of anthropogenic impacts on the river navigation channel sediment budget	2014 Brazil

Note: [a] Information regarding the different International or Southeast Asia SWAT conferences can be accessed at http://swat.tamu.edu/conferences/. NA= Not applicable

2 Development and Structure of SWAT

The development of SWAT is a continuation of USDA Agricultural Research Service (ARS) modeling experience that spans a period of over 30 years[2]. From the outset, SWAT has represented a physically-based modeling approach infused with key empirical routines, which was designed for continuous modeling applications performed on a daily time step. This simulation approach was greatly facilitated by a lumped modeling strategy, in which users subdivide a watershed into subwatersheds and then further subdivide the subwatersheds into hydrologic response units (HRUs) consisting of homogeneous soil, vegetation, landscape, and management characteristics. Flow and pollutant fluxes are generated at the HRU level, then aggregated to subwatershed outlets, and ultimately routed to the watershed outlet. This modeling platform has proved to be greatly flexible and has resulted in widespread adoption for a broad spectrum of watershed scales, environmental conditions, and management, land use, and other scenarios.

The evolution of SWAT between version 94.2 (SWAT94.2), the first formally released version, and the current version 2012 (SWAT2012) is summarized in Table 2 in terms of key model enhancements and incorporation of new components. Documentation associated with each major release of the model and key research articles which provide descriptions and/or advancements in relation to specific versions are also listed in Table 1. Srinivasan and Arnold (1994) provide the first peer-reviewed description of interfacing SWAT with soil, topographic, land use and other GIS data layers in conjunction with the release of SWAT94.2. Arnold et al. (1998) later summarized the theory of core components that were incorporated into SWAT per the release of SWAT98.2, and which remain foundational components of current SWAT versions. Arnold and Fohrer (2005) followed with a brief overview of historical SWAT development and application trends, with particular emphasis on SWAT version 2000 (SWAT2000) theory, components, and applications. Gassman et al. (2007) further provide a concise qualitative description of SWAT2005 components and improvements, and also present an in-depth review of the SWAT peer-reviewed literature which existed at that time. Several additional key improvements were then incorporated into SWAT2009 and 2012 (Table 2).

Table 2 Previous major releases of SWAT by version number, documentation, and important enhancements

SWAT version	Documentation and/ or key papers	Important enhancements[a]
94.2	1, 30, 31	Interface of SWRRB and ROTO models; Development of groundwater component; multiple hydrologic response units (HRUs) and EPIC crop growth model added; routing command language added
96.2	32	Autofertilization & autoirrigation options; canopy storage of water; crop growth CO_2 routine, Penman–Monteith potential ET option, soil lateral flow of water based on kinematic storage model, QUAL2E in-stream nutrient water quality equations& in-stream pesticide routing added
98.1	3, 33	Snow melt routines and in-stream water quality improved; nutrient cycling routines expanded; grazing, manure applications and tile flow drainage options added; model modified for use in Southern Hemisphere
99.2	34	Nutrient cycling routines and rice/wetland routines improved, reservoir/pond/ wetland nutrient removal by settling added; bank storage of water in reach and routing of metals through reach added; SWMM urban buildup/wash-off equations
2000	4, 35, 36	Pathogen transport routine, Green–Ampt infiltration method, Muskingum routing method&unlimited number of reservoirs added; weather generator improved; all daily climate inputs can be read in or generated; all potential ET methods updated; elevation band processes improved; dormancy calculations modified for proper simulation in tropical areas
2005	2, 5, 37, 38	Incorporated forecasting of future weather patterns, ET-based runoff curve number method, improved sediment transport routines, continuous manure application option, forest growth to mature stand, SWAT-CUP[c] software &new option for simulating perched water; bacteria transport routines improved; subsurface tile drainage routines improved
2009	39, 40	Incorporated onsite wastewater systems submodel, sub-hourly rainfall runoff, impoundment, soil erosion and transport, and related algorithms, improved routines for filter strips and grass waterways, algorithms that account for temporal changes in managent practices and land use, improved water table dynamics component, enhanced irrigation routines & new routines for bed load transport in channels; Reservoir sediment deposition algorithms modified to include a settling coefficient based on particle size
2012	41	Incorporated routing of flow and sediment across landscapes within a subwatershed, sediment-filtration basins and other types of urban practices, management operations to remove crop residues, improved algorithms to remove crop residues, improved representation of miscanthus and switchgrass growth processes, algorithms depicting glacier melt and other glacier processes, extension of one-reservoir baseflow approachby adding a slow-reacting reservoir, a second more physically-based subsurface tile drainage component, improved soil and in-stream phosphorus cycling routines, tropical conditions and senescence modifications and improved tree growth algorithms.

