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An Integrated Ecological Framework for Evaluating Agricultural Runoff Impacts on Aquatic Ecosystem Sustainability

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Abstract: This research was intended to investigate the effects of agricultural runoff on aquatic ecosystem sustainability based on physicochemical, nutrient, and biological parameters. Samples of water and biological components were collected from reference, runoff entry, and downstream locations. The physicochemical, nutrient, and biological parameters were examined and used to construct an index known as the Aquatic Ecosystem Sustainability Index (AESI). The environmental quality at the runoff entry points had degraded significantly. Total nitrogen content rose from 2.47 to 8.96 mg/L, while total phosphorus content rose from 0.18 to 0.84 mg/L compared to the reference locations. The taxonomic richness dropped from 31.4 to 20.7, and the macroinvertebrate integrity index fell from 76.4 to 51.7. AESI scores were generally lower at the runoff-entry sites (54.9) compared to the reference sites (83.7), with the downstream sites having a slightly higher score (62.5), suggesting some level of improvement. Agricultural runoff led to nutrient enrichment, decline in water quality, biodiversity, and ecosystem sustainability. This study illustrates the significance of adopting an ecosystem approach for evaluating the effects of runoff and the importance of improving agricultural runoff management.

Keywords: Agricultural Runoff; Aquatic Ecosystem; Nutrient Enrichment; Water Quality; Biodiversity; Macroinvertebrates; Ecosystem Sustainability.

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I. Introduction

Agricultural runoff relates the farming process to the ecological status of freshwater systems. The use of fertilizers, pesticides, irrigation, and soil disturbances becomes a source of nutrients, chemicals, and sediments that travel through surface runoff and drainage systems. The ecological impact of these elements is a function of exposure, their transport, and the susceptibility of the impacted ecosystems. The importance of the distinction between contamination, exposure, hazards, and vulnerability is illustrated in pesticide risk mapping (Schriever & Liess, 2007). The integrated watershed assessment approach considers hydrology, water quality, environmental conditions, and aquatic ecology (Ahn & Kim, 2017). The sustainability assessment of agriculture is well aware of the necessity to account for both the environmental effects and the ecosystem services (Soule et al., 2023). These perspectives create a framework for assessing aquatic sustainability using integrated ecological components instead of stand-alone pollutants.

This research seeks to investigate the effects of agricultural runoff on aquatic ecosystem sustainability using an integrated field approach that will assess reference sites, sites where runoff enters the water body, and downstream sites. Parameters assessed include physicochemical factors, nutrient loading, and the biological response in the aquatic ecosystem, all of which are combined into an Aquatic Ecosystem Sustainability Index (AESI).

Previous assessment methodologies offer different perspectives on agricultural impacts, water quality, and ecology. Yet, the application of such assessment methodologies for agricultural runoff necessitates links between pollutant transport, receptor water conditions, and biological effects. An assessment of individual parameters might fail to establish links between nutrient enrichment, habitat degradation, and biological changes. This paper tries to bridge the gap by assessing environmental and biological indicators in reference, runoff entry, and downstream sites using the same sustainability assessment approach (Van Cauwenbergh et al., 2007).

The primary contribution of the work is the use of an integrated ecological approach that links the features of agricultural runoff to the quality of water, nutrients, and the health of aquatic biota. The paper involves both the comparison of individual indicators and AESI to describe the ecological state and keep the meaning of individual indicators at the same time. Comparison of samples will help to identify deterioration caused by agricultural runoff and its variation between sites.

The structure of the paper is as follows: Section 1 describes the background of the research; Section 2 reviews relevant literature; Section 3 describes methodology; Section 4 gives results; Section 5 interprets results and limitations; Section 6 is a conclusion with future research.

II. Literature Review

Agricultural Runoff and Aquatic Ecological Risk

The ecological assessment of agricultural runoff needs knowledge of the way in which agricultural contaminants get into aquatic ecosystems and interact with vulnerable organisms. Pesticide runoff mapping differentiates between the concepts of contamination, exposure, hazard, vulnerability, and ecological risk, showing that just the presence of pollutants does not fully determine the possible impact of these substances on the ecosystem (Schriever & Liess, 2007). Such differentiation proves that the approach should consider agricultural pressure and properties of receiving waters.

