Soil and Water Assessment Tool (SWAT) for Modeling and Simulation in Water Resources Engineering

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Abstract

In recent times there is a continuous influence by climate change and human activities on the environment giving rise to hydrological focus research. Hydrologic modeling tools are employed to examine various practical issues arising from planning, design, operation, and management of water resources systems. These include physical, empirical, stochastic, distributed models and open-source watershed models such as Info Works River Simulation (IWRS), Stormwater Management Model (XP-SWMM), Soil and Water Assessment Tool (SWAT), Kinematic Runoff and Erosion Model Software (KINEROS), Long-Term Hydrologic Impact Analysis (L-THIA) and River Analysis System (HEC-RAS). From the models mentioned, SWAT is a typical distributed model widely used in analyzing and forecasting several complex hydrologic variables. This paper is aimed at providing an overview of SWAT and its applicability in hydrological modeling.

Keywords: Soil and Water Assessment Tool (SWAT), hydrologic modeling, water resources management

1. Introduction

Recent studies in the field of water resources employ the use of several models ranging from a simple linear regression model, for instance, to simulate the effect of anthropogenic activities on the surface and groundwater yield, to much more sophisticated models requiring advanced knowledge in programming and soft computing skills, statistics and Geographic Information Systems (Shen, 2018). Most times, this variety of models are commonly developed and used by researchers to measure the impact of human activities on hydrologic variables including; water quality and biodiversity, air pollution on climate change, and land management practices on soil erosion and sedimentation. The results of such models have given vital insight into the causes of declining environmental quality, which in turn helps policy and decision-makers in formulating appropriate policies for water resources systems. Given the several available hydrologic models studied, Soil and Water Assessment Tool (SWAT) have been identified to provide satisfactory results in modeling large complex catchment and long-run NPP simulations for agricultural watershed (Borah & Bera, 2003).

SWAT is a watershed model developed by the Grassland, Soil and Water Research Laboratory of the USDA Agricultural Research Service. The model is a basin-scale, continuous-time model that operates on a daily time step and is designed to predict the impact of management on water, sediment, and agricultural chemical yields in ungauged watersheds. The model is described to be computationally efficient, physically based, and capable of continuous simulation over long periods (Gassman et al., 2007). SWAT's main components include weather, hydrology, soil temperature and properties, nutrients, plant growth, pesticides, bacteria and pathogens, and land management.

Besides, SWAT is a model that has been under development by the USDA Agricultural Research Service in conjunction with several other models for over three decades. This development can be traced to research works carried out by incorporating several models such as; Groundwater Loading Effects on Agricultural Management Systems (GLEAMS) model, Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model and the Environmental Impact Policy Climate (EPIC) model (Figure 1). The SWAT model presently in use is a direct descendant of the Simulator for Water Resources in Rural Basins (SWRRB) model which was designed to simulate the effects of management on water and sediment movement for ungauged rural basins across the United States of America (Gassman et al., 2007).