Note: [a] Descriptions for versions 96.2, 98.1, 99.2, and 2000 are based on references 2 and 4.

[b] References 31 and 32 are no longer in print and are not available.

[c] SWAT-CUP software was subsequently removed from SWAT2009 and is now a stand-alone utility[42].

3 Overview of the studies in the SWAT Special Issue

The studies in the SWAT special issue include applications of the model that were performed in four countries on four different continents (Table 1). The use of SWAT has been well established in the United States during the past two decades as evidenced by well over 400 documented peer-reviewed journal articles[15] and hundreds of other studies reported in conference proceedings and other publications. However, increasing use of the model has also occurred during the past decade in the other three countries represented in the special issue (Table 1), with over 300 peer-reviewed journal articles identified that describe SWAT applications in China and over 40 such studies representative of watershed conditions in Brazil and Ethiopia. The studies reported in this special issue span a wide range of watershed scales (from 54 km^2 to 630 000 km^2), environmental conditions and types of applications. We describe each study below in terms of application region and/or application category.

3.1 SWAT applications in Brazil

Bressiani et al. (2015)[13] present a comprehensive overview of over 110 SWAT applications performed in Brazil, which captures the majority of dissertations, conference papers and journal articles published during 1999 to 2014 including many written in Portuguese. Initially, the authors review the complex biome, climatic and soil conditions that exist in Brazil, which pose major challenges for applying ecohydrological models such as SWAT. The characteristics of 102 SWAT publications are then surveyed in terms of application regions, watershed size, type of application, and calibration/ validation time periods and results. This is followed by a more in-depth summary of 19 recently published SWAT peer-reviewed studies published during 2012 to 2014, which includes descriptions of the types of applications and results of baseline hydrologic and sediment transport testing. They conclude by discussing common input data problems faced by SWAT users in Brazil, list an extensive array of possible input data sources and provide a summary of nine research needs that need to be addressed to improve the use of SWAT for future Brazilian applications.

Bressiani et al. (2015)[28] address SWAT climate data input issues for the Jaguaribe River watershed located in the state of Ceará in northeast Brazil. Baseline SWAT hydrologic testing results are described first, taking into account different evapotranspiration (ET) methods and a unique analysis of the effects of different warm-up period durations. Four different combinations of local, regional, global and/or generated weather combinations were then evaluated on the basis of the accuracy of replicating measured streamflow at four different gauge sites within the watershed. It was concluded that a combination of precipitation data obtained from local rain gauges, other climate data obtained from airports in the region and generated weather provided the best performance, and that the choice of climatic inputs is critical when conducting SWAT studies for the study region.

Creech et al. (2015)[29] describe a fascinating analysis of anthropogenic effects over the past 150 years on the sediment budget of the São Francisco River system that drains portions of seven states across much of eastern Brazil. They first present successful hydrologic and sediment transport testing results including a synopsis of net erosion sources and sinks. The calibrated model was then used to represent pre-European settlement conditions by removing dams constructed in the last century, adjusting stream widths in areas impounded by the dams (to represent pre-impoundment stream width conditions) and converting current agricultural and urban land use to original native Cerrado biome or Cattinga biome forest vegetation (see Bressiani et al (2015)[13] for biome descriptions). The comparison of pre-settlement versus present conditions revealed that sediment aggradation rates have increased by 20 Mt in the São Francisco River during the past 150 years.

3.2 Sensitivity Analyses in Indiana, United States

Yen et al. (2015)[22] explore the impacts of applying two Runoff Curve Number (RCN) methods available in SWAT for the Eagle Creek watershed located in central Indiana, United States. The authors evaluated the RCN method using both the traditional approach which is based on dynamically updated curve numbers (CNs) based on antecedent soil moisture versus an alternative approach which estimates runoff potential as a function of daily ET, which was introduced in SWAT version 2005 (Table 2)[5,37,38]. Both streamflow and nitrate transport results are reported in the context of Bayesian model averaging (BMA), Brier score model performance criteria and uncertainty analyses. They concluded that the ET-based RCN approach resulted in the best overall evaluation statistics for both the calibration and validation periods and the ET-based method also more accurately represented low flow and drought conditions.

Kalcic et al. (2015)[23] introduce an innovative scheme to configure HRUs based on crop field boundaries for the Little Pine Creek watershed located in west-central Indiana. They present their results on the basis of a comparison between the typical method of generating HRUs using non-spatially defined lumped land use, soil, slope and management versus the alternative property boundary defined approach. Successful streamflow testing results were found for both HRU methods but high erosion rates for a subset of vulnerable soils could not be discerned from the standard lumped HRU approach. They conclude that their alternative approach is flexible and adaptable to any watershed if the required data sets are available.

