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Quantitative Approaches to Agricultural Runoff: A Modeling Perspective

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Abstract

Agricultural runoff is a major environmental concern contributing to nonpoint source pollution, soil erosion, and water quality degradation in both developed and developing countries. In regions like India, the issue is further exacerbated by intense monso on rainfall, changing land use, and widespread use of fertilizers and pesticides. Hydrological and watershed models play a vital role in simulating and managing these runoff processes, especially in areas where direct field measurements are limited. This review analyzes various agricultural runoff models, including SWAT, Ann AGNPS, RZWQM, PRZM, SWMM, LAPSUS, and emerging hybrid models. These tools vary in their design, data requirements, and suitability across different environmental conditions. A comparative analysis highlights their strengths and limitations in predicting runoff, sediment loss, and nutrient transport. The study also identifies key research gaps such as insufficient calibration for Indian monsoon systems, underrepresentation of subsurface flow in tropical soils, and limited application of machine learning models in regional contexts. Future research should focus on developing integrated, region -specific hybrid models that combine physical process -based understanding with machine learning techniques. The findings aim to guide researchers, policymakers, and watershed managers in selecting appropriate models based on data availability, spatial scale, and specific objectives, ultimately contributing to more sustainable and climate -resilient agricultural practices.

Keywords: *Agricultural runoff, Hydrological modeling, SWAT, Monsoon rainfall, Machine Learning*

Introduction

Agricultural runoff is a significant source of nonpoint pollution that impacts freshwater quality globally. Intensive agricultural activities, particularly the use of chemical fertilizers and pesticides, have increased the transfer of nutrients and sediments from farmlands to rivers, lakes, and reservoirs, causing water quality degradation and ecosystem disturbances. Excess nitrogen (N) and phosphorus (P) often lead to eutrophication, while suspended sediments reduce water clarity and damage aquatic habitats (Hansen et al., 2021). The impacts of degraded water quality extend beyond local watersheds to downstream regions, contributing to large -scale environmental issues such as hypoxic zones in coastal areas.

The problem of agricultural runoff is further intensified by climate variability and land -use change. Rising temperatures, extreme rainfall events, and shifting precipitation patterns accelerate runoff, nutrient leaching, and soil erosion. Human -driven changes such as deforestation, overgrazing, urbanization, and farming on steep slopes further amplify sediment and nutrient transport from agricultural fields (Xiong et al., 2022; Zew de et al., 2024). In regions like the Upper Blue Nile Basin, agricultural expansion in erosion -prone landscapes has led to severe soil degradation and downstream sedimentation (Zewde et al., 2024). Similarly, global wetlands, which act as natural nutrient filters, are increasingly affected by fertilizer -driven runoff, thereby altering their biogeochemical cycles and contributing to increased greenhouse gas emissions (Pasut et al., 2021). Effective management of agricultural runoff relies heavily on hydrological and watershed models, as direct field measurements are often limited, particularly in ungauged or data -scarce regions. These models simulate rainfall -runoff processes, sediment transport, and nutrient dynamics, thereby supporting soil and water conservation planning. Tools ranging from simple empirical approaches to complex process -based models, such as the Soil Conservation Service Curve Number (SCS -CN) method, Soil and Water Assessment Tool (SWAT), and other physically -based runoff models, are widely applied to predict runoff and sediment yields under varying land -use and climate conditions (Rawat et al., 2020; Zewde et al., 2024).

However, each model has its strengths and limitations depending on data requirements, spatial scale, and environmental complexity. Comparative evaluations and review studies are essential to identify suitable models for different agricultural settings and to highlight knowledge gaps for future research. The objective of this review is to evaluate existing agricultural runoff models, summarize their applications and limitations, and identify research gaps that can guide effective watershed management and sustainable agricultural practices.

Model Classification

Based on widely accepted hydrological modeling frameworks, the reviewed models were classified into three categories:

1. **Empirical models:** simple, data -light approaches that estimate runoff and soil loss using statistical relationships (e.g., USLE, RUSLE, MUSLE) (Igwe et al., 2017).
2. **Conceptual models:** combine process understanding with simplified hydrological components to simulate runoff and sediment yield (e.g., AnnAGNPS, HSPF, STREAM) (Cerdan et al., 2001).

