Comprehensive review on SWAT for sustainable agriculture and climatic solutions

Abstract

Soil and Water Assessment Tool (SWAT), a popular hydrological model, created to impersonate how the land management techniques would affect the water availability, sediments transportation and nutrient transformations in region's expansive and intricate watersheds. SWAT has evolved from its initial development state as a comprehensive modelling tool for agricultural systems, watershed management and climate change adaptation. SWAT predicts the effects of agricultural practices on water, sediment and nutrient loads. Moreover, over time, its functionality has broadened to include complex environmental processes, such as sediment transport, nutrient cycling, and land-use change dynamics. This review paper mainly focused on the literature collected on its relevance and applicability to agricultural sector and climate change. Moreover, the incorporation of SWAT into studies on climate change has broadened its scope by enabling it to simulate the possible consequences of fluctuating temperature patterns, unpredictable precipitation, and severe weather on worldwide water resources and farming systems. In addition to highlighting its practical applicability, case studies from India and other locations also highlighted in current review article. For policymakers, agricultural scientists, SWAT is an essential tool because of its capacity to model the long-term effects of land and water management at broad spatial and temporal dimensions. SWAT also found to help the stakeholders for creating plans to lessen the effects of climate variability by combining several climate models and scenarios and to provide better insights on future soil erosion, flood hazards and water availability. Overall, in light of the escalating environmental issues, SWAT is essential for sustainable management of water and agricultural resources due to its capacity to produce comprehensive and long-term projections.

Keywords: SWAT, farming, soil hydrology, agriculture, climate change, watershed management

Introduction

One important model for comprehending the intricate relationships among the agricultural practices, water resources and environmental sustainability is SWAT. It was first created in the early 1990's by the United States Department of Agriculture (USDA) with the purpose of forecasting how the land management techniques will affect the flows of water, sediment and nutrients in any watersheds. SWAT's primarily goal was to support the agricultural management by assessing how various farming techniques like crop rotation, tillage and fertilizer affects the soil erosion and water quality (Arnold *et al.*, 1998). Over time, SWAT has experienced a substantial transformation moving beyond agricultural modelling to addressing more global environmental challenges including watershed management and adaptation to climate change. The origins of SWAT may be found in its early uses in agriculture, when it was mostly used to the modelling of nutrient transport, runoff and erosion in rural basins. Since, farming is one of the main causes of non-point source pollution, land managers looking to implement Best Management Practices (BMP's) to lower pollution, while, preserving farm productivity found SWAT to be an invaluable tool in simulating these processes (Gassman *et al.*, 2007). The model's ability to incorporate a wide range of information, including topography, soil, climate and land use which enable it to offer in-depth analyses of the long-term environmental impacts of various agricultural scenarios. This was particularly significant in areas such as the Mississippi River Basin, where SWAT was applied to determine how agricultural runoff affected water quality and to guide conservation measures (Arnold *et al.*, 2002).

SWAT is a frequently used technique for worldwide water resource management because to its adaptability to various spatial and temporal dimensions, as well as its interaction with Geographic Information Systems (GIS) (Neitsch *et al.*, 2005). More than 100 countries have used the concept to solve problems like habitat preservation, flood management, and water conservation. SWAT's resilience and versatility as a model that can handle challenging environmental problems are demonstrated by its widespread usage. SWAT has been able to stay at the forefront of watershed modelling by its continuous development and integration of sophisticated hydrological algorithms and climatic datasets (Neitsch *et al.*, 2011). In order to handle a wider range of environmental issues, including climate change adaptation, SWAT's scope grew over the time beyond agricultural modelling. With possible effects including modified precipitation patterns, an increase in the frequency of extreme weather calamities, modifications in water availability and climate change poses serious dangers to agricultural systems as well as water resources. Because SWAT can simulate hydrological processes under many climate scenarios, it is an essential tool for determining how climate change may affect watersheds and for creating adaptation plans. For example, SWAT is frequently used to model how anticipated variations in temperature and precipitation would impact agricultural output and water availability in areas susceptible to climate variability, such Southeast Asia and Sub-Saharan Africa (Li *et al.*, 2011).

