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SWAT model applications in hydrology: A systematic review

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Abstract
The Soil and Water Assessment Tool (SWAT) has become an indispensable tool in hydrological modeling. It is widely applied for simulating streamflow, sediment transport, nutrient cycling, and agricultural processes within watersheds. This review provides a detailed analysis of SWAT's capabilities, theoretical framework, applications, strengths, limitations, and future research directions. We explore SWAT's structure, including its division of watersheds into hydrologic response units (HRUs) and the representation of key hydrological processes like evapotranspiration, infiltration, and routing. This paper delves into its applications in various fields, including water resource management, climate change impact assessment, and agricultural non-point source pollution modeling. The review critically examines SWAT's strengths, such as its user-friendly interface, physically-based approach, and vast user community. Discussion of limitations, including data requirements, computational intensiveness, and potential for regional bias. Finally, we explore emerging research directions for SWAT development, including integration with advanced climate models, improved representation of urban processes, and enhanced capabilities for real-time applications. This review aims to be a valuable resource for hydrologists, environmental scientists, and water resource managers seeking to understand and utilize the SWAT model for their research and decision-making needs.

Keywords: Hydrological modeling, SWAT, watershed, HRUs

1. Introduction

Water is a critical resource for life on Earth, and understanding the complex interactions within the hydrological cycle is essential for effective water resource management. Hydrological models play a vital role in simulating these processes and predicting future scenarios. Among various hydrological models, the Soil and Water Assessment Tool (SWAT) has emerged as a prominent tool for simulating watershed hydrology. Developed by the USDA Agricultural Research Service, SWAT is a physically-based, semi-distributed model widely used for assessing the impacts of land use change, climate variability, and agricultural practices on water, sediment, and nutrient fluxes within watersheds [Arnold *et al.*, 1998] [3].

This comprehensive review aims to provide a thorough understanding of SWAT, its capabilities, applications, strengths, limitations, and future research directions. We will explore the theoretical framework of SWAT, its model structure, and the representation of key hydrological processes. Following this, we will delve into the diverse applications of the model in various fields of hydrology and environmental science. We will then critically evaluate SWAT's strengths and limitations, highlighting its user-friendliness, physically-based approach, and potential limitations related to data requirements and regional bias. Finally, we will discuss future research directions for SWAT development, focusing on areas such as integration with advanced climate models, improved urban process representation, and real-time applications.

2. Swat Model Structure and Theory

SWAT operates on a semi-distributed framework, dividing a watershed into subbasins, which are further subdivided into unique hydrologic response units (HRUs). HRUs represent the smallest land management units within a subbasin and are defined by a combination of land use, soil type, and slope characteristics. This approach allows SWAT to account for spatial heterogeneity within a watershed and simulate hydrological processes at a finer scale compared to fully lumped models [Neitsch *et al*., 2011] [12].

2.1 The model simulates various hydrological processes within the watershed, including

- **Precipitation:** SWAT can incorporate various precipitation data sources and accounts for spatial variability through interpolation techniques [Gassman *et al*., 2007] [6].
- **Snowmelt:** The model simulates snow accumulation and melt based on temperature and radiation data [Singh and Frevert, 2002] [21].
- Evapotranspiration: Potential evapotranspiration is estimated using different methods, and actual evapotranspiration is calculated based on soil moisture and vegetation cover [Srinivasan *et al*., 2002] [13].
- **Infiltration:** SWAT employs various infiltration models to simulate the process of water entering the soil [Liu *et al*., 2012] [9].
- **Surface runoff:** Overland flow is estimated using the kinematic wave equation, accounting for slope and land cover characteristics [Liew *et al*., 2017] [8].
- **Soil water movement:** The model simulates vertical water movement within the soil profile using multi-compartment storage models [Abbaspour *et al*., 2015] [1].
- **Groundwater recharge:** SWAT accounts for the process of water infiltrating deeper into the ground and contributing to groundwater resources [Wu *et al*., 2017] [18].
- **Channel routing:** The model simulates the movement of water through the stream network using different routing methods [Yu *et al*., 2020] [20].
- **Sediment transport:** SWAT simulates soil erosion and sediment transport through the watershed, considering factors like rainfall intensity, soil properties, and slope [Beaumont *et al*., 2014] [5].
- **Nutrient cycling:** The model simulates the transport of nutrients like nitrogen and phosphorus within the watershed, accounting for processes like mineralization, immobilization, and leaching [Yang *et al*., 2018] [19].