Pesticide toxicity research makes another link between exposure to the substance and biological effects of chemicals at the cellular and organism levels. The review considers the effects of pesticides on behavior, physiology, biochemistry, genetics, and the endocrine system with an emphasis on fish (Dorraju et al., 2026). Chronic exposure and interactions between pesticides are also pointed out as important aspects of pesticide toxicity assessment. All these make the approach more comprehensive by including biological effects together with chemical ones. Nonetheless, it is necessary to note that pesticide toxicity is only a part of the assessment process.

Hydrological Connections and Watershed Health

The use of water in agriculture is one area that highlights interactions between agricultural production systems and freshwater systems. Studies of water use involving green and blue water have explored the impact of agriculture on the world water cycle (Rost et al., 2008). Another relevant approach involves water accounting, focusing on water security and flow requirements (Rodrigues et al., 2014). This approach is relevant to the hydrological aspects of sustainability assessments, but does not involve any assessment of the toxicity of agricultural runoff.

Watershed health assessments that integrate natural environment, hydrology, water quality, and aquatic ecology are also relevant to the issue (Ahn & Kim, 2017). The significance of this approach comes from the fact that the watershed condition is analyzed through the relationship between various components of the environment. The hydrologically based agricultural land use intensity index can be used to assess impacts of agriculture on streams and rivers (Agyekum et al., 2025). In addition, research on environmental factors and aquatic invertebrates can also be used to evaluate stream ecosystem condition (Lee et al., 2025).

Integrated Sustainability and Ecosystem Assessment

The principles behind sustainable agriculture assessment frameworks can be useful in structuring indicators of assessment. The hierarchical framework proposed in (Van Cauwenbergh et al., 2007) defines relationships between sustainability principles, criteria, and indicators. The relatively new framework incorporates both environmental impacts and ecosystem services, noting that agriculture has both positive and negative impacts on ecosystems (Soule et al., 2023). Such frameworks enable transparent choice and interpretation of indicators; however, adaptation of these principles for the purposes of assessing agricultural runoff will need explicit links between agricultural practices and ecosystem responses.

An ecosystem-based framework for bivalve aquaculture combines ecological and societal aspects into management decisions (Cranford et al., 2012). While it deals specifically with aquaculture, its structure is an interesting example for structuring ecosystem interactions in this study. A similar example of such a framework for solar parks, which combines land use and water ecosystem services, was proposed in (Alqadi et al., 2025). Such frameworks contribute to the assessment principles, not evidence of agricultural runoff impacts.

Management Priorities and Ecological Resilience

The integrated eco-environmental risk assessment approach helps in defining areas of priority in watershed management (Li et al., 2023). The geographical nature of such an approach is related to the organization of the monitoring and definition of the areas that need to be explored from an ecological point of view. Nature-based solutions research can be used as another aspect of management since it examines the impact of those solutions on the water ecosystem services (Marijuan et al., 2024).

A socio-ecological approach to agricultural water resilience links the environment, agricultural production, and institutions under climate change (Zhang et al., 2026). The relation to the runoff management problem lies in the wider background of management. For the suggested approach, this kind of management can be helpful in defining management options and sustainable goals.

Literature Synthesis and Framework Rationale

The collective findings of these papers can form complementary frameworks to evaluate the aspects of agricultural pressures, hydrologic pathways, ecological conditions, ecosystem services, and management considerations. This paper's review suggests a framework that connects all of the mentioned factors using the pressure-pathway-condition-response-management construct. This connection represents a conceptual development that will need empirical verification in the future. It can be used to justify an aggregation of chemical, habitat, and biological indicators while keeping their individuality in mind.

III. Methodology

Study Design and Integrated Ecological Framework

An integrated ecological assessment based on the field approach was created to investigate the impact of agricultural runoff on the sustainability of aquatic ecosystems. The assessment was carried out through the combination of parameters such as runoff properties, water and sediment quality, nutrient enrichment, ecological response of the aquatic ecosystem, and indicators of ecosystem sustainability. Agricultural drainage into receiving water bodies was the main route of exposure, whereas upstream or little-impacted sites served as the reference points.

Selection of Agricultural Runoff and Receiving Water Sites

Sampling locations were chosen from agricultural drainage systems that reflect varying degrees of runoff effect. The reference locations were set up prior to agricultural runoff, followed by sampling sites set up near the runoff entry point and the downstream receiving water. The sampling sites reflect the differences in cultivated land, fertilizer use, irrigation, drainage, and the distance from water body habitats. Geographical coordinates, land use, types of crops, and drainage and anthropogenic activities were noted for each sampling site.