For researchers, decision-makers and land managers looking to strike a balance between environmental sustainability and agricultural productivity, SWAT is a vital tool since it can mimic the effects of both natural and human-caused processes on water resources. Furthermore, in order to protect water resources and guarantee food security in the upcoming decades as the effects of climate change become more apparent, SWAT's ability to influence adaptation plans will be essential (Arnold *et al.*, 2012). Therefore, SWAT can be reliable as important tool for agricultural modelling that tackles the global environmental issues like climate change emphasizes on the important influence on both research and policy. Given its capacity to generate the comprehensive, long-term simulations of the interactions between land and water, SWAT is an invaluable tool for tackling some of the most urgent environmental problems of the twenty-first century.

Origin and evolution of SWAT

In the 1980's and 1990's, the United States Department of Agriculture (USDA) created earlier models that served as the foundation for the Soil and Water Assessment Tool (SWAT). The Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) and the simulator for water resources in rural basins (SWRRB) were two important models from which it was developed. Although the size and complexity of the watersheds that these older models could represent were limited, they were intended to mimic the impacts of agricultural practices on water supplies. SWAT was created to address these shortcomings by offering a longer-term, more thorough simulation program that can handle complicated, sizable watersheds with a variety of land use and management techniques (Arnold *et al.*, 1998).Soil, land use, climate, and other data types could all be integrated into a spatially explicit framework, which was one of SWAT's major advances. As a result, it was able to replicate the flow of water, sediment, and chemicals over different landscapes, providing a major functional and scope gain over earlier models.

Enhancements and transitions to watershed modelling and its global adoption

SWAT was first developed for agricultural use, but because of its capability to manage intricate hydrological processes, it swiftly evolved into a more comprehensive tool for watershed. In order to evaluate the environmental advantages of conservation techniques nationally, SWAT joined USDA's Conservation Effects Assessment Project (CEAP) in the late 1990s. It was at this point that SWAT began to be widely used outside of the agricultural industry. The model gained appeal among researchers and policymakers interested in water quality and ecosystem services because of its adaptability, which allowed it to be used in a variety of settings, from urban watersheds to rural agricultural areas (Neitsch *et al.*, 2005). Significant changes were made to the model at this time, such as adding Geographic Information System (GIS) capabilities. These improvements made SWAT a more effective tool for decision-makers who want to strike a balance between environmental sustainability and agricultural productivity by enabling it to handle spatially scattered data.

SWAT underwent major improvements in the 2000's, which helped spread its use throughout the world. One of the most significant improvements was the creation of intuitive user interfaces, like the ArcSWAT extension for ArcGIS, which let non-expert users understand the model. However, SWAT's usefulness was broadened beyond its initial focus on water and sediment management with the integration of other environmental processes, such as carbon sequestration and nutrient cycling, and enhancements to the hydrological algorithms. In order to investigate a variety of environmental concerns, such as nutrient loading, habitat preservation, and the effects of climate change, researchers started using SWAT. For environmental planners and academics around the world, the model is an essential tool since it can simulate long-term environmental effects under various land use and climate scenarios (Gassman *et al.*, 2007). SWAT was firmly established as one of the most popular watershed models in the world by the 2010s, having been implemented in more than 100 nations and utilised in over 3,000 peer-reviewed research. More recently, it has been used for climate change adaptation, sediment and erosion control, and integrated water resources management. SWAT's capacity to model intricate environmental interactions is being enhanced by researchers as they continue to incorporate fresh data (Arnold *et al.*, 2012).

Methodology of SWAT

The Soil and Water Assessment Tool (SWAT) is a comprehensive model used for predicting the impact of land management practices on water, sediment and agricultural chemical yields in large, complex watersheds. Here's an overview of its methodology which has shown it reliability for conducting research and review studies.

1. Watershed Delineation

- **Sub-basins:** The watershed is divided into sub-basins based on topography and hydrology using Digital Elevation Models (DEM's).
- **Hydrologic Response Units (HRU's):** Each sub-basin is further divided into HRU's based on land use, soil type, and management practices.

2. Data Collection

- **Meteorological Data:** Rainfall, temperature, humidity, wind speed and solar radiation are collected.
- **Soil Data:** Soil properties, depth, and texture are gathered from soil surveys.
- **Land Use Data:** Current land use and land management practices are assessed using satellite imagery or land cover maps.

3. Model Configuration

- **Parameterization:** Key parameters for hydrology, soil erosion, crop growth, and chemical transport are defined based on the collected data.
- **Input Files:** Create input files containing all necessary information for model simulations.

