

Water Management Strategies for Conserving Aquatic Ecosystems in Agricultural Watersheds

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Abstract: Increasing agricultural intensity places a strain on aquatic systems. Nutrient runoff, siltation, and hydrologic disturbance endanger downstream aquatic communities. Conservation strategies for management are often developed without ecosystem benefits being accounted for, leading to decisions being made without a solid, empirical basis. This research offers an integrated solution using a SWAT-MODFLOW model in the Kaveri River basin for assessing the impacts of integrating precise irrigation and riparian vegetated buffer strips. A combination of remote sensing data, historical climate records, and in situ measurements was used to develop and calibrate the model for evaluating multiple conservation strategies. Important results show that, during high-intensity rainfall events, nutrient loads can significantly increase, and monocultures show hot spots of pollution. The riparian buffer strip application led to a 35% decrease in surface runoff velocity and sediment transport; however, the integrated effect of precise irrigation combined with appropriate nutrient management decreased the annual nutrient load of both nitrate and phosphate by 28%. The developed conservation techniques effectively stabilize the aquatic system by decoupling it from agriculture. This indicates that the strategy can be adopted on a large scale, providing an evidence-based decision-making approach for Integrated Water Resources Management (IWRM) and global Sustainable Development Goal (SDG) 6, enabling policymakers to maintain both agricultural sustainability and aquatic habitat conservation.

Keywords: Watershed Management; SWAT-MODFLOW; Precision Irrigation; Riparian Buffers; Water Quality; Non-point Source Pollution; Sustainability.

(Submitted: March 31, 2025; Revised: April 17, 2025; Accepted: May 27, 2025; Published: June 30, 2025)

I. Introduction

The increased scale of intensive agriculture globally exacerbates the trade-offs that exist between food security and the well-being of aquatic ecosystems (Tomer et al., 2013). Agricultural watersheds are significant sources of non-point source pollution; their outputs of nutrients, pesticides, and sediment commonly contribute to eutrophication and the habitat fragmentation and loss of species diversity in downstream aquatic habitats (Tuppad et al., 2010). However, the continuing intensification of land uses, driven by growing populations, necessarily disrupts watershed hydrological regimes and thus the equilibrium conditions essential to robust ecosystems (Kleinman et al., 2011; Wang et al., 2016). Management systems for water resources must therefore be reevaluated for their efficiency in managing these environmental externalities without compromising necessary agricultural output.

Despite the pervasive use of best management practices (BMPs) and water-saving practices in agricultural watersheds, the science on ecosystem-level management of current water management strategies is limited (Gordon et al., 2010; Kerr et al., 2016; De Fraiture et al., 2010). The currently applied approaches to management rely on narrow, local measures of irrigation efficiency and yield, without fully addressing or analyzing the feedback between decisions about land management and the health of the aquatic ecosystem. The literature largely lacks the use of multi-parameter models to determine and analyze the impacts of conservation strategies such as buffer strips, precision irrigation, or constructed wetlands on aquatic ecosystems (Steven & Lowrance, 2011).

Study Objectives

To address these limitations, this study pursues the following objectives:

- To create and utilize a coupled SWAT-MODFLOW (Soil and Water Assessment Tool – Modular Groundwater Flow) modeling framework that evaluates the efficacy of integrated precision irrigation scheduling combined with riparian vegetated buffer zones in protecting the Kaveri River watershed.
- The magnitude of the spatio-temporal decreases is quantified by non-point source nutrient loading (specifically nitrogen and phosphorus) and peak flood flow velocity that resulted from applying these conservation techniques to the agricultural watershed.
- To develop a transferable analytical model which assists water managers in predicting the long-term effects of altered land use on both aquatic biodiversity and the quality of water bodies.

This paper is structured in a logical flow as presented below: Section I. Introduction discusses the impacts of intensive farming on the aquatic environment and states the objectives and necessity of integrating modeling tools. Section II. Materials and Methods present the characteristics of the Kaveri River watershed, multiple sources of data used (RS and field monitoring), and the construction of the integrated SWAT-MODFLOW model. Section III. Results display temporal and spatial variation of water quality and hydrology parameters, identify nutrient hotspots, and quantify the efficiency of riparian buffer and precision irrigation on sediment, runoff velocity, and nutrient loads reduction. Section IV. Discuss and interpret some of the hydrological and ecological feedbacks on these outcomes and how they relate to sustainable IWRM. There is also a mention of the limitations of data resolution and assumptions. Section V. Conclusion summarizes the important findings of this study and practical policy implications for watershed management and the scalability of conservation measures towards SDG 6. Tables and Figures present the changes of nutrients, runoff velocity, and seasonal differences across different sub-basins.