Agricultural Runoff Characterization

The following parameters were analyzed in runoff: pH value, electrical conductivity, total suspended solids, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, nitrate, nitrite, ammonium, total nitrogen, soluble reactive phosphorus, and total phosphorus. The runoff discharge rate and flow rate during the sampling time were also measured.

Assessment of Aquatic Water Quality

Samples were taken from the reference, inflow, and outflow stations during the study period. The in-situ analysis was done for water temperature, pH, dissolved oxygen, electrical conductivity, turbidity, and oxidation-reduction potential. Laboratory analysis was carried out on nutrients, organic material, suspended particles, and some agricultural contaminants. Comparison was made among the sampling stations in order to establish the range of influence of the runoff on water quality.

Sediment Quality Assessment

Surface sediments were sampled from representative sampling sites within the aquatic receptor ecosystem to investigate any contamination that cannot be established by means of water quality analysis alone. The sediment samples were tested for organic content, total nitrogen, total phosphorus, pesticides, and other chemical properties. Sediment properties were compared against water quality data to see if there had been any long-term changes in the benthic environment caused by agricultural runoff.

Nutrient Enrichment and Eutrophication Assessment

Nutrient enrichment was determined using the amounts of nitrogen and phosphorus components in the runoff and in the receiving waters. Nutrient load was calculated by combining the measured concentrations of the components with the rate of runoff discharge. An integrated eutrophication evaluation was carried out using nutrient concentration, chlorophyll-a, water transparency, dissolved oxygen, and algal population.

Aquatic Biological Response Assessment

The biological responses were evaluated via the use of phytoplankton, periphyton, macroinvertebrates, and in some cases, the aquatic macrophyte communities. The parameters that were determined included the species richness, abundance, Shannon diversity, evenness, and community composition for each sampling site. Sensitive and tolerant taxa were identified in order to establish whether the runoff has any effect on ecological community change.

Microbial and Ecological Health Indicators

Microbial indicators were used to determine any changes in biological water quality related to the impact of agriculture on the environment. Appropriate microbial indicators were counted using standard methods based on culture or molecular biology. The microbial content was considered along with nutrient levels, organic water quality indicators, and dissolved oxygen in the water.

Ecological Risk Assessment

An estimate of the potential ecological risk of agricultural runoff was made based on the integration of contaminant levels, toxicity, exposure conditions, and ecological effects. Risk quotients were determined as the ratio of environmental contaminant concentrations to the predicted-no-effect concentration or guideline concentration for these contaminants. Nutrient, pesticide, and organic pollution risk were assessed individually before being considered within an ecological risk profile.

Aquatic Ecosystem Sustainability Index

An ecosystem sustainability index was created by using standard ecological indicator values for water quality, nutrient, contamination, biodiversity, habitat quality, and biological integrity. Normalization was done such that larger values indicated better ecological conditions. A weighted sum approach was employed to create the Aquatic Ecosystem Sustainability Index (AESI).

Statistical Analysis

All quantitative variables were checked for their distributional patterns prior to any statistical analyses. Differences between reference, runoff-entry, and downstream sites were tested with analysis of variance or suitable non-parametric tests. Post-hoc tests were done whenever there were statistically significant

differences among the sites. Correlation and regression analyses were used to examine the relationships between the properties of the runoff and its water quality, concentration of contaminants, enrichment by nutrients, and biological properties.

Environmental gradients and relationships between sampling sites were identified through the use of multivariate ordinations, such as principal component analysis and principal coordinates analysis. Differences among communities in biological aspects were tested using suitable multivariate procedures. Contribution of runoff variables to ecological status was assessed with multivariate regressions or constrained ordinations. Significance level was set at $p < 0.05$.

Integrated Ecological Pathway Analysis

The connections between agricultural activities, runoff production, pollutant transport, changes in the aquatic environment, biological responses, and ecosystem sustainability were combined into an ecological pathway concept. The agricultural activities were considered upstream factors, runoff was a transport mechanism, nutrient and chemical contamination were the intermediate stressors, and the biological and water-quality responses were an ecological impact. The final conceptual framework connected these elements to ecosystem sustainability to highlight the main pathways of agricultural runoff impacts on aquatic ecosystem sustainability.

