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Advances in Hydrological Modelling: A Comprehensive Review of SWAT Applications and Developments

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ABSTRACT

Surface water modelling plays a pivotal role in our ability to comprehend and effectively manage the intricate dynamics of watershed hydrology. It serves as a cornerstone for making informed decisions across a spectrum of critical domains, including environmental conservation, water resource planning, and land use management. In this context, the Soil and Water Assessment Tool (SWAT) has risen to prominence as a versatile and widely embraced modelling framework, uniquely suited for simulating the complex hydrological processes that unfold within watersheds. It helps in simulating water balance components, predicting streamflow, estimating sediment and nutrient transport, and evaluating the effectiveness of conservation practices. The SWAT model assists in understanding the impacts of land management decisions on water resources and aids in making informed decisions for sustainable water management. This comprehensive review paper serves as a thorough exploration of SWAT, covering a broad spectrum of facets that include its fundamental features, its diverse array of real-world applications, its inherent limitations, and the latest advancements that have propelled its utility.

Key words: *Surface Water Modelling, SWAT, Hydrological Processes*

Introduction

Hydrological modelling is a crucial tool in understanding the complex dynamics of surface water systems. It empowers us to make informed decisions across various critical domains, such as water resource management, environmental conservation, and land use planning. Hydrological models have been advanced and refined over the past four decades (Jajarmizadeh *et al*., 2012). These models are used to simulate the water cycle, which includes processes such as precipitation, runoff, infiltration, evapotranspiration, and groundwater flow (Agrawal and Desmukh, 2016; Pomeroy *et al*., 2007). Hydrological models can be used to study a wide range of hydrological problems, such as water availability, flood risk, soil erosion, and nutrient pollution. To use these models effectively, it is important to have a thorough understanding of their characteristics (Jajarmizadeh *et al*., 2012). In recent years, it has addressed the challenges posed by a changing climate and growing human impact on watersheds.

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Within the expansive landscape of hydrological modelling tools, the SWAT has emerged as a versatile and widely embraced framework capable of simulating the nuanced hydrological processes inherent to watersheds (Kumar *et al*., 2023).

The SWAT model, a widely used semi-distributed hydrological model, has been applied to various watersheds globally (Khatun *et al*., 2018), dividing them into hydrological response units (HRUs) characterized by unique soil, land use, and slope properties. It simulates the water cycle, including precipitation, runoff, infiltration, evapotranspiration, and groundwater flow, while also modeling sediment and nutrient transport in watersheds (Lotz *et al*., 2018; Sajikumar and Remya, 2015). This versatility makes SWAT a powerful tool for studying hydrological problems such as water availability, flood risk, soil erosion, and nutrient pollution (Aloui *et al*., 2023). Recent advances in hydrological modeling, driven by new computer technologies, better data availability, and the increasing need to understand climate change impacts on water resources, have further enhanced SWAT's utility (Javaid *et al*., 2023). This review paper aims to comprehensively analyze SWAT, exploring its essential features, diverse real-world applications, and the latest developments that have elevated its effectiveness in addressing hydrological challenges.

Hydrological Modelling using Swat Model

SWAT is a widely used model for hydrological simulation and understanding of watershed processes, integrating climate, land use, soil, and topography to simulate water movement, sediment transport, and nutrient cycling. It estimates streamflow and sediment transport by incorporating hydrologic processes like surface runoff, lateral flow, and channel routing and simulates nutrient movement within the watershed.

Runoff modelling

Runoff modeling using the Soil and Water Assessment Tool (SWAT) is a crucial process for simulating and predicting water movement within watersheds or catchment areas, aiding in water resource management. Santra and Das (2013) utilized ArcSWAT modeling to assess runoff potential in the Chilika Lake catchment area, emphasizing the substantial impact of sediment-laden runoff on the lake's ecosystem. Similarly, Jothiprakash *et al*. (2017) compared spatial water availability in the Musi River basin with observed data, highlighting the SWAT model's capability to generate valuable runoff data for improved water resource management. They employed rigorous analyses and performance metrics to validate the model's effectiveness. Additionally, Reddy *et al*. (2020) employed the SWAT model to assess runoff in the Rela Watershed, demonstrating its utility in estimating runoff across diverse hydrological contexts. These studies collectively underscore the significance of the SWAT model in runoff modeling and its pivotal role in informing water resource management and ecosystem protection strategies.

The SWAT has been effectively utilized in various studies for watershed modeling across diverse geographic contexts. Akhter *et al*. (2022) demonstrated its accuracy in assessing runoff in the Aripal watershed in India, despite some limitations in predicting extreme flood events. Similarly, Diriba (2021) used the SWAT model to simulate surface runoff in the Dabus watershed in Ethiopia, revealing a strong correlation between observed and simulated streamflow. The study emphasized the model's potential for improved watershed management and the importance of considering land use changes in future research. Additionally, Sime *et al*. (2020) substantiated the effectiveness of the SWAT model in assessing and modeling surface runoff in the Ketar watershed, Ethiopia, providing valuable insights for understanding water resource dynamics and environmental management. The study's findings support the applicability of the SWAT model for analyzing hydrological responses in similar geographic areas, reinforcing its potential for broader environmental assessments.

