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An Assessment of Ongoing Developments in Water Resources Management Incorporating SWAT Model: Overview and Perspectives

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ABSTRACT

Land and water are the most necessary natural resources because the entire life system depends on them. It requires proper management to achieve maximum utilization. When used in conjunction with Arc GIS, the Soil and Water Assessment Tool (SWAT) is a promising model for simulating the agricultural watershed since it can forecast runoff, sediment and nutrient transport, and erosion under various management scenarios. Furthermore, the model is better at evaluating both the spatial and non-spatial variation of hydrological methods under a very large watershed. This study uses the methodology employed by the SWAT model for the estimation of surface runoff and sediment yield and discusses in detail the setup of the model computer file needed by the model sensitivity analysis parameter and validation area unit. SWAT is a well-known hydrological modeling method used in many hydrologic and environmental simulations. Over 17 years (2005-2021), 212 studies were found from various peer-reviewed scientific publications listed on the SWAT online database (CARD). Applicability studies were divided into five categories: water resources, streamflow, erosion, land-use planning and agricultural settings, climate change scenarios, and model parameterization. Hydrologic phenomena and adaptations in various river basins have been investigated. They mostly examined environmental impacts and preventive techniques to ensure an understanding of effective environmental regulation. Streamflow susceptibility to climatic changes was shown in climate change studies. Modeling streamflow parameters, model modifications, and basin-scale calibrations were investigated. Future simulation aspects such as data sharing and the opportunity for improved future analysis are also discussed. A multimodal approach to future simulations, as well as more efforts to make local data available, are both very good ideas.

INTRODUCTION

Simulators of hydrological and water resources have been widely utilized to overcome global water resource concerns. The assessments were mostly done using computer simulations, which save money by simulating real-world processes in space and time. They are also utilized to understand physical processes better and quantify water distribution in varied environments. Hydrologic models and new improvements in GIS have made this technique a good choice for water resources and environmental assessment. So, they have been used more recently to assess water resources (Krysanova & White 2015, Zhang & Al-Asadi 2019). The SWAT model is widely recognized as one of the key hydrological models used to address hydrologic and environmental concerns globally. Derived from the SWAT model, it is physically dependent, semi-distributed, and continuous-time to analyze water resources and anticipate the implications of land use/cover changes and land management strategies on soil degradation, sedimentation, and non-point source pollution (Arnold et al. 1998, Gassman et al. 2007). It has also been reported in peer-reviewed journals in curve number alteration, wetland applications, and best management practices (Akoko et al. 2021). Previous SWAT model uses have been studied. For example, compared to other models identified and reviewed, the historical development and applications of the SWAT model (mainly in the USA and parts of Europe) (Akoko et al. 2021, Arnold & Fohrer 2000, Harper et al. 1999). More than 20 peer-reviewed journal articles describing the SWAT model used in the Upper Nile Basin were identified and reviewed (Van Griensven et al. 2012). Since 2006, 126 articles have been highlighted and assessed in Southeast Asia, focusing on model applications, existing complexities, and potential research suggestions (Tan et al. 2019). Over 100 SWAT studies (published 1998–2016) were identified and reviewed in Brazil (de Almeida Bressiani et al. 2015). This article review attempted to consolidate and classify SWAT applications into similar domains as the research mentioned above, even though some of these topics are strongly related or overlap. The objectives of this review study are to describe the significant findings of SWAT applications in various studies, examine the existing problems associated with SWAT model applications, and identify prospective SWAT model modifications that could be used in future research.

OVERVIEW OF REVIEWED PAPERS

On April 30, 2021, the SWAT literature database (https://swat.tamu.edu/) returned almost 3500 articles using the keyword "SWAT". After selecting the articles written in India, the number of papers was reduced to 212. The database contains peer-reviewed publications (CARD). Fig. 1 depicts the review methodological framework.