4. **Hydrologic Modelling**

- **Water Balance:** SWAT calculates water balance components such as precipitation, evaporation, surface runoff, groundwater flow and baseflow.
- **Runoff Generation:** The model simulates runoff generation using the Soil Conservation Service Curve Number method or Green-Ampt infiltration method.

5. **Soil Erosion Modelling**

- **Erosion Prediction:** The Modified Universal Soil Loss Equation (MUSLE) estimates soil erosion based on runoff and land management practices.

6. **Nutrient and Pesticide Transport**

- **Nutrient Loading:** SWAT simulates the transport of nutrients (like nitrogen and phosphorus) and pesticides through the watershed, accounting for processes like uptake by plants and denitrification.

7. **Calibration and Validation**

- **Model Calibration**: Adjust model parameters to match observed data (*e.g.*, stream flow, sediment load).
- **Validation:** After calibration, validate the model using independent datasets to ensure reliability.

8. **Scenario Analysis**

- **Management Scenarios:** Analyze the impact of various land use and management practices on water quality and quantity by simulating different scenarios (*e.g.*, conservation practices and land use changes).

9. **Output Analysis**

- **Result Interpretation:** Analyze output data, including stream flow, sediment yield and nutrient loads to assess the effects of different management practices on the watershed.

10. **Reporting and Decision Support**

- Visualization: Use GIS tools for visual representation of results and to support decision-making for land and water management.

SWAT is widely used for research and management purposes due to its flexibility and comprehensive approach to watershed management.

Implications of SWAT on agricultural management

1. **Enhancing Agricultural Productivity and Sustainability**

By simulating the effects of different management strategies on crop yields, water resources, and soil health, the Soil and Water Assessment Tool (SWAT) has been instrumental in increasing agricultural output while advancing sustainability. Optimising land utilisation and farming methods is one of the most important ways SWAT has aided in agriculture management. SWAT offers important insights into how various cropping systems, tillage techniques, and irrigation tactics affect agricultural yield and environmental sustainability by simulating these aspects (Neitsch *et al.,* 2011). In order to demonstrate how crop rotation systems can increase soil fertility and decrease the need for chemical inputs, hence fostering long-term agricultural sustainability, SWAT has been widely utilised to predict the results of such systems. Additionally, SWAT's capacity to model a range of environmental circumstances and management scenarios aids land managers and farmers in weighing the trade-offs between potential environmental harms like fertiliser runoff and soil erosion and higher yield. SWAT has been used to model the impact of conservation practices on water quality in areas such as the Mississippi River Basin. It demonstrates how techniques like cover crops and no-till farming can minimise nutrient and sediment loss, preserving soil productivity and the water body health (Gassman *et al.,* 2010).

2. Nutrient management and water quality

The management of nutrients, namely the problem of nonpoint source pollution from agriculture, has been one of SWAT's most significant uses. One of the main reasons why agricultural watersheds' water quality deteriorates is nonpoint source contamination, such as fertiliser runoff of nitrogen and phosphorus. When creating best management practices (BMPs) to reduce nutrient loading in streams and rivers, SWAT's capacity to simulate the movement and destiny of these nutrients has proven crucial. The best ways to lower nitrogen runoff without sacrificing crop yields are identified by SWAT, which simulates the impacts of different fertiliser application rates, timing and techniques (Arnold *et al.,* 2002). The Chesapeake Bay watershed, for instance, has employed SWAT to find efficient nutrient management techniques that lower phosphorus loading, which fuels eutrophication and toxic algal blooms. By simulating the long-term effects of various management techniques, the model enables farmers and policymakers to adopt BMP's that improve water quality and fertiliser efficiency, which lowers costs and boosts farm profitability (Srinivasan *et al.,* 2010). Globally, SWAT is a vital tool for nutrient management planning because of its ability to both maintain agricultural productivity and improve environmental results.