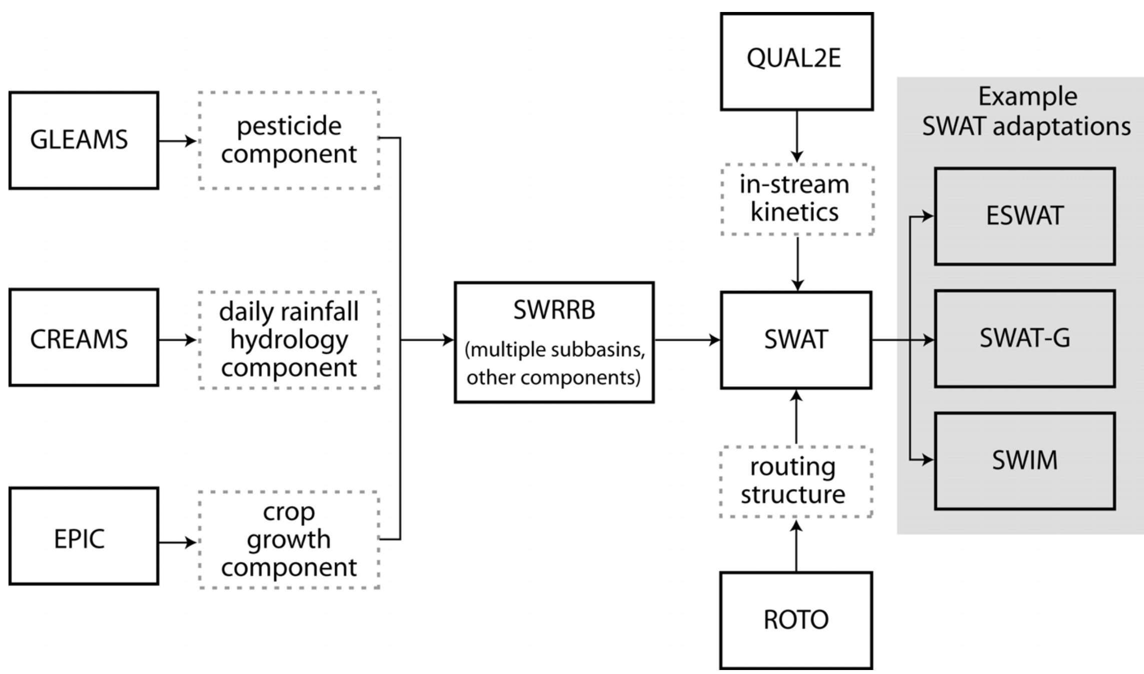

Figure 1. Schematic of adapted models for SWAT development (Gassman et al., 2007).

SWAT has been subjected to constant review and its capacity expansion has continued, such as the incorporation of an in-stream kinetic routine from the QUAL2E model. Furthermore, several versions have been developed for unique purposes such as; (i) Soil and Water Integrated Model (SWIM) used to assess the effects of climate change-related to land-use change, (ii) SWAT-G model used to forecast streamflow in Germany; and (iii) Extended SWAT (ESWAT) which allows for an hourly time step (Arnold et al., 1998).

The availability and knowledge of hydrologic modeling tools are essential in applying the appropriate model to suitable scenarios. This paper illustrates the applicability of SWAT as a useful tool for modeling. The following section presents short reviews of selected published research papers.

2. Water resources assessment with SWAT

Hydrological research has been conducted in different parts of the world using SWAT to address hydrological questions including the following selected fields; sediment and erosion, irrigation, dams and impoundments, surface and groundwater shortage, and climate change. SWAT applicability for modeling and simulations in highlighted areas of study is elaborated in the subsections presented below.

2.1 Sedimentation

Anthropogenic activities such as urbanization, extensive agricultural land cultivation, and deforestation give rise to enhanced erosion and sedimentation globally (Muhammad et al., 2019). Sedimentation and erosion have affected several countries globally regarding the extent, intensity, and their economies even though its measurement is still not widespread. In this subsection, three published research articles on sediment yield and concentration are reviewed. One in Malaysia at the upper Langat River basin (Nor et al., 2014) while, the other two are in Africa specifically at the upper watershed of Kainji hydropower dam in Nigeria (Adeogun et al., 2020) and Ziway Lake basin in the rift Valley of Ethiopia (Aga et al., 2020).

The paper published by Nor et al. (2014) suggests that urban areas are responsible for substantial sediment contribution to the upper Langat River Basin. This conclusion was reached as a result of the integration of streamflow and sediment yield using the SWAT model, with the simulation results of 30 years precipitation record indicating suspended sediment not likely to be affected by average water quantity.