The SWAT model is a physically-dependent continuous time scale, deterministic and long-term simulation model (Mishra et al. 2006). It is an open-source model and was put together by the United States Department of Agriculture and Agriculture Analysis Service (USDA-ARS) and the Texas A & M University system (Mishra et al. 2006). This model's major goal is to understand how land management affects water, agriculture, and sediment outputs.

Application Considering for Streamflow Simulations

Water resource studies have focused on extreme weather occurrences (floods and droughts) at several regional and national levels. For example, the SWAT model can simulate stream flows in ungauged basins (Chaibou et al. 2016). Analyze runoff processes to help build water resources (Dessie et al. 2014), and calibrate the rainfall-runoff model using remote sensing data (Milzow et al. 2011). The SWAT model was used to study surface and groundwater resources. In dry regions, measuring water supplies is important for simulating major hydrologic processes (Ouessar et al. 2009, Sultan et al. 2011).

Application Considering as a Context of Climate Change

The SWAT model was used to evaluate future climate change impacts on water supplies. The research looked at water management, the availability of water, and agriculture, as shown in Fig. 2. The results were utilized to manage and develop water resources in the Nzoia catchment, Kenya (Githui et al. 2009), and emphasize the importance of the precipita-

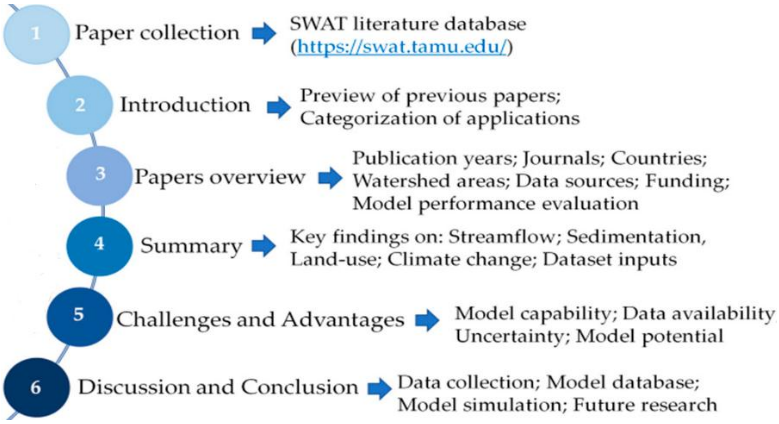

Fig. 1: Review methodology framework (Akoko et al. 2021).

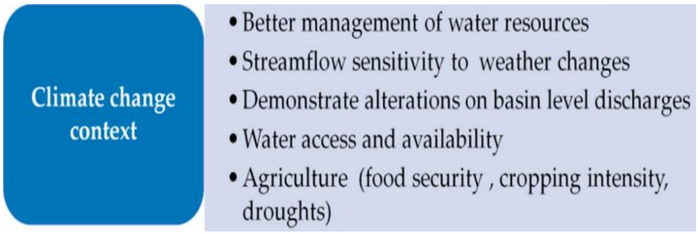

Fig. 2: SWAT model application in climate change context (Githui et al. 2009).

tion–evaporation balance in the river Mitano basin, Uganda (Kingston & Taylor 2010). Increased rainfall and greater temperatures predicted by SWAT will put an enormous strain on Ethiopia's Keleta River watershed's hydrologic cycle (Bekele et al. 2019).

Application Considering for Sediment Yield Erosion

The SWAT model was used to study sedimentation in numerous Indian river basins and designate and prioritize soil erosion-prone locations (Gessesse et al. 2015), and provide quantitative insight into the efficiency of erosion control strategies (Hunink et al. 2013). Various researchers found that installing filter strips, stone bunds, and forestry reduced current sediment outputs using the SWAT model. The SWAT model does not adequately reflect several physical phenomena, making the exact interpretation of quantitative data difficult (Betrie et al. 2011). The model was made to replace the sediment-rating curve and long-term sediment yield rate forecast. It was used to see how dams would affect semi-arid watersheds (Ndomba et al. 2008, Zettam et al. 2017).