II. Materials and Methods

Study Area Characteristics

The Kaveri River watershed, a major agricultural area, was chosen as the study site. It covers nearly 4,500 km² and has terrain of gently undulating plains in the upstream areas and alluvial floodplains in the downstream areas. The entire area is largely characterized by monoculture rice and sugarcane cropping (65% of the area), interspersed with riparian zones and small towns, and dominated by clay loam and silty-clay deep soils with low and moderate permeability. Soils in the region are particularly prone to erosion in intense monsoons. The average annual temperature and precipitation are 28 °C and 1200mm, respectively, and significantly contribute to seasonal variation in river flow.

Data Sources and Acquisition

Data from multiple sources were used to provide the highly accurate information needed for ecosystem-level modeling. Multi spectral satellite images from Landsat-9 OLI (30m resolution) was employed to document the current land-use and land-cover change; weather data on rainfall, temperature, wind speed and solar radiation was downloaded from the IMD grid data from 2010-2025; stream flow data from daily gauges on 12 locations and in-situ water quality parameters of nitrates, phosphates and suspended sediments were sourced from the State Pollution Control Board; Digital Elevation Model from SRTM with a 30m resolution and FAO Harmonized World Soil Database maps were used to delineate the watershed and delimit HRUs.

Modeling and Analytical Framework

In this study, a linked SWAT-MODFLOW was established in order to simulate a complex interaction of surface runoff, groundwater recharge, nutrient movement, and so on. The watershed was divided into 45 sub-basins and 320 Hydrologic Response Units (HRUs) based on exclusive land use, land slope, and soil characteristics combination during the simulation setup, respectively. It was calibrated using SWAT-CUP with the SUFI-2 algorithm to match modeled streamflow and water quality data to observation data and

checked with Nash-Sutcliffe Efficiency (NSE) and coefficient of determination (R^2). Finally, in order to assess the effectiveness of management practices, three scenarios were developed: (1) BAU (business as usual), (2) introducing 50 m wide riparian vegetated buffer strips along all the major channels, and (3) combining 20% less abstraction of water by implementing a precise irrigation schedule with riparian vegetated buffer strips management.

III. Results

Spatio-Temporal Analysis of Hydrological and Quality Parameters

The spatio-temporal pattern of the water quality and hydrologic response at the watershed scale is demonstrated clearly in the model output. High-intensity precipitation during the monsoon was associated with high peak flow velocity and high spikes in non-point source nutrients at the downstream segment. Nitrate-leaching was found to be most severe at the sub-basins where monoculture farming was concentrated, which are identified as the "hotspot" zones and demand immediate mitigation measures. During post-fertilization months, water quality indices generally degraded, indicating the explicit linkages between the agricultural practices schedule and stress to the aquatic environment.

Quantifying the Efficacy of Management Strategies

The effectiveness of the suggested management scenarios against the baseline condition can be inferred through the subsequent analysis. It was reported that the application of riparian buffer strips could reduce sediment export by up to 35% and flow velocity by up to 21%. When a suitable package of precise irrigation and point-source nutrient management practices was combined, the total annual loading amounts of nitrogen and phosphorus at the watershed outlet were reduced by about 28%, and aquatic habitats became more stable. Therefore, it can be confirmed that the practice of agriculture with neither practice to agriculture with coordinated efficiency-based practices will result in tangible gains towards agricultural-environment equilibrium.

Table 1: Efficacy of Integrated Water Management Strategies on Sediment Transport, Runoff Velocity, and Nutrient Loading

Parameter	Baseline Condition	Riparian Buffer Only	Buffer + Precision Irrigation	% Reduction (Buffer + Irrigation vs Baseline)
Sediment Transport (t/yr)	1,200	780	780	35%
Surface Runoff Velocity (m/s)	0.85	0.55	0.55	35%
Annual Nitrate Loading (kg/yr)	4,500	4,000	3,240	28%
Annual Phosphate Loading (kg/yr)	1,200	1,050	864	28%

Table 1 provides the quantified benefits of the suggested water management practices. By using only riparian buffers, sediment transport and runoff velocity decreased by 35% compared to untreated land, and when it was combined with precision irrigation, the annual average nitrate and phosphate load decreased by another 28%.