3. Applications of SWAT

SWAT's versatility has led to its application in a wide range of hydrological and environmental studies. Here are some key application areas:

3.1 Water Resource Management

SWAT is a valuable tool for water resource managers as it can be used to:

- **Assess water availability:** By simulating streamflow patterns, SWAT can help assess the available water resources within a watershed. This information is crucial for water allocation planning and ensuring sustainable water use [Abbaspour *et al*., 2019] [2].
- **Analyze streamflow patterns:** SWAT can be used to analyze historical streamflow patterns and identify trends in water availability. This information can be used to assess the impacts of climate change and develop strategies for adapting to future water scarcity scenarios [Li *et al*., 2019] [7].
- **Evaluate the impacts of water withdrawals:** SWAT can be used to simulate the effects of water withdrawals for various purposes, such as irrigation, industry, and domestic water supply. This information can be used to assess the potential impacts on water availability downstream and inform sustainable water management practices [Wang *et al*., 2018].

3.2 Climate Change Impact Assessment

Climate change is a major threat to water resources worldwide. SWAT can be a valuable tool for assessing the potential impacts of climate change on hydrological processes:

- **Simulate the effects of climate change on streamflow:** By incorporating climate change scenarios with projected changes in precipitation and temperature, SWAT can simulate the potential impacts on streamflow patterns. This information can be used to develop adaptation strategies for water resource management in a changing climate [Ayah *et al*., 2019] [4].
- **Assess the impacts on water quality:** Climate change can also affect water quality by altering flow regimes and pollutant transport processes. SWAT can be used to simulate these changes and assess the potential risks to water quality [Beaumont *et al*., 2014] [5].
- **Evaluate the impacts on water availability:** Climate change can lead to changes in water availability by altering precipitation patterns and increasing evapotranspiration. SWAT can be used to assess these impacts and inform strategies for managing water resources under future climate scenarios [Liu *et al*., 2014] [10].

3.3 Agricultural Non-Point Source Pollution Modeling

Agricultural activities can significantly contribute to non-point source pollution of water bodies. SWAT is a powerful tool for:

- **Simulating the transport of agricultural pollutants:** SWAT can simulate the transport of pollutants like fertilizers, pesticides, and pathogens within a watershed. This allows for identifying areas with high pollution risks and evaluating the effectiveness of best management practices (BMPs) in reducing pollution [Yang *et al*., 2018] [19].
- **Assessing the impacts of agricultural practices:** By simulating the effects of different agricultural practices on water quality, SWAT can inform the development of sustainable agricultural management strategies that minimize environmental impacts [Beaumont *et al*., 2014] [5].
- **Optimizing best management practices:** SWAT can be used to evaluate the effectiveness of various BMPs, such as cover cropping, buffer strips, and nutrient management practices, in reducing agricultural non-point source pollution [Liu *et al*., 2012] [9].

3.4 Land Use Change Impact Assessment

Land use changes significantly impact hydrological processes within watersheds. SWAT's ability to simulate the effects of different land use scenarios makes it valuable for assessing potential consequences of these changes:

- **Deforestation:** Studies have shown that deforestation can increase surface runoff, leading to flash floods and soil erosion, while also reducing baseflow and impacting aquatic ecosystems [Ndiaye *et al*., 2005 [11]; Yang *et al*., 2018] [19]. SWAT can be used to simulate these impacts and inform land-use planning decisions that minimize negative environmental consequences.

- **Urbanization:** Urbanization alters the hydrological cycle by increasing impervious surfaces and reducing infiltration. SWAT can be employed to assess the impacts of urbanization on peak flow, stormwater runoff, and water quality [Wang *et al*., 2020] [17]. Studies have shown that urbanization can lead to increased peak flows and pollutant loads in streams, with significant impacts on water quality and aquatic ecosystems [Wang *et al*., 2010]. By simulating these effects, SWAT can inform urban planning strategies that incorporate green infrastructure and storm water management practices to mitigate the impacts of urbanization on water resources.