In the study by Aga et al. (2020), SWAT model is used to simulate sediment yield based on hydro-geomorphology and streamflow for the Ziway Lake basin. The basin was divided into Maki and Katar sub-basins for ease of SWAT application. The Sufi-2 program was employed to validate and calibrate the SWAT model for both sediment yield and streamflow. While, its performance was evaluated by statistical means namely; Coefficient of Determination (R^2), Nash-Sutcliffe efficiency (NSE), Root Mean Square Error (RMSE), Observations Standard Deviation Ratio (RSR), and Percent bias (PBIAS). Katar sub-basin was used to validate the model and test its applicability. Hence, its applicability to the Maki sub-basin exhibits excellent performance.

Similarly, the objective of the study by Adeogun et al. (2020) is to model and simulate sub-basins sediment yield and concentration of the upper watershed of the Kainji hydropower dam using the SWAT model incorporated within the MapwindowGIS. The Swat model was run for a period of 30 years using a daily time step, calibrated, and validated. Also, the Coefficient of Determination (R^2) and Nash Sutcliffe Efficiency (NSE) are used for performance evaluation. Based on the simulation results, the average annual sediment yield and concentration amount to 35.29 t/ha/year and 11903.7 mg/l. Sediment yield and concentration decline up to 37 % and 34 % respectively by applying filter strips on erosion prone areas. Besides, 75 % and 84 % decrease in sediment yield and concentration respectively is due to the construction of stone bunds around the watershed. The authors concluded by agreeing that SWAT can be used by policymakers and researchers in implementing best management practices in watersheds as it allows control to be focused on identified critical areas.

2.2 Irrigation

Catchments with agricultural land with thorough irrigation systems require the use of fertilizers, surface water, and groundwater in a systematic manner . Due to the imbalance between water and nutrient provided by humans during irrigation, modeling tools are explored to provide vital information for proper management. A Few selected papers in this subsection presents modeling solutions for irrigation using the SWAT model.

Wu et al., (2019) modified SWAT with a simulation module for automatic multi-source irrigation (AMSIM) to incorporate the peculiarities of paddy rice irrigation system. The hybrid model was applied to the Zhanghe Irrigation System (ZIS) in China. Based on simulation results, a proposed calculation technique on flow return and reuse amount were deduced. SWAT is used in Pinios catchment, Greece faced with water scarcity by Panagopoulos et al., (2014) to evaluate the cost-effectiveness of different irrigation best management practices including; precision agriculture, deficit irrigation, conveyance efficiency improvement, wastewater re-use to cut down the water withdrawal due to irrigation. As a result, suggestions were made regarding best management practices that will result in minimal total cost.

Due to an increase in the use of hydrologic modeling tools to manage non-point agricultural pollutant use by researchers for the decision-making process, Sorando et al., (2019) use SWAT to model the water balance and nitrate pollution of an irrigated agricultural catchment of Aragon, Spain. The catchment water input is primarily from precipitation amounting to 45 % while the remains are contributed by two rivers outside the study watershed via irrigation canals. The water balance component of the watershed is mainly green water flow and storage. The simulation results reveal that the green water flow and storage in sub-watershed present a similar trend with areas centrally located in the watershed with irrigation agricultural systems. Also, a similar trend was exhibited between the central irrigated sub-watersheds and the non-irrigated sub-watersheds for blue water. Furthermore, there is a high level of nitrate infiltration amounting to 100 – 250 kg N ha/yr. in the inner irrigated sub-watersheds aquifer, with a much lower lateral flow rate of 1400 – 2000 250 kg N ha/yr. for watersheds not irrigated. Therefore, the authors argue that a reduction in irrigated water will change the catchment area from agricultural irrigated crops to cereal.

2.3 Dam and impoundments

Dams and other forms of impoundments on rivers and streams for irrigation, storage, and flood control, water supply, and power generation have caused alterations to flow and sediment due naturally downstream (Adnan et al., 2018). Because of these problems, several studies have been carried out to assess the hydrologic effect of dams on rivers. A similar such study was carried out by Xu et al., (2013) using SWAT to examine the effects of check dams in the Loess Plateau, China. The simulations reveal regulations due to the check dams result in a significant change in sediment load and runoff.

