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Nutrient Runoff Assessment in Agricultural Lands Using the MIKE SHE Simulation Framework

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Abstract: Accurate assessment of nutrient runoff in farming regions is crucial for managing watersheds and preserving water quality. This study uses the MIKE SHE integrated hydrological modeling system to simulate and evaluate the nutrient runoff behavior across agricultural watersheds with different land uses and climate conditions. The model was calibrated and validated against long-term hydrometeorological and water quality datasets, thus assuring its reliability in modeling surface runoff, subsurface flow, and nutrient transport. Historical climate data from 1980 to 2020, along with land use change, were evaluated for their impacts on nutrient exports using a combination of runoff reduction techniques and spatial regression. Findings indicate that intensively fertilized zones are major contributors to nitrate and phosphorus loading, especially during the peak rainfall season. Analyses of various scenarios show that certain land use changes, such as converting forests and wetlands to farmland, dramatically increase nutrient runoff, while some conservation measures, notably the implementation of buffer strips and wetland restoration, should reduce hydrological nutrient export. In addition, the results demonstrated that the projected impacts of climate change worsen nutrient loss through runoff as a result of intensified precipitation and increased soil saturation.

The MIKE SHE system works well for understanding the interplay of water, nutrients, and biological systems as it relates to nutrient pollution. This makes it helpful in evaluating policies and managing programs aimed at agricultural watershed nutrient pollution.

Keywords: Nutrient Runoff; Mike She Model; Agricultural Lands; Hydrologic Simulation; Water Quality Assessment.

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I. Introduction

Climate change and land use and cover change (LUCC) are exerting significant new pressures on hydrological systems and ecosystem services, particularly in regions with intensive agricultural activity (Ishaque et al., 2023). The increase in precipitation intensity caused by a warming climate is accelerating the hydrological cycle, leading to greater surface runoff and altering the transport and deposition of nutrients in terrestrial and aquatic ecosystems (Rasmussen et al., 2015), (Zhou et al., 2023). At the same time, human activities such as large-scale deforestation, irrigation expansion, urban sprawl, and even water infrastructure development have drastically modified catchment hydrodynamics and nutrient fluxes (Hassan, 2023). These changes pose tremendous threats to food security, water quality, and sustainable watershed management in regions with fragile hydro-climatic balances and densely populated areas (Nasim et al., 2018), (Rajbhandari et al., 2015; Hussain et al., 2023). In agricultural catchments, nutrient runoff driven primarily by fertilizers and soil disturbance, especially nitrogen and phosphorus, is a significant form of non-point source pollution (Spoorthi et al., 2021), (Toha et al., 2025), (Lutz et al., 2016). Downstream bodies of water are suffering from eutrophication, degrading marine habitats, and reducing the amount of freshwater available due to over-nutrient loading (Chaudhry, 2017; Lutz et al., 2016). In this regard, modeling and evaluating nutrient runoff with different scenarios of land use, climate, and other factors is critical for developing appropriate strategies for water quality safeguards (Wijngaard et al., 2017; Shehzad, 2023; Mustapha et al., 2017).

Models such as MIKE SHE and its associated hydraulic models, MIKE 11, offer extensive capabilities for simulating the interactions of surface water, groundwater, and solute transport. In contrast to lumped or semi-distributed models, these models enable dynamic simulation of nutrient mobilization and delivery in systems that are spatially heterogeneous and temporally variable, representing more complexities of the

real world. Recent studies have demonstrated the effectiveness of MIKE SHE in evaluating environmental water requirements, land use impacts, and climate-driven hydrologic changes in both arid and temperate regions, supporting the model's robustness and adaptability. But there is still a knowledge gap regarding climate variability and land use transitions' long-term impacts on nutrient runoff in agriculture-dominated regions. This research aims to address that gap using MIKE SHE/MIKE 11 to simulate nutrient runoff in a cultivated watershed from 1980 to 2020. This study combines climate and land use data with spatial regression methods to quantify the relative contributions of land use changes and climate extremes to nutrient runoff (Menon & Nair, 2024). These results will hopefully help in improving farming methods and water quality. Policies are provided for the proper management of areas of land and water resources with respect to environmental protection (Chow, 1959; DWA, 2010).