Model Application for the Agricultural Land Use/Land Cover Management

The use of the SWAT model to assess the influence of agricultural conservation strategies on water and sediment output helped to develop ecologically sound watershed management and development plans (Mwangi et al. 2015). The SWAT model was used to demonstrate how afforestation in dry sub-basins can counteract afforestation stress in wet sub-basins without affecting the basin's water balance (Nyeko et al. 2012). An analysis of daily flow sensitivity to changes in land use (converting a portion of the forestland to agricultural) found that a decrease in rainfall equals an increase in annual flow (Melesse et al. 2008). The SWAT model was used to investigate the effects of agriculture production on the hydrological processes and simulate the effects of agricultural conservation measures such as contour farming, grass strips, and filter strips on sediment and water yield (Mourad & Sang 2018).

Model Application for the Parameter Selection and Input Dataset

According to Fig. 3, the following applications are included in the case of a model application for the selection of parameter and input datasets such as basin-scale calibration, water yield evaluation, and simulations using rain-gauge and worldwide rainfall data. The SWAT model was used to characterize and assess effective soil moisture capacity distribution across hydrological response units (HRUs) and systematically calibrate a complicated basin-scale model without explicitly matching model outputs to measured streamflow (Easton et al. 2011). By comparing uncalibrated SWAT model simulations of the leaf area index (LAI) utilizing the modified (SWAT-T) and normal SWAT vegetation growth modules, the structural improvements of SWAT's vegetation growth module for tropical forests were proved (Alemayehu et al. 2017). In the Wami River basin, the SWAT model was further constrained to reduce equivocality and forecast uncertainty, suggesting that adopting extra constraints leads to more reliable and accurate predictions (Wambura et al. 2018).

SENSITIVITY ANALYSIS

SWAT model standardization and Validation first determine the most sensitive parameter for a given watershed or sub-watershed that considerably affects the model output at intervals of the given model input. SWAT may be a complicated model and manual standardization of the many parameters may be quite troublesome (Setegn et al. 2010). Sensitivity analysis helps to see the relative ranking of which parameters most affect the output variability (Shang et al. 2012). Sensitivity analysis indicates the necessity of the parameters in determining the sediment concentration, nutrient loss, and streamflow of the study space to reduce the maximum uncertainty in model output. It permits the attainable reduction in various parameters that must be tagged, thus reducing the standardization method procedure time. It also reduces the model's uncertainty and gives ideas for how to figure out the parameters for the standardization method. Table 1 and Table 2 represent the initial parameters utilized in the sensitivity analysis for the surface runoff

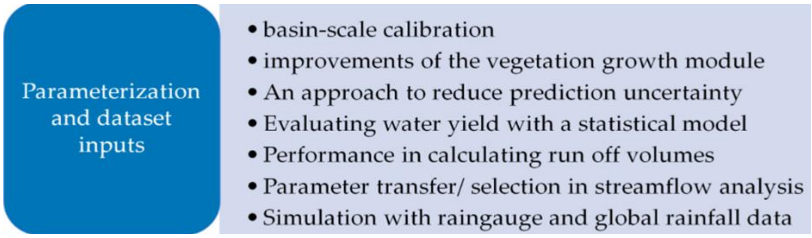

Fig. 3: Model application for the parameter selection and input dataset (Akoko et al. 2021).

and sediment yield standardization. Model standardization attempts to increase parameterization for a given set of native conditions, thereby reducing the prediction uncertainty. Standardization has been performed by rigorously choosing the model input parameters at intervals in their counseled uncertainty ranges. Calibration is nothing but adjusting the selected sensitive parameter within a recommended range to obtain a close agreement between observed and simulated due to uncertainty in model input, spatial variability, budget constraints, and access difficulties (Lweendo et al. 2017). Calibration becomes computationally extensive and complex when the number of parameters in the model is substantial.