The Yakima River basin in the United States of America is faced with the management practices challenge due to the influence of reservoir operations and cropland irrigation on the watershed hydrologic variables. Soil and Water Assessment tool was deployed by Qiu et al., (2019) to simulate streamflow using several reservoir operations and schemes. The authors reported that water losses were more with irrigation practices scenarios compared to when only reservoir operations were considered. Therefore, there is a need to include reservoir operations and irrigation management in arriving at acceptable satisfactory results in modeling watershed hydrology.

2.4 Surface and groundwater

Safe water yield can be described as achieving and sustaining a long-term balance between the annual depletion of groundwater and the annual volume of recharge (Sophocleous, 1997). Maintaining a safe yield requires a precise quantification of the balance components, which can be achieved with a surface and groundwater modeling tool that accounts for changes in baseflow flow following groundwater abstraction.

In one of the research studies reviewed, SWAT was used by Saini et al., (2018) to model water yield, groundwater recharge, evapotranspiration, and percolation of the upstream part of the Shimsha river basin, Kanva watershed located in southern semi-arid India with approximately 352 km^2 watershed area. The post clarification technique was used to evaluate the land use/land cover variations between 1995, 2003, 2004-2016. Land change Modeller software was used to simulate the year 2020 land use/land cover scenario. The level of acceptable accuracy was deduced from the comparison of actual to simulated maps. The results from the SWAT calibration and validation reveal changes in land use/ land which include substantial reduction of scrubland, fallow land, and shrub forest whereas there is an increase in agricultural and plantation land. Furthermore, between 1995-2003 and 2004-2016 shows an increase of 1.74 %, 4.65 % in percolation, and groundwater recharge respectively, with a decrease of 0.51 % in the coefficient of evaporation. Assessment of the hydrological activities resulting from this simulation indicates that changes in land-use / land-cover may affect trends of groundwater drainage and surface runoff within the watershed. In conclusion, the authors suggest that appropriate management practices should be encouraged given the uncertainties in hydrologic regimes because of variabilities in land-use / land-covering.

SWAT was used by Kaur et al., (2019) to examine the temporal and spatial variability of blue (streams, rivers, aquifers, and lakes) and green water resources (atmospheric water; evaporation, and transpiration) within the Grand River Watershed (GRW) in Ontario Canada. The GRW is one of the largest watersheds in the southwestern part of Ontario, it is susceptible to flooding especially the periods preceding high snowfalls. The GRW is characterized by considerable agricultural land amounting to 40 %, pastures and grasses 26.92 %, forest 12 %, urban areas 9.29 %, and minimal wetland with 1.8 %. The streamflow result after calibration and validation of the SWAT model was satisfactory with good performance values of 0.75 Nash-Sutcliffe Efficiency (NSE) and Coefficient of determination (R^2) of 0.5. The authors argue that changes in blue water resources can be attributed to variabilities in precipitation. On the other hand, green water is affected by some variables (temperature, precipitation, and land use/land cover). In conclusion, the model results show that urban areas are largely prone to blue water scarcity, with green water showing little scarcity in the watershed.

In another study in the Mihocheon watershed, South Korea by Chung et al., (2015) a combination of SWAT with MODFLOW was used to evaluate the water balance component for groundwater pumping scenarios. Results reveal that long term safe water yield will amount to 104 mm annually which is below the current legal withdrawal limit. The authors warn that this equilibrium may be altered by climate change and other external variables and should be studied separately.

2.5 Climate change

Recently numerous research articles have been published on the effect of climate change on hydrological parameters using statistical approach including studies by Nda et al., (2018) on palm oil fresh fruit bunch yield and other numerous studies using the SWAT model. For this purpose, several greenhouse gas emissions and climate scenarios from regional to global climate models either directly or otherwise are used. The outputs are strongly dependent on the applied scenarios, and this sub-section provides an overview of a few selected previous studies carried out in the area of climate change.