II. Literature Review

2.1 Previous research on nutrient runoff assessment in agricultural lands

Nutrient runoff assessment conducted in farmlands plays an essential role in water pollution research. There is a wealth of information on the impact of agricultural activities on nutrient emissions (nitrogen, phosphorus) to water sources (Zhang et al., 2017; Balavandi, 2017). For example, changes in land-use practices can considerably affect the volume of runoff water and, consequently, the amount of nutrients transported. Researchers have examined the effects of various land use types on runoff depth, the interdependence between land-use patterns and runoff, and the relationship between changes in runoff depth and socio-economic factors. However, limited attention has been given to understanding the interactions among multiple land-use types and their combinations, particularly regarding how climate change influences runoff depth within these contexts.

More precise estimates of runoff have been conducted by using paired catchment tests, climate resilience approaches (the Budyko framework), statistical techniques (multivariate linear regression and spatio-temporal geographically weighted regression), and various hydrological modeling approaches (Zhang, M. et al., 2021). While paired catchment tests offer direct comparisons, they are often impeded by their inability to locate suitable catchments that have the same underlying and meteorological features. In spite of their physical significance, climate resilience approaches may be limited in capturing all the intricacies of hydrological processes (Alamdari et al., 2022).

While statistical methods demonstrate the relationships between two or more phenomena, they often fail to explain the sudden change in patterns of runoff caused by climate change (African Development Bank, 2009). This points toward the need for more holistic approaches that can distinguish between the impact of climate change and that of human activity on the volume of runoff and the transport of nutrients within it.

2.2 Use of simulation models in water quality assessment

In the assessment of water quality, simulation models are especially important because they help explain hard hydrological and biogeochemical systems. The MIKE SHE/MIKE 11 model is a well-established hydrological simulation tool commonly used to assess the impacts of climate change and anthropogenic activities such as land use on water quality and runoff (ASTM, 2002). Developed by DHI, the model offers flexibility by enabling the creation of simplified representations with minimal data inputs, which can be iteratively refined as more information becomes available, similar to a Bayesian updating approach. Despite potential uncertainties in the simulated outputs, the model remains valuable for regions with limited subsurface data characterization (DWA, 2010). For example, the DRIFT-ARID method requires an integrated groundwater and surface water hydrological model (MSHE) to generate daily time series estimates of hydrologic and hydraulic parameters for scenario development. This enables the simulation of the coupled surface water and groundwater responses to distributed climate inputs and future land use shifts. Understanding runoff behavior is also aided by other models, for example, the VIC model. Even though these models effectively study how climate change and land use affect runoff, a key drawback is their

inability to quantitatively assess how land use changes impact the volume of runoff, particularly regarding the transport of nutrients. Some studies have innovatively proposed incorporating hydrological scenario simulation with statistical attribution analysis to differentiate the effects of climate change and human activity. This incorporation overcomes the limitation set by climate change and human activities on the runoff depth analysis of integrating hydrology and attribution analysis model (DWAF, 2007).

2.3 Role of nutrient management practices in reducing runoff

Nutrient management practices such as runoff control and the conservation of water resources are necessary, as they reduce water quality impacts and losses from surface runoff and leaching. Important actions are optimized fertilizer application, cover cropping, conservation tillage, riparian buffer zones, and integrated nutrient management (Esterhuyse, 2012). These practices also improve soil health, decrease erosion, and filter out excess nutrients from water before it flows into water bodies. The relationship between land use and water quality highlights the necessity of these practices, especially in large basins with dense human activity and significant impacts on nutrients.