3.5 Reservoir Management

Reservoirs play a crucial role in water resource management, storing water during wet periods and releasing it during dry periods. SWAT can be a valuable tool for reservoir operation planning by simulating reservoir inflows and outflows:

- **Reservoir Inflow Forecasting:** SWAT can be used to forecast streamflow based on weather data and historical patterns. This information can be used to predict reservoir inflows and inform decisions about reservoir operation, such as water storage and release strategies [Wang *et al*., 2018].
- **Water Allocation Planning:** SWAT can be used to simulate the impacts of different water allocation scenarios on reservoir water levels and downstream water availability. This information can be used to develop water allocation plans that consider the needs of various water users in a fair and sustainable manner [Abbaspour *et al*., 2019] [2].
- **Sedimentation Management:** Reservoirs can trap sediment transported by rivers over time. SWAT can be used to simulate sediment transport processes and predict the rate of reservoir sedimentation. This information can be used to develop strategies for managing reservoir sedimentation and maintaining its storage capacity, such as periodic dredging or sediment bypass structures [Wu *et al*., 2017] [18].

3.6 Wetland and Ecosystem Management

Wetlands play a vital role in maintaining healthy ecosystems by filtering pollutants, providing habitat for wildlife, and regulating water flow. SWAT can be used to understand the hydrological interactions within wetlands and assess the impacts of various management practices:

- **Wetland Inundation Dynamics:** SWAT can be used to simulate the water balance within wetlands, predicting wetland inundation depth and duration. This information is crucial for understanding wetland function and maintaining suitable habitat conditions for wetland-dependent species [Ayah *et al*., 2019] [4].
- **Water Quality Improvement:** Wetlands act as natural filters for pollutants by removing them from water through various physical, chemical, and biological processes. SWAT can be used to simulate the transport of pollutants into and through wetlands, assessing their effectiveness in removing specific pollutants from water (e.g., nitrogen, phosphorus, heavy metals) [Liu *et al*., 2012] [9]. This information can be used to design effective wetland restoration strategies for improving water quality at the watershed scale.
- **Climate Change Impacts (continued):** Climate change can alter hydrological regimes, impacting wetland health in various ways. SWAT can be used to assess the potential effects of climate change on wetland water levels, salinity, and plant communities. This information can inform strategies for adapting wetland management practices in a changing climate, such as water conservation measures or restoration of natural flow regimes [Li *et al*., 2019] [7].
- By simulating the hydrological interactions within wetlands and assessing the impacts of various management practices, SWAT can contribute to the development of effective strategies for wetland conservation and restoration. This ensures the ecological health and ecosystem services provided by these vital ecosystems, such as:
- **Flood control and erosion reduction:** Wetlands can help mitigate floods by storing excess water during high flow events and releasing it slowly over time. SWAT can be used to assess the flood control capacity of wetlands and inform strategies for wetland management in flood-prone areas [Ndiaye *et al*., 2005] [11].
- Habitat provision: Wetlands provide critical habitat for a diverse range of plant and animal species. SWAT can be used to simulate the impacts of water level fluctuations and other environmental changes on wetland ecosystems, informing strategies for maintaining suitable habitat conditions for wetland-dependent species [Beaumont *et al*., 2014] [5].
- Biodiversity conservation: Wetlands are hotspots for biodiversity, supporting a wide variety of species. By assessing the impacts of land use change, climate change, and other stressors on wetland ecosystems, SWAT can inform conservation strategies for protecting wetland biodiversity [Yang *et al*., 2018] [19].

4. Strengths and Limitations of Swat

4.1 Strengths

- **Physically-Based Approach:** SWAT utilizes a physically-based approach that represents hydrological processes using fundamental physical equations. This allows for a more mechanistic understanding of the model's outputs and the ability to generalize results to different scenarios [Singh and Frevert, 2002] [21].
- **User-Friendly Interface:** SWAT comes equipped with a user-friendly interface (ArcSWAT) that facilitates data input, model setup, and visualization of results. This makes the model accessible to a broad range of users with varying levels of expertise [Srinivasan *et al*., 2002] [13].
- **Extensive User Community:** SWAT boasts a vast and active user community that provides ongoing support, resources, and ongoing model development. This user community facilitates knowledge sharing, troubleshooting, and model improvement [SWAT website, https://swat.tamu.edu/].
- **Flexibility:** The model's modular structure allows for customization and adaptation to specific watersheds and research objectives. Users can modify various model

parameters and components to suit their specific needs [Gassman *et al*., 2007] [6].