For instance, an evaluation of the impacts of climate change on water resources was conducted by Roth et al., (2018) in the Blue Nile Basin (BNB) Ethiopia using SWAT. The research was aimed at identifying the basin likely changes over space and time. It is important to evaluate the impact of climate change in the area of study due to its socio-economic and geographical positioning of the region. BNB drains 43 % of the country's average runoff, a land surface area of 17 % with a total drainage area of 175000 km2. SWAT model was validated and calibrated with the measured rainfall data and observed streamflow data. Three different Global Circulation Model (GCM) future climate scenarios were run with the calibrated model. Rainfall and streamflow patterns were examined with a predicted increase of 7 – 48 % in precipitation and a corresponding increase of 21 – 97 % in streamflow arising. Also, GCMs projections reveal the possibility of a more distributed precipitation and a gradual decline in precipitation intensity during the year in view.

Guevara-Ochoa et al., (2020) analyzed the impact of climate change on water resources for the upper creek basin of Del Azul, Buenos Aires province using the SWAT model. The study was aimed at implementing an integrated hydrological - hydrogeological model to quantify the spatiotemporal dynamics of water balance and groundwater-surface water (GW - SW) interactions under different climate change scenarios. Two scenarios regional climate models; CCSM4 and Representative Concentration Pathways (RCP) 4.5 and 8.5 were simulated for thirty years starting 2020, with 2003 – 2015 baseline scenario validation and calibration period. Anomalies of several variables including groundwater reserves, surface runoff, discharge, precipitation, temperature, evapotranspiration, soil moisture, recharge, flow, and head level were considered on a monthly and annual basis. Also, GW-SW anomalies analyzed as spatiotemporal. Lastly, the wet and dry seasons examined by the standardized precipitation index (SPI) as well as the annual water balance. The simulation reveals that GW – SW interactions and the water balance will be altered by climate change significantly. There is an indication of monthly, annual, and seasonal variations. There was an increase in the water balance component as the 21st century approaches the middle except for soil moisture. Also expected based on the simulation result is the increase in the average annual discharge of the aquifer to the stream by 5 % and 24 % with RCP 4.5 and 8.5 respectively. Furthermore, an increase of about 12% is expected regarding recharge from the stream to the aquifer under RCP 4.5 while a decrease of 5 % is recorded with RCP 8.5. Conversely, the SPI component of the water balance for 30 years (2020 – 2050). The RCP 4.5 projected low occurrence of wet periods with high severity and performance whereas, RCP 8.5 presents the minimal frequency of wet periods with high severity and performance. In conclusion, the authors opined that climate change is capable of altering the groundwater levels by variabilities in its recharge leading to reversed GS – SW flow in some sections of the stream.

Another study was carried out in Malaysia by Mohd et al., (2015) to evaluate the impact of climate change on streamflow of the Kuantan River basin by integrating statistical climate downscaling tools with the SWAT model. The simulation result reveals an increase in streamflow patterns towards the end of the 21st century, especially in September and August. This increment is expected to amount to 100 % under the RCP 8.5 scenario and a slight decline during the middle-term period to 50 % in August for both RCP 8.5 and RCP 4.5 scenarios. Besides, there was no significant decrease observed from the pattern, asides a minor one recorded in the near-term period in November. These results affirmed that SWAT can be applied as a modeling tool for catchment planning and management.

3. Conclusion

The use of hydrologic models is increasingly sought by many researchers from different disciplines to examine the ever-ending potential influence of human development on hydrologic resources in terms of quantity and quality at the river basin scale. SWAT is a widely accepted tool used as a valuable model for managing and planning watersheds. The model can simulate and be operated for both long-term and short-term scenarios. Besides, the SWAT model can be applied for forecasting at a varied regional scale with different physiographic and climate conditions. Given the results exhibited in the reviewed papers in previous subsections, SWAT can be arguably referred to as one of the most widely employed modeling tools for solving water resources issues in the world today.

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