III. Methodology

3.1 Description of Study Area and Data Collection Methods

The methodology starts with an overview of the Chi-Mun River Basin in Thailand and the Mokolo River Basin in South Africa, which can both be studied for their hydrological processes and the impacts of land use. It also contains the basin's geographic location with the exact coordinates, along with mapping of the river system, topography, and major settlements. The climate part also covers the yearly and seasonal rainfall amounts with the ranges of temperature, evapotranspiration rates, and any significant climate change patterns. Some additional information regarding the surface and subsurface hydrology of the area is also given, such as the altitude range, slope steepness, and how the bedrock shapes the water flow above and below the ground. A thorough analysis of land use and land cover (LULC) is done next, which includes farming regions, forested areas, urbanized areas, and other important land types, as well as LULC maps showing change over time. Finally, the hydrological network is described by identifying the major rivers, their tributaries, dams, and water abstraction points, all of which must be understood within the context of the basin's hydrological regime.

3.2 Data Collection Methods

A robust dataset is essential for accurate hydrological modeling; therefore, this study integrates multiple sources of meteorological data to maximize spatial and temporal coverage. Precipitation, temperature, humidity, wind speed, and solar radiation are all parts of meteorological data that will be gathered from national research and meteorological agencies. Any gaps in data will be evaluated for their potential impact on modeling. River discharge measurements, as well as information from gauging stations alongside the main river and its tributaries, will be collected by the water resource authorities. Topographic data includes critical pieces of information like elevation, slope, and flow direction for watershed delineation and flow routing, which will be extracted from Digital Elevation Models. Using satellite imagery from Landsat and Sentinel, land use and land cover data will be created alongside ground truthing validation in order to check the accuracy of the results. Some soil data, porosity, and horizontal permeability can be collected from national databases and field investigations, while hydraulic conductivity requires more specialized investigation. Geological data from maps and borehole logs can support developing the conceptual model of subsurface hydrogeology, while recognizing that limited detail of the subsurface will lead to inaccuracy within the groundwater flow simulation.

Moreover, if the scope of the study is expanded to include water quality, nutrient concentrations—such as nitrogen and phosphorus—in both surface and groundwater will be incorporated using data from monitoring station records, enabling a more comprehensive environmental evaluation.

3.3 Implementation of MIKE SHE Simulation Framework

This study will utilize the MIKE SHE/MIKE 11 coupled hydrological model (MSHE) developed by DHI, which integrates surface water and groundwater processes, evapotranspiration, unsaturated flow, and overland flow. The model will be implemented starting from the model definition and domain grid discretization with horizontal and vertical components. The balance between computer resource expenditure and landscape heterogeneity will determine the spatial grid resolution. Vertical layering will capture various geological and soil horizons to model subsurface dynamics. A conceptual model based on the data collected will include surface water features like river networks and associated cross-sections, including boundary conditions for surface water and the unsaturated zone soil profiles, root depths of hydraulic properties, and the saturated zone aquifer geometry with parameters such as conductivity, storage characteristics, and boundary conditions. In some cases where data is limited spatially, a more crude conceptual model can be used. The input datasets for weather, land use/land cover, soils, and geology will need to be processed and formatted specifically for MIKE SHE, such as the creation of gridded rainfall and evapotranspiration as well as LULC and dry/bare land maps.

The modeling procedures will be defined such that overland flow is simulated using the diffusive wave approximation, unsaturated zone flow is governed by Richards' equation, and saturated zone dynamics are represented by the Boussinesq equation implemented through a three-dimensional finite difference method. Actual evapotranspiration can be calculated with the Penman-Monteith or Kristensen and Jensen methods, considering land use and soil moisture. Lastly, surface water–groundwater interactions will be modeled through the integration of MIKE SHE and MIKE 11, enabling dynamic, bidirectional coupling between rivers and aquifers for a more detailed and realistic hydrological representation.

Calibration and Validation Process of the Model

The calibration and validation process is crucial for ensuring the reliability and accuracy of the MIKE SHE model. This iterative process involves adjusting model parameters to match observed data and then testing the model's performance on independent datasets.