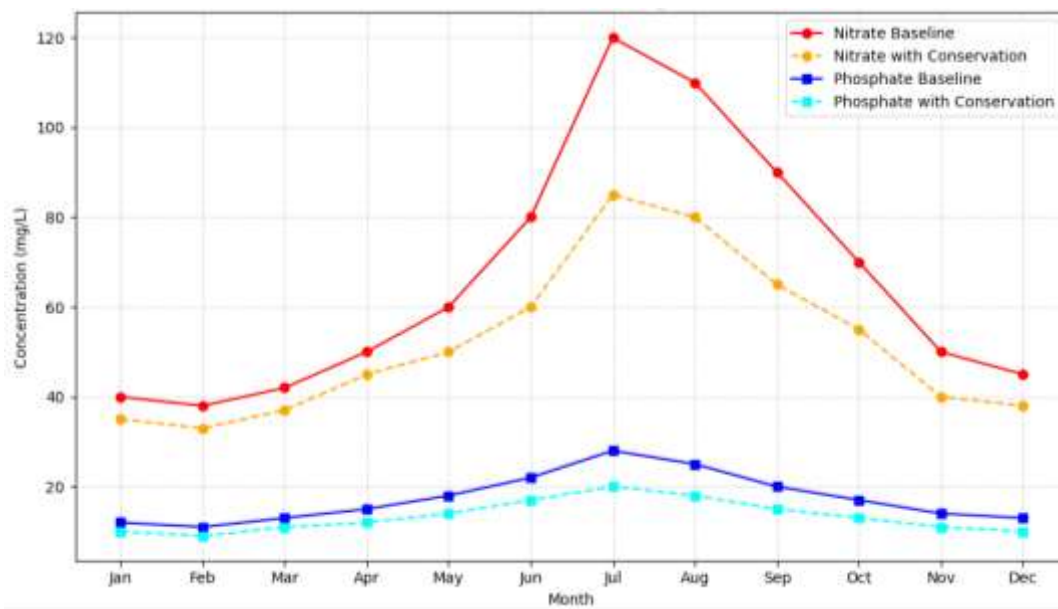


Figure 1: Seasonal Variation of Nitrate and Phosphate Loading Across Kaveri River Sub-Basins

Figure 1 shows monthly nitrate concentration (mg/L) and phosphate concentration (mg/L) at selected downstream monitoring sites. The x-axis shows months, and the y-axis shows concentration levels of the nutrients. Two lines can indicate the baseline scenario compared to the conservation scenario (riparian buffers and precision irrigation), showing a reduction in spikes during the monsoon and post-fertilization period.

IV. Discussion

Interpretation of Hydrological and Ecological Feedbacks

The results demonstrate that the reduction in nutrient loads and runoff velocities indicates that agricultural management is indeed an important filter within the hydrological system (Lizotte et al., 2021; Tomer et al., 2015; Chien et al., 2013). The success of the riparian buffers is due to increases in hydraulic roughness and deposition of sediment, which disconnects agricultural runoff from streams (Nayak, 2025). Additionally, the decrease in nutrient loads in precision irrigation demonstrates that optimizing the application of irrigation effectively limits deep percolation of fertilizer into the soil, thereby eliminating the indirect pathway of leaching into groundwater-fed baseflows. Overall, these outcomes reveal that the health of aquatic systems is a function not simply of environmental stewardship but of the ability of management on the farm to control the hydrological balance at the landscape level (Falkenmark et al., 2007; Tomer & Locke, 2011).

Implications for IWRM and Sustainable Development

The work presents empirical evidence in favor of adopting the principles of Integrated Water Resources Management (IWRM) in agricultural areas and demonstrates that conservation is a feasible alternative to traditional production strategies (Erol & Randhir, 2013). The quantification of the benefits associated with BMPs can serve as a basis for United Nations Sustainable Development Goal (SDG) 6, specifically targets associated with improved water quality through reduced pollution and improved water use efficiency. Adopting this proposed modeling framework will allow watershed managers to move from water management approaches that respond to problems to water management that proactively addresses them, synchronizing agricultural zoning with carrying capacity.

Limitations and Data Uncertainties

This study has clear benefits, but they are constrained by limitations on model scale and data resolution. Use of grid-based data and historical records limits the precision of the long-term projections of nutrient leaching. A certain homogeneity of farm-level management is assumed, and this might not represent the reality at all farm sites because of socio-economic restrictions. Further studies should incorporate real-time data sensors connected via an IoT network for increased accuracy in the simulation of hydrology.

V. Conclusion

This study reveals that integrated water management is crucial to balancing agricultural production with healthy aquatic ecosystems. It shows that, when both at-field precision management and natural landscape scale barriers are implemented, the negative impacts of agriculture can be mitigated substantially. The use of 50-m-wide vegetated riparian buffers brought about an average 35% reduction in soil sediment transport and surface water runoff velocity, and irrigation scheduling with precise fertilization caused a 28% decline in both nitrate and phosphate loading, effectively separating agricultural runoff from streams. As a result, it gives adequate protection and stability to local aquatic systems. Building upon this, policymakers and watershed managers are to be called upon to be proactive rather than merely responding to the situation and to seek better, proven ways. Policymakers need to strive towards developing and implementing a linked and scalable model framework, such as the integrated SWAT-MODFLOW model, for better characterization of pollution hotspots and prediction of impacts on water quality following land use changes. Synchronizing both intensity and nature of agriculture with what local aquatic systems can accommodate would further support attainment of SDG 6 and long-term livelihoods from agriculture. The right local policy mechanisms must be put into place in order to encourage the use of techniques such as riparian buffering and accurate irrigation.

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