Table 3: List of initially selected parameters for runoff modeling.

Parameter	Description of Parameters	Types of Parameters
SOL_K	Saturated hydraulic conductivity (mm.hr^{-1})	Soil water
SLP	Average slope steepness	Surface runoff
RCHRG_DP	Deep aquifer percolation fraction	Surface runoff
CN_2	SCS runoff curve number for AMC-2	Surface runoff
ALPHA_BF	Base flow alpha factor	Groundwater
GW_DELAY	Groundwater delay	Groundwater
SOL_BD	Moist bulk density	Soil water
CH_N1	Manning's "n" value for the tributary Channel	Channel process
ESCO	Soil evaporation compensation factor	Evapotranspiration
SURLAG	Surface runoff lag time	Surface runoff
GW_REVAP	Groundwater revamp coefficient	Groundwater
CH_K1	Effective hydraulic conductivity in the tributary Channel	Surface runoff
GW_SPYLD	Specific yield of the shallow aquifer	Groundwater
CH_K2	Effective hydraulic conductivity in the main channel	Surface runoff
SOL_AWC	The available water content of the soil	Soil water
SLSUBBSN	Average slope length	Geo-morphology
BLA1	Maximum potential leaf area index	Evapotranspiration
SOL_ALB	Moist soil albedo	Soil water
CANMX	Maximum canopy storage	Surface runoff
EPCO	Plant uptake compensation factor	Evapotranspiration

Referring to Fig. 4, SWAT-CUP is a computer program used within the SWAT-CUP package for calibration of the SWAT model. SUFI-2 (Sequential Uncertainty Fitting Version 2 program) is used for the above model calibration process.

However, model validation is nothing more than re-running the simulation, employing a different statistic for the input file while not dynamically adjusting any parameter that can be adjusted throughout standardization. To utilize the graduated model for estimating the effectiveness of future potential management practices, the model was performed against the freelance set of measured knowledge. With each standardization and validation phase, the model's prognostic capability was incontestable, and also the model was also used for future prediction.

MODEL EVALUATION

Several indices were used to evaluate the SWAT model outputs (see Fig. 5). The most widely used indexes were NSE, R2 (square of Pearson's product), PBIAS, IA, RVE, r bias, and VR (volume ratio). Each had one study. There were also RMSE, RSR (standardized RMSE), KGE (Kling Gupta efficiency), IVF (index of volumetric fit), and bR2

Table 2: List of initially selected parameters for sediment modeling.

Parameter	Description of Parameters	Types of Parameters
SPEXP	Exponential parameter for calculating sediment re-entertainment in the channel sediment routing	Channel
CH_N$_2$	Manning's "n" value for the main channel	Channel
SLSUBBSN	Average slope length	Geo-morphology
CH_S$_2$	The average slope of the main channel	Channel
OV_N	Manning's "n" value for the overland flow	Surface runoff
HRU_SLP	Average slope steepness	Surface runoff
SPCON	Linear amount of sediment that can be re-entertainment during channel sediment routing	Channel
CH_K$_2$	Effective hydraulic conductivity in the main channel	Channel process
PRF	Peak rate adjustment factor	Channel
CH_W$_2$	The average width of the main channel	Channel
CH_D	The average depth of the main channel	Channel
CH_I_2	The average length of the main channel	Channel

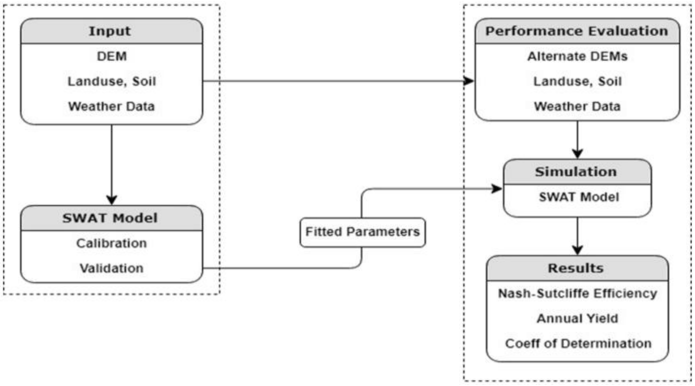

Fig. 4: Procedure for SWAT model run (Sedighi et al.2019).