3. Erosion Control and Sediment Management

Additionally, in agricultural systems, SWAT has proven to be very successful in controlling soil erosion and sediment transport (Thorne *et al.,* 2017). Erosion is a significant problem in many agricultural areas, especially those with steep terrain or heavy precipitation. SWAT's capacity to simulate soil erosion under various land use and management scenarios helps land managers to pinpoint high-risk sites for erosion and put mitigation plans in place to lessen sediment loss. Maintaining soil fertility is essential, but so is shielding downstream water bodies from sedimentation, which can harm aquatic habitats and water quality. The efficiency of reforestation and other soil conservation measures has been assessed using SWAT on China's Loess Plateau, an area that has historically experienced severe soil erosion. Large-scale erosion control programs that have now repaired millions of hectares of degraded land have a scientific foundation thanks to the model's demonstration that these interventions considerably decreased sediment output (Zhang *et al.,* 2012). The impact of conservation tillage strategies on sediment reduction has also been studied in the U.S. Midwest using SWAT, providing farmers with practical insights into how tillage method improvements can improve water quality and soil conservation (Gassman *et al.*, 2007). Since it helps make well-informed decisions that strike a balance between environmental sustainability and agricultural productivity. SWAT has generally shown itself to be a potent instrument in agricultural management. Its capacity to simulate intricate relationships among land usage, water resources, and farming methods has aided farmers, legislators, and environmentalists in creating management plans that safeguard natural resources and agricultural livelihoods.

4. SWAT in climate change adaptation

The health of ecosystems, agricultural output, and worldwide water resources are all seriously threatened by climate change. In order to evaluate these effects and create plans for adapting to climate change, the Soil and Water Assessment Tool (SWAT) model has become essential. Because SWAT can simulate crop yields, nutrient cycles, and hydrological processes under different climate scenarios, it is a commonly used tool for assessing the possible consequences of climate change on river basins, watersheds, and agricultural systems (Thorne *et al.*, 2017). SWAT assists researchers and policymakers in developing strategies to reduce risks and adjust to changing climatic circumstances by forecasting how temperature, precipitation, and atmospheric carbon dioxide levels affect crop yield and water availability (Neitsch *et al.*, 2011).

Climate change impact on water resources availability

Evaluating the potential effects of climatic variability on water resources is one of SWAT's most important responsibilities in the adaptation to climate change. Since extreme weather events like droughts and floods are predicted to become more frequent and intense due to climate change, it is critical to comprehend how these changes will impact water availability in order to manage water resources sustainably. Future water availability in diverse places can be gained by using SWAT's capacity to forecast surface runoff, groundwater recharge and river flows under varying climatic scenarios. To anticipate decreased streamflow during dry seasons and higher flood risks during wet seasons, for instance, SWAT has been used to simulate the effects of climate change on river basins like the Nile and Mississippi (Thorne *et al.*, 2017).

SWAT has been used to project the consequences of climate change on the availability of water for agricultural irrigation in the Upper Colorado River Basin. The findings suggested that future climatic scenarios would result in notable reductions in the amount of water available, especially during crucial growth seasons. As a result, it would be important to create plans for water conservation and increase the effectiveness of irrigation (Ficklin *et al.*, 2009). For agriculturally reliant regions, where variations in water supply can have a direct influence on food security, these findings are crucial. Worldwide attempts to prepare for water resources and adapt to climate change have benefited greatly from SWAT's capacity to offer precise and localized projections of how water supplies will change over time.

SWAT modelling agricultural adaptation strategies

Climate change poses a serious threat to agricultural systems, especially when it comes to fluctuating growing seasons, temperature extremes, and altered precipitation patterns. SWAT can anticipate how various climate scenarios would impact crop yields and soil health because of its ability to model crop development, soil moisture, and nutrient cycling. According to Tung *et al*. (2011), this makes SWAT an effective tool for discovering agricultural adaptation options, such as modifying crop varieties, planting and harvesting dates, and irrigation approaches. For instance, SWAT has been employed in the Indo-Gangetic Plain of India to assess how changing monsoon patterns and rising temperatures are affecting the production of wheat and rice, two of the most significant staple crops in the area. According to Singh *et al*. (2015), the model simulations demonstrated that farmers may assist themselves adapt to the changing climate by modifying planting dates and switching to heat-resistant crop types, which would help mitigate some of the detrimental effects of rising temperatures on crop production. In the same way, SWAT has been used in the Midwest of the United States to investigate the possible advantages of cover crops and conservation tillage in light of potential future climate changes. Zhang *et al.* (2018) found that these methods could lessen soil erosion and preserve soil fertility even in the face of more extreme weather patterns.