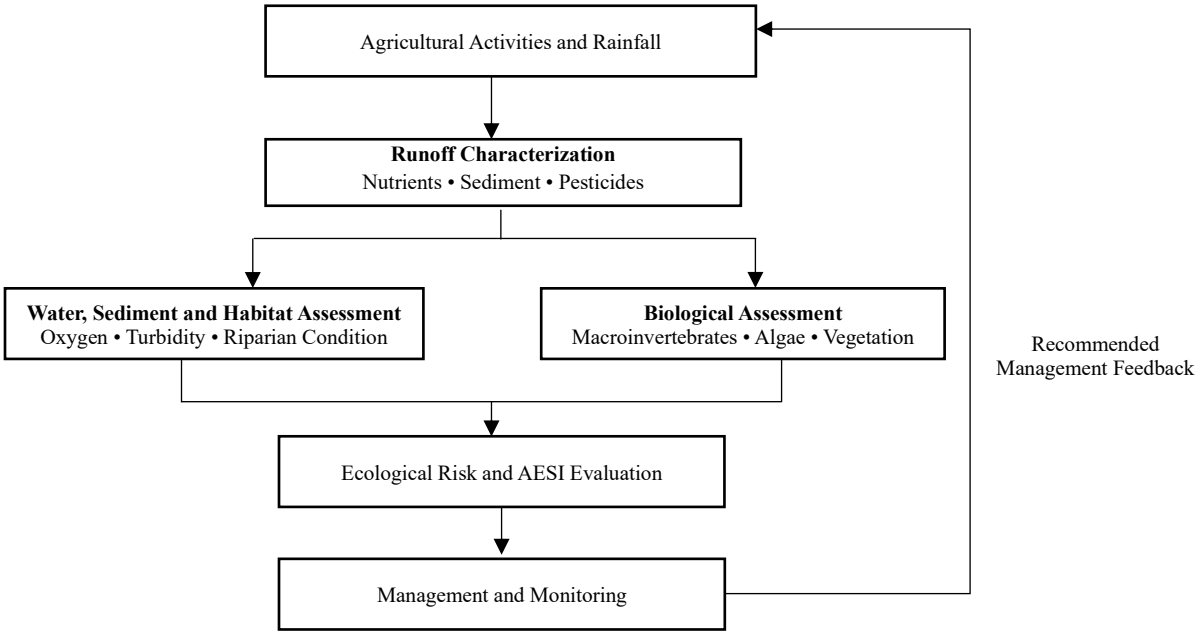


Figure 1: Integrated Ecological Framework for Assessing Agricultural Runoff Impacts on Aquatic Ecosystems

Figure 1 represents the comprehensive framework developed for analyzing agricultural runoff impacts on aquatic ecosystems. Agricultural runoff analysis becomes an input for water quality, habitat, and biological analyses, which are used in sustainability analysis. The results lead to management and monitoring processes, and the feedback mechanism improves agriculture and ecosystem analysis.

IV. Results

Agricultural Runoff and Water-Quality Characteristics

Agricultural runoff caused some alterations to the physicochemical properties of the receiving water body. Entry points for agricultural runoff had higher electrical conductivity, turbidity, nutrient content, and

organic pollution than reference points. Further downstream, there was a partial decrease in the above factors, but their values were still higher than at the reference points.

Table 1: Physicochemical Characteristics of Water at Different Sampling Locations

Parameter	Reference Sites	Runoff-Entry Sites	Downstream Sites
pH	7.21 ± 0.18	7.48 ± 0.21	7.39 ± 0.20
Electrical conductivity (µS/cm)	386 ± 54	624 ± 81	571 ± 76
Turbidity (NTU)	4.8 ± 1.6	18.7 ± 5.2	14.9 ± 4.6
TSS (mg/L)	21.6 ± 6.4	78.4 ± 18.3	64.7 ± 16.2
BOD (mg/L)	2.1 ± 0.7	5.8 ± 1.4	4.9 ± 1.2
COD (mg/L)	18.4 ± 4.9	46.7 ± 10.6	39.8 ± 9.4

Values are presented as mean ± SD. TSS = total suspended solids; BOD = biochemical oxygen demand; COD = chemical oxygen demand.

Table 1 indicates that pollutant indicators at runoff entry points were higher compared to the reference points. Conductivity values went up from 386 ± 54 to 624 ± 81 µS/cm, turbidity values went up from 4.8 ± 1.6 to 18.7 ± 5.2 NTU, total suspended solids (TSS) went up from 21.6 ± 6.4 to 78.4 ± 18.3 mg/L, biochemical oxygen demand (BOD) went up from 2.1 ± 0.7 to 5.8 ± 1.4 mg/L, and chemical oxygen demand (COD) went up from 18.4 ± 4.9 to 46.7 ± 10.6 mg/L.