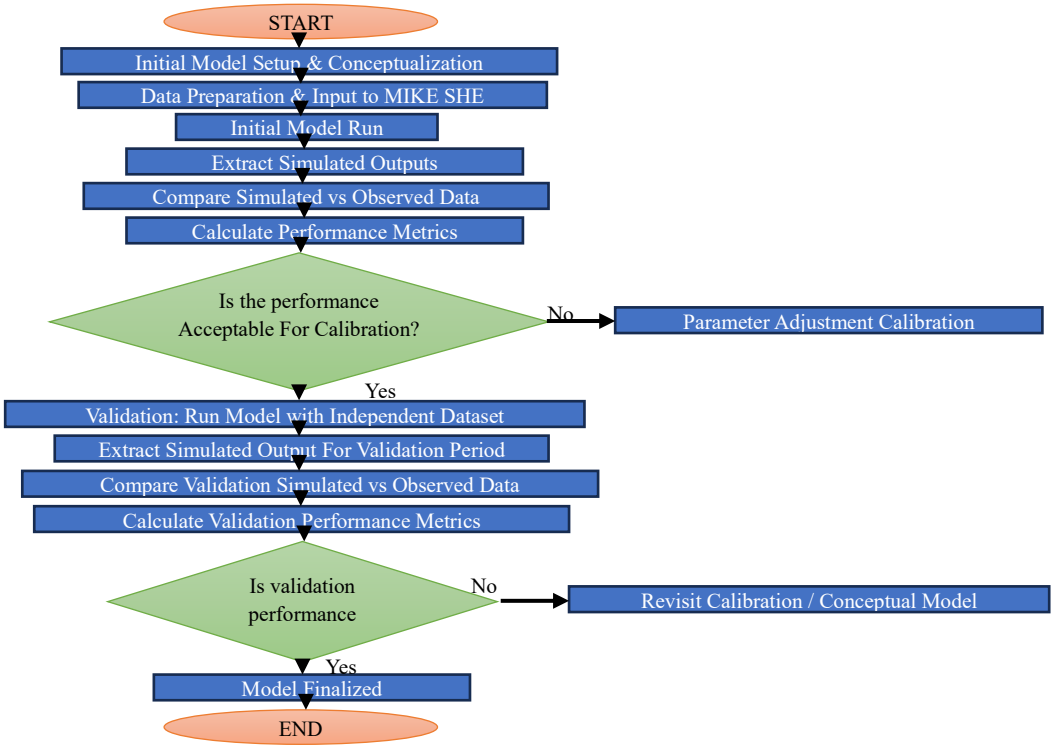


Figure 1: Calibration and Validation Process

As seen in Figure 1, there are steps to calibrating and validating a hydrological model such as MIKE SHE. While calibrating the model, a discrete portion of the model's MIKE SHE output, like river discharge, is compared to simulated outputs. Adjustments are made iteratively to model parameters for performance metrics to reach acceptable benchmarks (NSE, R^2, RMSE, PBIAS). After calibration, during the validation phase, the model is run on a set of observed data that was not used during calibration, and model performance is re-evaluated with the same metrics used in the previous stage. Accepting validation results marks a robust model, which can then be utilized for targeted nutrient runoff assessments. Failing to meet restrictions requires revisiting the calibration or initial conceptual model loop, meaning further refinement is required.

3.4 Formulas Used in Calibration and Validation

1. Nash-Sutcliffe Efficiency (NSE): This measures how well the plot of observed versus simulated data fits the 1:1 line. People use this model to measure performance metrics during validation and calibration. NSE also ranges from -infinity to +1, scoring differently based on situations. A perfect score is indicative when both data sets are in sync.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{o,i} - Q_{s,i})^2}{\sum_{i=1}^{n}(Q_{o,i} - \overline{Q_o})^2}$$

Where:

- $Q_{o,i}$ = i-th observed discharge
- $Q_{s,i}$ = i-th simulated discharge
- $\overline{Q_0}$ = Mean of observed discharge
- n = Number of observations

Coefficient of Determination (R2): This metric measures how much of the change or difference in the dependent variable (observed discharge) can be forecasted by the independent variable (simulated discharge). It falls between 0 and 1, where 1 shows the best relation or a perfect fit.