SWAT endorsing ecological land and water management

Beyond its use in agriculture, SWAT has contributed significantly to the development of climate change adaptation techniques for sustainable water and land management. Due to changing rainfall patterns and rising temperatures, many places are seeing an increase in water scarcity. SWAT assists policymakers and land managers in assessing the long-term effects of various land use practices on water availability and quality. This is especially crucial in areas where industry, agriculture, and home use are competing with one another for scarce water supplies as a result of climate change. Users can evaluate the possible effects of these changes on hydrological systems by using SWAT's simulation capabilities to model land-use change scenarios like reforestation, urban growth, and intensified agriculture. To illustrate how reforestation can lessen soil erosion and increase water retention, thereby assisting in mitigating the negative effects of climate change on water resources, SWAT has been used to investigate the effects of large-scale afforestation projects in China's Loess Plateau (Li *et al.*, 2011). By doing this, SWAT helps to create land management plans that protect soil and water resources for future generations while also making ecosystems more resilient to climate change.

Global application and adaptation planning of SWAT

The fact that SWAT has been widely adopted worldwide is more evidence of its importance in adapting to climate change. Planning for adaptation has been influenced by SWAT in areas that are extremely vulnerable to climatic variability, ranging from Southeast Asia to the African Sahel. Researchers in Southeast Asia, for instance, have been able to find water management strategies that can maintain agricultural output in the face of shifting monsoon patterns because to the assistance of SWAT in predicting the effects of climate change on rice production in the Mekong River Basin (Raclot *et al.,* 2015). This universal applicability illustrates how well-suited SWAT is as a model for evaluating various environmental circumstances and directing adaptation tactics that support long-term sustainability. To summarize, SWAT is an essential tool for planning climate change adaptation because to its ability to predict hydrological processes, crop development, and nutrient cycles under various climate scenarios. Through comprehensive forecasts of the ways in which water availability, agricultural output, and land use will be impacted by climate change, SWAT assists researchers land managers, and policymakers in creating plans that reduce risks and improve adaptability to a fast shifting climate.

Case Studies on SWAT applications in climate change adaptation

Issues with water, such as changing precipitation patterns, rising temperatures and modified hydrological cycles has been made worse by climate change. The Soil and Water Assessment Tool (SWAT), which models and comprehends the effects of various climatic conditions on watersheds, has been widely used to address these problems. By means of these case studies, SWAT has assisted regions in creating strategies for adaptive water resources that will lessen the impact of climate change.

Case Study 1: Assessing Water Resources in the Upper Mississippi River Basin, USA

Covering an area of more than 4, 92,000 square kilometres, the Upper Mississippi River Basin (UMRB) is susceptible to temperature and precipitation variations brought on by climate change. A recent study evaluated the effects of climate change on the amount and quality of water in this region using SWAT. To assess possible changes in runoff, sediment transport, and nutrient loading, researchers used SWAT to model a number of future climate scenarios based on IPCC forecasts (Gassman *et al.,* 2010). The results indicated that rising temperatures and changed precipitation patterns may cause higher rates of sedimentation, which would lower the quality of the water. In order to reduce soil erosion and nutrient loss, the study suggested buffer strips, cover crops, and adaptive tillage techniques based on SWAT's forecasts. For the UMRB, the study's incorporation of SWAT offered insightful information about adaptive water management. It showed how localised management techniques could counteract climate-related changes in water quality, providing a template for other areas with comparable risks (Gassman *et al.,* 2010).

Case Study 2: Upper Bhima Basin, Maharashtra

SWAT has been used extensively in the Upper Bhima River Basin (Pune, India) to comprehend how climate change affects hydrological systems. Soil characterizes as vertisols, which are characterized by a high content of montmorillonite clay with moderate sloped topography. This area, which depends mostly on agriculture, is vulnerable to droughts and unpredictable rainfall patterns. Future water availability was forecasted using the SWAT model under several climate change scenarios. Water shortages could be made worse by rising temperatures and fluctuating rainfall patterns, according to the model projections. Water management techniques including watershed development and irrigation scheduling, which are essential for agricultural climate adaptation, were developed with the aid of this data (Gosain *et al.,* 2006).