In a different approach, Salele *et al*. (2023) utilized a coupled SWAT-EANN model to simulate runoff and urban flooding in pervious and impervious urban areas. The integration of the Emotional Artificial Neural Network (EANN) model with SWAT improved simulation accuracy, particularly in precipitation. This highlights the potential of the SWAT-EANN model for informing urban planning to address flooding and environmental challenges. These findings emphasize the versatility of SWAT in analyzing hydrological responses in different areas and its potential for broader environmental assessments.

Sediment yield modelling

Sediment Yield modelling predicts the amount of sediment transported from a watershed to a river system. SWAT is a widely used model for this purpose, simulating hydrology and water quality in agricultural watersheds.

Setegn *et al*. (2010) utilized the SWAT model to predict monthly sediment yield in the Anjeni-gauged watershed in Ethiopia, demonstrating good agreement between observed and simulated sediment yield values. The study's findings supported the model's potential for analyzing management scenarios to plan and implement soil and water conservation strategies in the watershed. In a similar vein, Ghosh and Maiti (2022) employed the SWAT model integrated with ArcGIS to estimate annual sediment yields in the Mayurakshi River Basin, emphasizing the high sediment yield capacity in specific areas due to increased gully erosion, with the use of ANN and RF models enhancing prediction accuracy. Additionally, Panda *et al*. (2021) utilized the SWAT model to estimate soil loss in the Upper Subarnarekha catchment in Odisha, India, with the model demonstrating good performance during calibration and validation periods, identifying highly vulnerable sub-watersheds and recommending suitable soil and water conservation measures.

Singh *et al*. (2014) compared the performance of the SWAT model with the RBNN model in simulating sediment load in the Nagwa watershed, India. They found that the RBNN model exhibited lower uncertainty and higher accuracy than the SWAT model, providing more precise estimates of sediment yield.

Nutrient cycling modelling

Nutrient cycling modelling involves simulating the movement and fate of nutrients, such as nitrogen and phosphorus, within a watershed. SWAT integrates various components, including climate, land use, soil, and topography, to capture the dynamics of nutrient cycling processes. To model nutrient cycling, SWAT considers inputs of nutrients from various sources, such as fertilizers, manure, and atmospheric deposition.

Grizzetti *et al*. (2003) employed the Soil and Water Assessment Tool (SWAT) model to simulate the natural removal of nitrogen and phosphorus in the Vantaanjoki basin in Finland. The study encompassed calibration and validation processes, yielding Nash-Sutcliffe coefficients ranging from 0.59 to 0.81 for flow, nitrogen, and phosphorus loads during calibration and from 0.43 to 0.57 during validation. The model estimated annual average diffuse emissions and nutrient removal over 9 years, with comparisons between predicted and statistically evaluated emissions indicating the model's reasonable predictions. Additionally, the study revealed a 24% retention estimation for total nitrogen and 51% for total phosphorus. In a similar vein, Ferrant *et al*. (2011) conducted a comparative analysis of the agro-hydrological models TNT2 and SWAT to analyze nitrogen dynamics in an agricultural catchment over a 15-year monitoring period. The models exhibited distinct seasonal cycles for soil nitrogen, with differing patterns of denitrification and spatial distribution of nitrogen processes. While both models accurately simulated the overall trend and inter-annual variability of nitrogen losses, the study emphasized the importance of meticulous calibration and validation of nitrogen processes in prediction models.

Several studies utilized the SWAT model for assessing nutrient emissions and best management practices (BMPs) in watersheds. Koskiaho *et al*. (2020) evaluated ecotechnologies' effectiveness in the Baltic Sea catchments, while Himanshu *et al*. (2019) assessed BMPs in the Marol watershed. Saravanan *et al*. (2023) evaluated nutrient loads in the Vamanapuram River Basin. These studies contribute to understanding nutrient dynamics in agricultural watersheds and the need for robust modeling approaches to capture nitrogen cycling complexities.

Limitation of SWAT model

While the SWAT model is widely used and effective, it has limitations, such as the need for extensive input data, which can be time-consuming and resource-intensive to acquire and process. A study by Rostamian *et al*. (2008) focused on using the SWAT to model runoff and sediment in the Beheshtabad and Vanak watersheds in the central Karun catchment in Iran. The study identified weaknesses in the model's ability to simulate runoff and sediment in certain months. The weaknesses were due to inadequate representation of snowmelt processes in mountainous watersheds, limited discharge data, insufficient input data for groundwater, and unreliable measured sediment data. Accurate runoff and soil loss prediction is crucial for assessing erosion risks and making informed decisions on land use and conservation strategies within a catchment.

Moreover, the model's performance may vary depending on the specific characteristics of the watershed being studied, and it may not capture all the intricacies of local hydrological systems.

So, despite its value, it's important to acknowledge the SWAT model's limitations and supplement its results with field observations and local knowledge for a comprehensive understanding of water resources and environmental management.

Conclusion

Hydrological modelling is vital for understanding water systems and making informed decisions in areas like water resource management and land use planning. The SWAT model is an invaluable asset in this field, offering comprehensive analysis of runoff, sediment load, and nutrient cycling. Its ability to seamlessly integrate climate, land use, soil, and topographic data empowers researchers, land managers, and policymakers to make well-informed decisions spanning critical domains, including water resource management, environmental conservation, and land use planning. While calibration and validation are crucial, SWAT continues to be an essential tool for tackling modern hydrological challenges in the context of changing climate patterns and human impacts on watersheds. It holds a crucial position in fostering sustainable practices within the realms of water resources and environmental management.

Conflict of Interest

The authors declare that there is no conflict of interest.

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