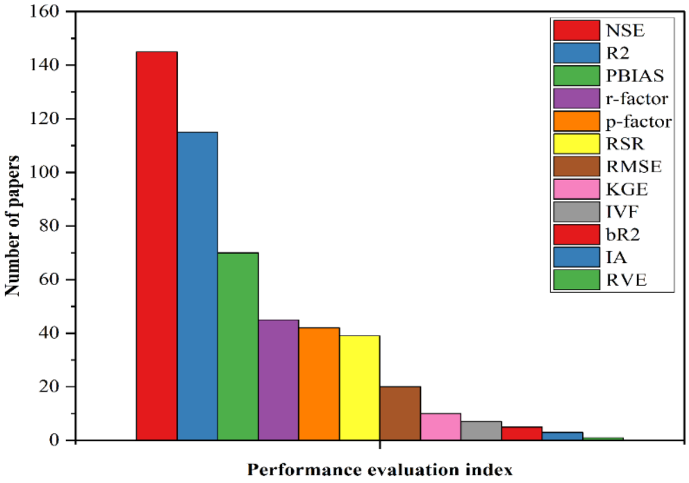

Fig. 5: Number of papers by different performance evaluation indexes.

(coefficient of determination x regression line between actual and predicted data).

ADVANTAGES AND CHALLENGES OF THE SWAT MODEL

1. SWAT has got worldwide acceptance, to integrate various environmental processes and is used for sustainable and effective watershed management.
2. The SWAT model is mostly applied in large watersheds due to the availability of accurate data.
3. SWAT is a continuous time scale deterministic model capable of simulating the long-term effects of management changes.
4. It is highly capable of integrating with the Geographical Information System (GIS).
5. It incorporates DEM, soil map, and land use map, meteorological parameters to generate runoff at the basin scale.
6. It provides a useful tool to fill in the missing daily data in the observed records.
7. The SWAT studies reviewed in this review highlighted several concerns. Data availability/gaps, quality of data, and model restrictions were all concerns. The SWAT model could not reproduce the dynamics of sediment yield transport at a watershed outlet in some seasons, highlighting its limitations in small catchments (Shendge et al. 2018). Calibration and validation of runoff and sediment processes enhance the accuracy of SWAT model simulations (Mwangi et al. 2015). The SWAT model's poor performance in streamflow modeling was attributed to the insufficient spatial correlation of datasets (Le & Pricope 2017).
8. Despite its limitations, the SWAT model has many

advantages, prompting numerous scientists to use it for hydrological applications. Thus, the SWAT model may be implemented more simply with fewer parameters but possess higher data needs, compared to certain other well-known (continental scale) hydrological and land surface models (Trambauer et al. 2013).

9. The above model is useful in assessing the costs and advantages of adopting sediment control BMPs (Jayakrishnan et al. 2005, Briak et al. 2016). Assessing the implications of land-use changes (Gyamfi et al. 2016), and in drought planning and mitigating in data-scarce locations (Lweendo et al. 2017). These were all suggested for watershed management. As a result, the SWAT model can predict water productivity and assess alternative water management approaches (Ouessar et al. 2009).

Limitation of SWAT model

1. SWAT does not simulate sediment routing and detailed flood routing because it was developed to predict the long-term erosion, sedimentation rates, and agriculture management impact.
2. It does not represent the heterogeneity of an aquifer, such as specific yield, spatially varying hydraulic conductivity, or hydraulic head.
3. It is limited to simulating stream seepage to the aquifer and groundwater discharge to the stream because it compares the shallow aquifer depth.
4. It does not consider the river bottom elevation and aquifer depth.
5. According to the SWAT user manual, it is better to use many sub-basins than many HRUs in a sub-basin. A maximum of 10 HRUs in a sub-basin is recommended.