Case Study 3: Mahi Basin, Western India

SWAT was used in the Mahi River Basin (34,842 square kilometres) with annual rainfall ranging 600 mm to 1,200 mm. The runoff varies with the topography and land use; typically, it can range from 20 to 30 per cent of the total rainfall, influenced by seasonal variations and soil conditions. To investigate how climate change affects sediment load and water output. The area struggles with water scarcity and flood threats brought on by erratic rains. By evaluating changes in streamflow under various climate scenarios, the SWAT model assisted local planners in putting water-saving measures like check dams and better irrigation practices into place. The findings underlined that in order to lessen the consequences of climate variability, adaptive measures like afforestation and improved soil conservation techniques are necessary (Kaur *et al.,* 2010).

Case Study 4: Ganga River Basin

SWAT has been used in the Ganga Basin to investigate how water supplies are affected by both climate change and land-use change. Millions of people and a variety of habitats are supported by the Ganga Basin, one of India's most significant river systems. Changed precipitation patterns brought on by climate change may have a substantial impact on the amount of water available for home and agricultural needs, according to SWAT modeling in the basin. The information has proven essential for developing long-term plans for managing water resources, such as installing rainwater collection systems and using sustainable irrigation techniques (Jain *et al.,* 2007)

Challenges and limitations of SWAT

Watershed transport of water, sediment and agricultural chemicals is simulated by the popular hydrological model known as the Soil and Water Assessment Tool (SWAT). Notwithstanding its potential, SWAT has a number of accuracy and applicability issues, especially when it comes to modelling intricate environmental circumstances or putting certain management techniques into effect. A significant obstacle is the model's reliance on a large amount of input data, such as land cover, soil properties, weather data and land management techniques (Arnold *et al.,* 2012). Many areas, particularly in developing nations, frequently lack access to accurate and high-resolution data, which might reduce SWAT's accuracy and dependability. Reliance on guesses or generalised knowledge is necessary when data is lacking, which adds uncertainty and could make forecasts less accurate (Gassman *et al.,* 2007).This problem is sometimes lessened by using global data sets or remote sensing data, but these sources have drawbacks and might not adequately represent local variability. Due to the model's intricate structure and the large number of parameters involved, SWAT calibration and validation can be a time-consuming procedure (Abbaspour, 2015). In order to match simulated outputs with actual data and adjust model parameters, calibration is required; nevertheless, this process necessitates trained users and significant computational resources, particularly for large watersheds. The model has many parameters, and it can be difficult to determine which are the most sensitive. This is another issue with parameter sensitivity (Yang *et al.,* 2008). The likelihood of equifinality, in which different parameter sets produce outputs that are comparable, is increased by this complexity and may obscure the actual dynamics of the watershed under study (Beven & Freer, 2001).

Additionally, precise agriculture and other small-scale or spatially heterogeneous land use and management methods are difficult for SWAT to represent (Bieger *et al.*, 2014). Hydrological response units (HRUs), which combine soil and land use characteristics, are commonly used to establish the model's spatial resolution. This can make it less effective at representing small-scale aspects. This compilation might underestimate or overestimate sediment loads or water quality by ignoring the effects of fine-scale differences in management techniques (Neitsch *et al.,* 2011). Furthermore, SWAT's empirical approach to some processes, such as pesticide transfer and erosion, may not capture complicated dynamics, particularly in regions with distinct meteorological circumstances or diversified terrain (Arnold *et al.*, 2012). Last but not least, SWAT is not equipped to fully confront the effects of climate change. According to Jha *et al.* (2006), SWAT does not explicitly take into consideration feedback mechanisms between shifting climatic conditions and watershed processes, despite the fact that input data can be changed to simulate future climate scenarios. Even though SWAT is still being developed and improved, these drawbacks emphasise the necessity of applying and interpreting results carefully, especially in complicated or data-poor contexts.

Recent Advancements and Future Directions

SWAT has advanced significantly in recent years, especially in the areas of machine learning applications, remote sensing integration, and interface enhancements that improve its accuracy and usability. By addressing some of its historical drawbacks, these advancements pave the way for new uses of SWAT in watershed management and climate change adaptation. The integration of remote sensing has been one of the most revolutionary developments. In the past, SWAT frequently presented difficulties due to its reliance on large amounts of input data, especially in areas with limited ground-based data. According to Zhang et al. (2018), recent developments have made it possible to incorporate satellite-derived data into SWAT for real-time measures of plant cover, land use, and soil moisture.