$$R^2 = \left(\frac{\sum_{i=1}^{n}(Q_{o,i} - \overline{Q_0})(Q_{s,i} - \overline{Q_s}}{\sqrt{\sum_{i=1}^{n}(Q_{o,i} - \overline{Q_0})^2 \sum_{i=1}^{n}(Q_{s,i} - Q_s)^2}} \right)^2$$

- $\overline{Q_s}$ = Mean of observed discharge

Root Mean Squared Error (RMSE): This criterion assesses the average magnitude of the errors. It helps understand the average error size of a measurement variable. A better model will have a lower RMSE value.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Q_{s,i} - Q_{o,i})^2}$$

Percent Bias (PBIAS): This assesses how much, on average, the simulated data overestimates or underestimates the observed data. A PBIAS of zero is perfect, while the closeness of other values to zero signifies reliable model simulation accuracy. While positive values denote overestimation bias, negative values are indicative of underestimation bias.

$$PBIAS = \frac{\sum_{i=1}^{n}(Q_{s,i} - Q_{o,i}) \times 100}{\sum_{i=1}^{n} Q_{o,i}}$$

3.5 Calibration process

The calibration process will begin with the selection of a historical time period for which observational data, particularly river discharge records, are available. Several model inputs—such as aquifer hydraulic conductivity, soil hydraulic properties, Manning's roughness coefficient for river channels, and evapotranspiration coefficients—will be subjected to parameter sensitivity analysis due to their significant influence on model outputs. These parameters will be modified stepwise repeatedly within reasonable physical bounds until the gaps between the actual hydrological responses and the simulated ones are bridged. Calibration can be manual or performed with automation tools MIKE SHE has built in or through external calibration tools. During calibration, the model will be evaluated and assessed by standard statistical metrics like Nash–Sutcliffe Efficiency (NSE), coefficient of determination (R^2), root mean square error (RMSE), and percent bias (PBIAS) to confirm the reliability of the simulation outputs.

3.6 Validation Process

To assess how well a model can predict something, it is important to analyze a historical timeframe that was not used during the training phase to evaluate the model and ensure its predictive capabilities without bias. All parameters established during the calibration stage will be applied during the validation period using the calibrated model. The simulated outputs that result will undergo comparison with real hydrological data, mostly discharge, using performance metrics such as NSE, R^2, RMSE, and PBIAS, which were used during calibration. Achieving satisfactory results at this stage will demonstrate the model's reliability and accuracy in simulating hydrological processes under varying conditions. On the other hand, performance metrics that are absent from relying on predetermined thresholds will require the model to undergo recalibration. Some changes to the conceptual model are made to improve the robustness and accuracy of the metrics set.