Nutrient Enrichment and Eutrophication Response

Nutrient enrichment was much more pronounced in areas that were affected by agricultural runoff. There were higher total nitrogen and phosphorus at points where there was agricultural runoff, and they remained high downstream. There was also increased chlorophyll-a and algal biomass with decreased dissolved oxygen, thus suggesting the relationship between agricultural nutrients and eutrophication.

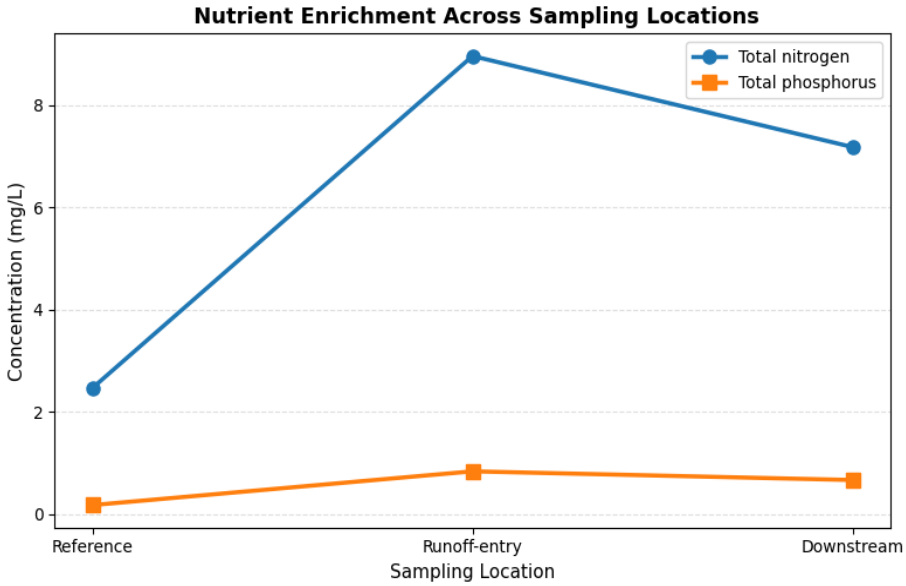


Figure 2: Nutrient Enrichment and Eutrophication Response Across Sampling Locations

Figure 2 illustrates high levels of nutrients due to agricultural runoff. The amount of total nitrogen rose from 2.47 mg/L at reference points to 8.96 mg/L at runoff entries. On the other hand, the total phosphorus rose from 0.18 mg/L to 0.84 mg/L. However, the downstream levels decreased to 7.18 mg/L and 0.67 mg/L for total nitrogen and phosphorus, respectively.

Aquatic Biological Community Response

Community structure showed clear differences from one location to another based on the biological evaluation. The reference site had more richness and diversity, while the runoff site had fewer sensitive species and higher numbers of tolerant species. Intermediate characteristics were observed in downstream sites.

Table 2: Biological Community Characteristics at Sampling Locations

Biological indicator	Reference Sites	Runoff-Entry Sites	Downstream Sites
Taxa richness	31.4 ± 4.8	20.7 ± 4.1	23.6 ± 4.3
Shannon diversity	2.91 ± 0.32	2.08 ± 0.29	2.34 ± 0.31
Sensitive taxa (%)	42.6 ± 6.1	21.8 ± 5.4	27.5 ± 5.8
Tolerant taxa (%)	18.3 ± 4.7	39.6 ± 6.2	33.8 ± 5.9
Macroinvertebrate integrity index	76.4 ± 8.2	51.7 ± 7.6	59.8 ± 7.9

Values are presented as mean ± SD.

Table 2 shows reduced biological integrity at the affected sites. Richness of the taxon showed a decrease from 31.4 ± 4.8 at the reference sites to 20.7 ± 4.1 at runoff entry points. Shannon diversity index also exhibited a decrease from 2.91 ± 0.32 to 2.08 ± 0.29. The sensitive species dropped from 42.6 ± 6.1% to 21.8 ± 5.4%, but the tolerant species rose from 18.3 ± 4.7% to 39.6 ± 6.2%. The index for macroinvertebrate integrity decreased from 76.4 ± 8.2 to 51.7 ± 7.6.