DISCUSSION

Dataset unavailability was cited as a problem in many of the articles identified. Numerous studies have identified inadequate land use/land cover data quality as a problem, especially in land-use analyses. In future SWAT model investigations, good spatial and temporal data will be needed to provide more precise assessments and findings and reduce uncertainty. Also, SWAT model simulations should collect enough data to enable future evaluations and analysis by other modelers. Developing databases using model parameterization data could improve SWAT+ (Bieger et el. 2017). Accessing additional data could help expand the SWAT+ dataset with data from around the world, minimizing model setup and parameterization time. The SWAT model can predict how water will look in the future, and it can be used in agricultural development and strategic planning. The prior SWAT model featured a restricted number of concurrent components and no modeling of salt. SWAT+ provides the modeling of salt as a constituent, allowing for more extensive simulation of constituents and the routing of many pesticides simultaneously. Continued studies could use SWAT+ simulations to model nutrient transport, non-point pollution, and nutrient accumulation in water resources. The previous SWAT model included reservoirs on main channels at sub-basin exits, no pumping, canals, livestock herds, or managing water objects, and only one crop growing at a time. Water rights are described as spatial objects, and an endless number of crops can be planted simultaneously (Schuol et al. 2008). These changes allow for anthropogenic water evaluation. Future research could use SWAT+ to simulate future water availability for agriculture and other needs. Modeling of freshwater resources can help assess current sustainable water status and highlight areas requiring further investigation (Schuol et al. 2008). This is vital in creating regional and national agricultural infrastructure policies. Previous research has used the SWAT model to show the linkage between deforestation, sediment transport, and soil erosion. The model classifies water areas as HRUs and sub-basins as HRUs. SWAT+ separates water and land areas and identifies water areas as ponds/reservoirs (Bieger et el. 2017). Future studies could use this innovation to effectively understand environmental dynamics and incorporate population expansion and corresponding socio-economic challenges.

CONCLUSIONS

A method based on SWAT and other models can be powerful. Local, national, and regional policies should be aligned with scientific investigations. Researchers should emphasize changes, trends, and related impacts using defined environmental thresholds at the local and regional levels. Obtaining additional data for future studies will allow other researchers to conduct new studies, for example, as supplemental material for journals. We should encourage governments to undertake more research (especially local data collection) that addresses/incorporates, or adopts integrated watershed management and associated environmental topics, with which the SWAT model has demonstrated proficiency. Local data for modeling is insufficient, so many researchers use global data instead. Some of the data needed for such studies can be acquired from worldwide datasets. Researchers at government agencies, universities, and other academic institutions should use SWAT and SWAT+ to plan and manage the larger ecosystem and develop policies. The SWAT model estimates sediment yield and runoff individually in the routing and soil phases, improving model simulation precision. This work is based on the principle of water balance. Soil runoff is calculated using the SCS curve number method, and the process of routing phase Muskingum method is most commonly used in the SWAT model. In addition, the SWAT model is also helpful in understanding the effect of land use on runoff, sediment, and the practice of agriculture. Because the SWAT model has a lot of uncertainties and flaws, the results may have been different.

FUTURE SCOPE

1. SWATMOD can be used to overcome the limitations of the SWAT model in terms of groundwater modeling.
2. To study comparison and combination between SWAT and other models like ANN, EPIC, AGNPS, APEX, MIKE SHE, MIKE11, and NAM11 to predict the runoff and sediment load.
3. Research on water quality impacts due to sedimentation and different approaches to forecasting the effect of future climate change on dam sedimentation.
4. Between the upstream and downstream, complex soil erosion dynamics, sediment yield, and river sedimentation can be formed.

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