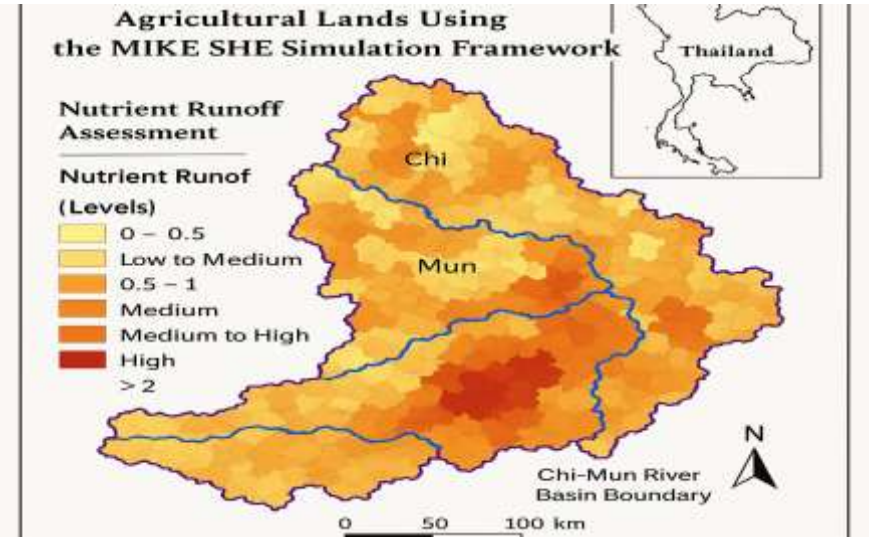


Figure 2: Agricultural Land Using the MIKE SHE Simulation Framework

Using the MIKE SHE hydrological modeling system, Figure 2 shows the levels of nutrient runoff in agricultural fields around Thailand's Chi-Mun River Basin. The area is divided into sections with different levels of nutrient runoff, and each section is marked with colors ranging from light yellow for low intensity to dark red for high intensity. The main rivers of the area, the Chi and Mun Rivers, are marked, and an inset shows the basin's location in Thailand. The illustration shows regions that suffered the most from agricultural nutrient discharge, which is useful for maintaining water quality and sustainable land-use planning.

IV. Results

4.1 Analysis of Nutrient Runoff Patterns in Agricultural Lands

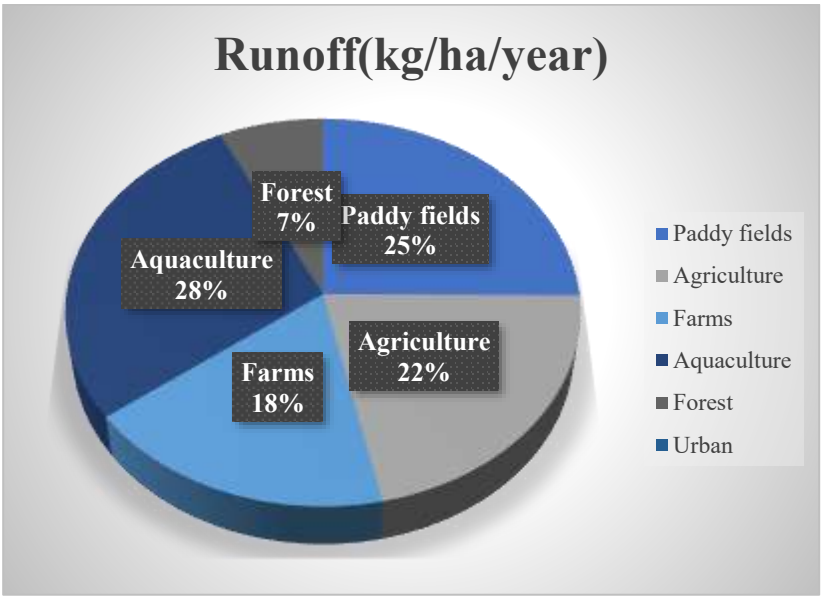


Figure 3: MIKE SHE In the CHI-MIN River

Figure 3 illustrates how the MIKE SHE model simulates the Chi-Mun River Basin and captures the variability in nutrient transport via runoff across different land use types. The most elevated nutrient discharge centers are paddy fields and aquaculture zones with mean runoff values of up to 20.4 kg/ha/year. This is caused by high runoff coupled with heavy fertilization and inadequate water retention on flatter topography.

4.2 Comparison of Different Nutrient Management Scenarios

The simulated future land use scenarios—'Natural', 'GameFarm ', 'Combined ', and 'Expansion' were evaluated in comparison to the Present-Day (PD) baseline. Scenarios that included the change from irrigated land to native vegetation (GameFarm and Combined) showed a drastic improvement in mean flow, up to 600% more than the PD scenario. The greatest observed flows also showed dramatic increases, especially in the Combined scenario, reaching up to 70 times the current maximum flow value.

Table 1: Scenario-Based Hydrological Impact Table

S.No	Scenario	Mean Flow	Max Flow
1	PD	0	1.0
2	Natural	150	2.0
3	Game Farm	450	30.0
4	Combined	600	70.0
5	Expansion	80	1.5

Presented here is Table 1 with scenario-based graphs depicting hydrological impacts. The graphs represent the effects of land use as well as irrigation practices on the average flow and peak flow within the Chi-Mun River Basin, all of which were captured in the MIKE SHE simulations.

V. Discussion

5.1 Implications of the Study Findings for Agricultural Practices

The results highlight the importance of buffer zones, seasonal fertilizer application, and wetland restoration as part of nutrient management strategies. Restoration of native vegetation in regions with high irrigation can greatly lower nutrient pollution, stabilize baseflow, and reduce flood risks during peak rainfall.