3. **Physical models:** simulate water and sediment movement using physical laws and distributed parameters (e.g., SWAT, WEPP, MIKE SHE) (Anteneh et al., 2022; Liu et al., 2017). Models were further categorized by temporal resolution (event-based vs. continuous) and spatial scale (plot, field, or watershed), following approaches used in previous hydrological model comparison studies (Carlos Rogério de Mello et al., 2016; Ba bak Mohammadi, 2021).

Model Description

Agricultural runoff modeling has advanced significantly over the years, with several models developed to predict surface runoff, sediment loss, and nutrient or pesticide transport. These models vary in their theoretical foundation, data requirements, spatial -temporal scales, and suitability for specific hydrological conditions. This section categorizes and compares major agricultural runoff models based on insights from multiple studies.

1. **SWAT (Soil and Water Assessment Tool):** SWAT is a physically based, semi -distributed model used to simulate the long -term impact of land use, management prac tices, and climate on water quantity and quality at the watershed level. It divides the watershed into sub -basins and further into hydrologic response units (HRUs). In a study by Victoria Ningthoujam (2024), SWAT was successfully calibrated using remote sensing -based evapotranspiration data (ETa) in an ungauged basin in Manipur, India. The results showed high model accuracy ($R^2 > 0.7$, NSE > 0.7) and demonstrated the effectiveness of ETa -based calibration in data -scarce regions.

2. **RZWQM (Root Zone Water Qualit y Model):** The RZWQM is a mechanistic model developed by USDA – ARS to simulate hydrology, nutrient cycling, crop growth, and pesticide transport. It operates at a field scale and includes features like tile drainage simulation and sub -daily time steps. Zhang et al. (2015) reported that RZWQM effectively simulated pesticide runoff and sediment erosion under both rainfall and flood irrigation events in California. It showed good accuracy and flexibility in integrating management practices like tillage and pestic ide formulations.

3. **PRZM (Pesticide Root Zone Model):** Developed by the USEPA, PRZM is a one -dimensional model used primarily to simulate pesticide movement in the unsaturated soil zone. It uses the SCS curve number method for surface runoff. Though simpler, i t cannot simulate subsurface processes or dynamic land management. According to Zhang et al. (2015), PRZM performed adequately under sprinkler and rainfall irrigation but was less accurate for flood irrigation compared to other models.

4. **LAPSUS (Landscape Process and Soil Erosion Model):** LAPSUS is a dynamic, spatially distributed model that simulates long -term landscape evolution due to erosion and deposition. In a study by Jetten et al. (1999), LAPSUS accurately predicted runoff patterns and sediment deposit ion across different terrains and rainfall events.

5. **AnnAGNPS (Annualized Agricultural Non -Point Source Pollution Model):** AnnAGNPS is a continuous simulation, watershed -scale model developed by the USDA to evaluate non -point source pollution. It integrates cl imate, land use, and field management data. Bhadra et al. (2010) used AnnAGNPS in a sub -humid Indian watershed and achieved high agreement between observed and simulated runoff and sediment load (NSE = 0.71).

6. **SWMM (Storm Water Management Model):** SWMM is often applied in urban and peri -urban catchments but has also been adapted for mixed land-use watersheds. Ashiagbor et al. (2013) applied SWMM in a Ghanaian catchment and found it effective in identifying peak flow and runoff variability across land cover types.

7. **Hydrus -1D and WEPP:** These models were described by Aouissi et al. (2012) for their detailed simulation of infiltration and erosion processes. Hydrus -1D is strong in simulating soil -water interactions in vertical profiles, while WEPP models slope -scale erosion and has been widely validated in semi -arid areas.