- **Wide Range of Applications:** SWAT's versatility makes it suitable for a diverse range of hydrological and environmental studies, as demonstrated in the applications section (Section 3). These applications include water resource management, climate change impact assessment, agricultural non-point source pollution modeling, land use change impact assessment, reservoir management, and wetland and ecosystem management.

4.2 Limitations

Despite its strengths, SWAT has some limitations that users should be aware

- **Data Requirements:** SWAT requires a significant amount of input data, including meteorological data, soil properties, land use maps, and streamflow data. This can be a challenge for applications in data-scarce regions [Abbaspour *et al*., 2015] [1]. Strategies to address this limitation include using spatial interpolation techniques for meteorological data and employing surrogate data sources where possible.
- **Computational Intensity:** Running complex SWAT simulations for large watersheds can be computationally demanding and require significant computing resources [Liew *et al*., 2017] [8]. This can be a barrier for some users with limited access to high-performance computing facilities. Cloud computing platforms offer a potential solution for addressing this limitation in the future (see Section 5. Future Research Directions).
- **Regional Bias:** Although SWAT is a physically-based model, it may exhibit some regional bias depending on its calibration and validation in specific regions. Careful calibration and validation are crucial for reliable results in new applications [Wu *et al*., 2017] [18]. Techniques like multi-site calibration and utilizing data from diverse geographical regions can help reduce regional bias.
- **Urban Process Representation:** The current version of SWAT may not accurately represent the complex hydrological processes occurring in urbanized areas, such as the effects of impervious surfaces, stormwater infrastructure, and combined sewer overflows. Further development is needed to improve its capability in simulating urban hydrology [Yu *et al*., 2020] [20]. New modules or extensions specifically designed for urban applications can address this limitation.

5. Future Research Directions

SWAT development continues to evolve, and several promising research directions are emerging:

- **Integration with Advanced Climate Models:** Future research efforts should focus on seamless integration of SWAT with advanced climate models to improve the representation of climate change impacts on watershed hydrology. This would allow for more accurate simulations of future water availability, streamflow patterns, and extreme weather events [Li *et al*., 2019] [7].
- **Improved Urban Process Representation:** The model's capabilities for simulating urban hydrology need further development to account for impervious surfaces, stormwater infrastructure, and combined sewer overflows. This would enable more accurate assessment of water management challenges in urban environments [Liu *et al*., 2014] [10].
- **Real-Time Applications:** Developing real-time forecasting capabilities using SWAT would be valuable for flood prediction, water quality monitoring, and reservoir operation. This would require integration with real-time data sources like stream gauges and weather stations [Wang *et al*., 2018] [15].
- **Enhanced Data Assimilation Techniques:** Incorporating real-time data like streamflow and soil moisture observations into the model through data assimilation techniques can improve the accuracy of SWAT simulations. This would allow for continuous model updates and improved representation of the current hydrological state of the watershed [Liu *et al*., 2012] [9].
- **Coupling with Biogeochemical Models:** SWAT primarily focuses on the hydrological cycle. Coupling SWAT with biogeochemical models can provide a more holistic understanding of the interactions between hydrology, nutrient cycling, and ecosystem processes within watersheds. This would allow for simulating the impacts of land use change and climate change on water quality, nutrient dynamics, and ecosystem health [Beaumont *et al*., 2014] [5].

6. Conclusion

The SWAT model has become a cornerstone of hydrological modeling, offering a valuable tool for simulating watershed processes and assessing the impacts of climate change, land use change, and agricultural practices on water resources. Its user-friendly interface, physically-based approach, and vast user community have contributed to its widespread adoption. While limitations exist regarding data requirements, computational demands, and regional bias, ongoing research efforts are addressing these challenges and expanding SWAT's capabilities. By integrating with advanced climate models, improving urban process representation, and developing real-time applications, SWAT will continue to play a vital role in advancing our understanding of hydrological processes and supporting effective water resource management strategies.

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