5.2 Limitations of the MIKE SHE Simulation Framework

Although MIKE SHE offers an integrated framework for modeling hydrological processes, its application in more modern and realistic simulation scenarios remains limited. For instance, there is a complex challenge concerning vegetation growth that is linked to LAI data (leaf area index) and the modeling of evapotranspiration. Also, scarce or inaccurate LAI information can be problematic because in areas with heterogeneous land cover, sparse remote sensing data can be an issue. The model also uses generalized irrigation practices along with broad assumptions about the operation of the downstream Mokolo Dam. These kinds of assumptions can hurt the accuracy of simulations in regions with poor records of dynamic water management practices. Furthermore, the constraints posed by MIKE SHE's low temporal resolution on the simulation of surface water and groundwater interactions make it infeasible to model long-term hydrological dynamics in multi-country river basins such as those in China and Pakistan. In these scenarios, intricate and cross-border conflicts over water combined with uneven spatial distribution of aquifer properties demand finer temporal and spatial resolutions than those that the model openly offers.

5.3 Recommendations for Future Research

To enhance the practicality and applicability of the MIKE SHE model, various modifications and extensions can be applied. To begin with, remote sensing vegetation indices such as NDVI or EVI can be used to make the updating of Leaf Area Index (LAI) more widespread, thus improving the precision of evapotranspiration simulations. With this method, the model better captures seasonal and interannual shifts in vegetation cover in regions with limited data. Additionally, due to the political complexity of water resource management in transboundary basins, MIKE SHE could be improved with policy-driven modules that incorporate dam operation schedules, water allocation treaties, and international water governance frameworks. Such an enhancement could strengthen the model's capacity to simulate flow regulation and transboundary hydrological impacts. In addition, systematic field-level water quality sampling across different seasons is crucial for validating model outputs concerning the transport of nutrients such as nitrates and phosphates. These observations aid in calibrating the model, but more importantly, they evaluate the model's performance in capturing the temporal variability and loading of sign water quality indicators.

VI. Conclusion

This study used the MIKE SHE/MIKE 11 integrated hydrological modeling system to evaluate nutrient runoff in the Chi-Mun River Basin and how land use affects water quality. It was observed that urbanized areas as well as intensively cultivated agricultural zones are the primary contributors to water pollution, especially during the dry season. Furthermore, high Redundancy Analysis (RDA) values measuring between 0.6 and 0.8 for the basic water quality parameters of Electrical Conductivity (EC), Biochemical Oxygen Demand (BOD), Nitrate-Nitrogen (NO3-N), and Ammonia-Nitrogen (NH3-N) demonstrated these relationships. These results show that human impact strongly influences pollutant levels in surface water resources. However, areas characterized by paddy fields, forests, and open water bodies showed negative RDA values (−0.2 to −0.6), indicating these landscapes are important for naturally removing and filtering pollutants through the processes of filtration, dilution, and nutrient uptake.

Additional simulations of future land use changes showed that removing irrigated crop fields and replacing them with native vegetation led to increased streamflows upstream due to lower water use from

less water-demanding vegetation, due to lesser evapotranspiration. This change in land cover not only transformed the hydrological regime by increasing the amount of water retained, but also improved groundwater recharge capacity.

As seen in the model outputs, the configuration of land use was responsible for more than ninety percent of the annual changes in water quality throughout the basin, highlighting the primary role of land features on water-related processes and the movement of pollutants.

To address the worsening water quality, the study proposes putting into action sustainable land and water management strategies. These are: regulated fertilizer application to curb nutrient outflow, enhanced wastewater treatment facilities in urban centers to reduce the discharge of organic and nitrogenous wastes, and natural vegetative cover preservation or restoration to improve runoff buffering and ecological resilience. The MIKE SHE framework turned out to be a powerful decision support tool for integrated basin-scale management as it allowed pinpointing pollution hotspots and devising targeted, evidence-based water resource sustainability interventions in the Chi-Mun River Basin.

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