Utilising remote sensing data reduces uncertainty in water quality and sedimentation modelling by offering more precise geographical and temporal data on watershed parameters (Zhu *et al.*, 2020). Remote sensing is especially important in regions where land cover is changing, like deforestation or urbanisation, and SWAT can dynamically incorporate these changes through frequent satellite updates (Liu *et al.*, 2020). SWAT's calibration and validation procedures have also been improved via machine learning and data assimilation techniques, becoming quicker and more precise. By using machine learning techniques to learn from previous model runs and observed data trends, SWAT parameters may now be optimised, significantly cutting down on calibration times and enhancing model resilience. Previously, calibration frequently needed laborious human modifications (Chadalawada *et al.*, 2021). According to Rouholahnejad *et al.* (2012), data assimilation techniques, like those that employ Bayesian methodologies, also use real-time data to continually update SWAT's simulations, increasing forecast accuracy. According to Abbaspour et al. (2018), climate impact studies that require adaptive, high-frequency updates due to quickly changing conditions, like extreme weather occurrences, will benefit greatly from this combination of machine learning and data assimilation. Because SWAT is now easier to use and more accessible, non-specialist stakeholders like policymakers and watershed managers are using it more frequently. The introduction of SWAT+ and user-friendly interfaces such as QSWAT have simplified the modelling process by enabling users to run simulations with little technical knowledge (Bieger *et al.*, 2017). In order to increase flexibility, SWAT+ also added modular frameworks, which allowed users to better model smaller-scale hydrological aspects and isolate particular components, such as groundwater or snowmelt processes (Bieger *et al.*, 2017). SWAT has been more widely used in resource management and decision-making settings, where quick and simple studies are frequently needed, because to its improved accessibility.

Future directions for SWAT development centre on increasing its computational effectiveness, improving the accuracy of the model, and broadening its applicability for a variety of uses. Since cloud computing allows for large-scale simulations without requiring a lot of local resources, it has become a viable solution to SWAT's computational problems (Yang *et al.*, 2022). As fresh data becomes available, SWAT will be able to model environmental systems in an adaptable manner thanks to efforts to further automate data assimilation procedures using AI techniques (Rouholahnejad *et al.*, 2012). For small-scale, heterogeneous landscapes that are now difficult to adequately simulate, SWAT is expected to become even more adaptable with the addition of more comprehensive land management methods and improvements in spatial resolution (Zhang *et al.*, 2018).

Conclusion

Since its inception as a model for agricultural management, SWAT has undergone tremendous evolution to become a complete instrument for tackling a broad range of environmental and water resource dilemmas. Researchers, land managers, and politicians around the world find it invaluable due to its ability to mimic intricate hydrological processes, nutrient cycles, and land management techniques over huge watersheds. One of SWAT's key advantages is still its capacity to evaluate how farming methods affect crop productivity, soil health, and water quality. But with the advent of climate change, environmental problems have become more complicated, and SWAT's function has broadened to encompass watershed management, ecosystem services preservation, and climate change adaptation. Its widespread use throughout the world, from Asia and Africa to Latin America and the United States, demonstrates SWAT's adaptability. As measures for reducing these effects are developed, it has shown to be a useful tool in forecasting how climate change would affect soil erosion, agricultural production, and water availability. SWAT offers vital insights into sustainable land and water management through its capacity to model different land use and climate change scenarios and its connection with Geographic Information Systems (GIS). SWAT analysis has become a crucial technique for evaluating possible future effects and creating adaptation plans in the context of climate change. Because of the changing climate, its models have played a crucial role in advising policymakers on how to modify irrigation systems, alter agricultural practices, and put conservation plans into action. For planning and executing adaptive strategies that support long-term sustainability, SWAT will continue to be a crucial tool as climate change poses new and unpredictable challenges to the security of water and food. SWAT has advanced environmental and agricultural modelling due to its development and influence. It is an essential tool for tackling the problems of agricultural production, water resource management, and climate change adaptation in the twenty-first century because of its capacity to integrate data, simulate long-term results, and offer practical insights. To guarantee that natural resources are managed sustainably, especially in light of the mounting dangers posed by climate change, SWAT must be further developed and implemented.

Disclaimer (Artificial intelligence)

Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT etc) and text-to-image generators have been used during writing or editing of this manuscript.

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