Comparative analysis of Agricultural Runoff Models

The SWAT (Soil and Water Assessment Tool) model is a widely accepted tool for evaluating water quality and hydrology in large river basins. Its modular design, ability to integrate GIS, and history of over 250 global applications make it a top choice for non -point source pollution studies. However, it requires extensive input data and complex calibration using techniques such as SWAT -CUP and S UFI-2 (Arnold et al., 2012). The AnnAGNPS (Annualized Agricultural Non -Point Source Pollution model) is effective in simulating the impacts of BMPs (Best Management Practices) and modeling nitrogen and phosphorus migration under complex topography. It show ed high effectiveness in the Three Gorges Reservoir Area and proved suitable for spatially distributed pollution evaluation (Zhang et al., 2020). The RZWQM and its updated version RZWQM2 are 1D root zone models designed for detailed simulation of water, so lutes, and pesticide dynamics. RZWQM2 includes DSSAT crop modules and supports automated calibration through PEST. It is best suited for research involving nutrient leaching, irrigation scheduling, and pesticide behavior at the field scale (Ma et al., 2012 ; Ma et al., 2004). PRZM (Pesticide Root Zone Model) is a pesticide -specific model used to simulate chemical runoff and leaching. In comparative simulations, PRZM and RZWQM gave similar predictions for pesticide loss events, though PRZM is generally less robust for broader hydrologic simulations (Chen et al., 2017). SWMM (Storm Water Management Model), originally developed by the U.S. EPA for urban drainage, is gaining application in agricultural areas near urban zones. It effectively simulates low-impact development (LID) practices and green infrastructure (GI). However, it lacks the biophysical detail of models like SWAT or RZWQM (Niazi et al., 2017). LAPSUS LS is a catchment -scale landslide and slope stability model that integrates soil, hydrology, and vegetation parameters. It uses a limit equilibrium method to calculate the factor of safety at the grid level. Studies from Central America showed strong sensitivity to vegetation type and soil cohesion, making it suitable for erosion -prone agricultural landscapes (Rossi et al., 2017).

Discussion and Research Gaps

Despite considerable progress in hydrological modeling, several research gaps persist, especially in the context of Indian agro -hydrological systems. One major limitation is the lack of comprehensive calibration studies for monsoon -driven catchments. For instance, while Desai et al. (2020) demonstrated successful multi -site calibration using SWAT -CUP in the Betwa basin, many other Indian river basins still rely on single -point calibration or simplified assumptions that neglect spatial variability. Another persistent challenge is the underrepresentation of subsurface flow and shallow aquifer contributions in tropical soil systems, particularly under conditions of high rainfall intensity. This is a critical oversight in semi -arid to sub -humid Indian regions where lateral and base flow components play a dominant role in runoff formation but are inadequately modeled by existing frameworks like SWAT without customized local parameterization.

Further, there is a limited comparison between traditional models like SWAT and emerging region -specific tools or hybrid frameworks. Kumar et al. (2024) addressed this gap by introducing a hybrid ANN -WEAP model, which outperformed standalone physical (WEAP) and machine learning (ANN) models with NSE values of 0.955 and R^2 of 0.96, thereby showing the potential of integrated modeling in the data -scarce Upper Narmada Basin. There is also a lack of comparative studies involving machine learning (ML) -based models in Indian basins. Ojha et al. (2023) highlighted the superiority of Random Forest (RF) over other ML models for rainfall -runoff prediction in the Punpun river basin, achieving an NSE of 0.795. This study showcases the promise of ML models in data -limited regions but also reveals the need for hybridization and physical consistency in predictions.

Way Forwards

To bridge these gaps, future research should focus on the development of hybrid models that synergize the physical realism of deterministic models with the adaptive capabilities of ML techniques. This integration is crucial for handling the non-linear and non -stationary behaviors of monsoon -driven runoff systems and for managing the uncertainty in input datasets. Moreover, efforts must be intensified to regionalize hydrological models, including parameter retuning for tropical Indian soils and monsoon precipitation regimes. Incorporating enhanced validation protocols, such as multi -temporal and multi -site calibration, should become standard practice. Finally, there is a need to develop open -source, region -specific model benchmarking datasets, enabling a better comparative evaluation of SWAT, WEAP, ANN, and hybrid approaches across Indian agro -ecological zones. These efforts will support robust, scalable, and climate -resilient water management strategies.

Conclusion

This article explored the development and evaluation of agricultural runoff models with an emphasis on their applicability in diverse agro -ecological contexts, particularly within monsoon -affected regions. Through a detailed literature -based comparison, it is evident that no single model universally satisfies all criteria of hydrological accuracy, data efficiency, and regional adaptability. The performance and suitability of models such as SWAT, AnnAGNPS, RZWQM2, and newer hybrid frameworks vary significantly depending on catchment size, climatic zone, data availability, and study objectives. While SWAT and AnnAGNPS are robust for large watershed -scale assessments with sufficient s patial and temporal data, models like RZWQM2 are better suited for field -scale investigations involving nutrient leaching and crop –soil interactions. Hybrid and machine -learning -enhanced models show promise in addressing data scarcity and nonlinear runoff behavior, especially in tropical and semi -arid Indian conditions. However, their success heavily depends on proper calibration, validation, and integration with physical process understanding.

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