Integrated Aquatic Ecosystem Sustainability

The integrated sustainability assessment results exhibited considerable variation between sampling sites. The reference sites indicated the highest sustainability values, while runoff sites showed lower values of ecological sustainability. The downstream sites showed medium sustainability values, indicating that there had been improvement after the runoff pollutants were diluted and processed.

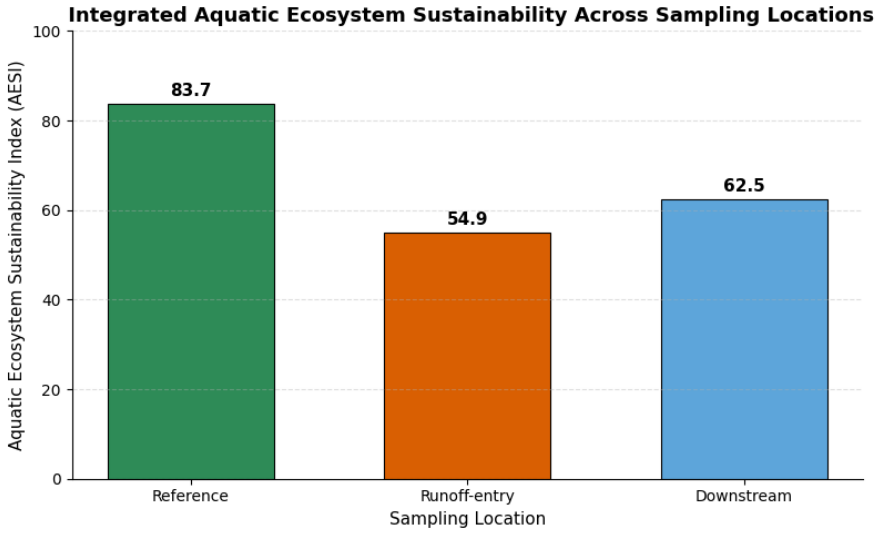


Figure 3: Integrated Aquatic Ecosystem Sustainability Across Sampling Locations

As seen in figure 3, there is a clear difference between the AESI values for the different sampling locations. AESI value at reference sites was 83.7, which decreased to 54.9 at runoff-in point sites and increased to 62.5 at downstream sites. The decrease in index value of 28.8 between reference sites and runoff-in point sites represents a much lower ecological state at sampling locations affected by agricultural runoff.

V. Discussion

The study has shown that there was an evident correlation between agricultural runoff and significant degradation of aquatic ecosystem quality. There was evident enrichment in nutrients, which was indicated through a sudden increase in total nitrogen and total phosphorus at places where agricultural runoff entered, accompanied by a decrease in taxonomic diversity, macroinvertebrates, and overall AESI index. This indicates that the nutrient enrichment and organic pollution in agricultural runoff caused eutrophication and deoxygenation of water. This work is significant in that it has been able to illustrate the impact of runoff on different ecosystem components at the same time, making the ecological assessment an essential tool in managing water resources sustainably. Nevertheless, the findings only illustrate what happens during the sampling period; hence, there may be seasonal fluctuations that are not well represented in the study. Future research should therefore consider more monitoring periods, wider geographic scope, contaminant assessment, sedimentation, and practices aimed at reducing runoff.

VI. Conclusion

Agricultural runoff is among the notable stressors affecting aquatic ecosystems; however, the impacts are often assessed by measuring individual water quality indicators. This research addressed this by analyzing the impacts of agricultural runoff on the physicochemical parameters, nutrient load, aquatic biological community, and the sustainability of the whole ecosystem. The results revealed a significant difference in the ecology between the reference site and the runoff-entry site. The total nitrogen content rose from 2.47 to 8.96 mg/L, and the total phosphorus from 0.18 to 0.84 mg/L. The taxonomic richness was reduced from 31.4 to 20.7, while the macroinvertebrate integrity index was reduced from 76.4 to 51.7. Most significantly, the Aquatic Ecosystem Sustainability Index was reduced from 83.7 to 54.9. Partial recovery was recorded at the downstream sites, although the AESI at these sites still fell below those observed under reference conditions. This study indicates that agricultural runoff has the potential to affect water quality, nutrient dynamics, and biological condition at the same time. The main lesson from this study is that it is important to assess and manage the impact of agricultural runoff not through one single indicator, but through three parameters: physical-chemical, chemical, and biological.

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