3.3 Climate change, land use change and other scenario analyses

Panagopoulos et al. (2015)[21] evaluate potential future climate impacts for the Ohio-Tennessee River Basin (OTRB), a large system that drains portions of several states in the east central United States, using an ensemble of seven global circulation models (GCMs) in combination with alternative cropping or management systems. The results of baseline calibration and validation are first presented, followed by comparisons of current climate (1981 to 1999) versus future climate (2046 to 2065) impacts for current cropping systems (dominated by rotations of corn and soybean), a total shift of cropland to continuous corn (representative of a greatly expanded biofuel scenario), adoption of notill on all cropland or adoption of cover crops on all cropland. The environmental impacts of the baseline and other scenarios were very similar between the current climate and the average future climate, except that a 20% reduction in nitrate loss was predicted for the average future climate relative to baseline conditions simulated with the current climate. Hydrologic and crop yield impacts are also reported.

Mittelstat et al. (2015)[27] extended a typical SWAT application by interfacing SWAT streamflow output with a regression equation to estimate in-stream salinity levels for the North Fork of the Red River which is located in southwest Oklahoma and the Texas Panhandle, United States. Baseline testing of SWAT is reported first for both streamflow and wheat, dryland cotton and irrigated cotton crop yields followed by development of the relationship between SWAT streamflow and salinity using electrical conductivity estimates. Possible future variation in crop yields and in-stream salinity levels are then evaluated on the basis of 10 different generated weather sequences executed over a 50-year period. The results show that some portions of the stream system are too saline to support irrigation of wheat and cotton crops and that this can be overcome only with the installation of salinity control measures.

Can et al. (2015)[25] analyzed six different historical or hypothetical land use scenarios versus baseline land use that consist of different combinations of agricultural land, rice paddies, forest, pasture, urban and other land use for the Fuhe River watershed located in southeast China. They report successful streamflow calibration and validation results at the watershed outlet and provide further validation results for one year for seven other gauge sites located in the watershed, which is an extensive number of testing sites compared to the majority of SWAT literature[15]. The scenario results showed that surface runoff declined while groundwater recharge and ET levels increased in response to increases in forest, agricultural land or pasture, or when urban areas or areas managed with rice paddies decreased. The results further indicate that increases in urban land result in largest changes in key hydrologic indicators and that forest has a greater capacity to conserve water compared to pasture.

3.4 New SWAT code and other software developments

Taylor et al. (2015)[24] discuss forthcoming code modernization and modularization that is being adopted for future versions of both SWAT and the closely related Agricultural Policy/Environmental eXtender (APEX) farm-scale model[2]. They initially provide background information regarding the historical development of the two models and the Fortran programming language, and then describe modern Fortran object oriented coding techniques that can be applied to APEX and SWAT. Several examples of object-oriented code structures for specific algorithms are described as well as enhanced streamflow and pollutant routing structures that provide multiple advantages relative to currently used routing procedures. The authors also clarify that the model codes are now being revised per these object-oriented coding methods and that ultimately seamless communication will be supported between APEX, SWAT and related models.

Ziadet et al. (2015)[26] describe the development and application of the Soil-Landscape Estimation and Evaluation Program (SLEEP), a novel software designed to estimate soil layer properties required for SWAT and other models in regions with limited available soil data. The underlying theory and software structure are first discussed including descriptions of SLEEP variables and attribute processing steps. They then provide an in-depth overview of required SLEEP processing steps, example testing of generating key soil properties and an example SWAT application demonstrating the effects of different soil input data; both examples were performed for a subwatershed of the Lake Tama watershed in Ethiopia. The SLEEP software is expected to become available for download on the SWAT website[42] sometime during the second half of 2015.

4 Conclusions

The studies included in this special issue demonstrate the flexibility of SWAT for investigating an extensive range of water resource problems across considerably different watershed scales and environmental conditions. These studies further confirm, within the context of the overall body of SWAT literature[15], that SWAT is one of the most versatile ecohydrological models currently available for addressing watershed-scale hydrological and water quality problems. However, considerable SWAT research and development needs remain to be addressed such as those described by Bressiani et al.[13] and in other previous studies[e.g.,10,12]. It is anticipated that the expansion of SWAT capabilities in the future will result in an even more viable tool that can be used worldwide to help solve critical water resource problems.

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