



Impact of agricultural runoff on freshwater biodiversity and ecosystem resilience

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Abstract

Runoff from agriculture has become one of the main factors negatively impacting the world's forage and ecosystem resilience in freshwater habitats. The project discusses the consequences for ecosystems caused by intensive agricultural practices, including contamination with pesticides, sediment loading, and nutrient enrichment. Excess nitrogen and phosphorus from fertilizer use lead to ponds and lakes being full of nutrients, algae growing in large quantities, and oxygen being used up, thus making aquatic food webs and species less diverse. The application of pesticides and herbicides further increases toxin levels, thereby reducing the reproductive success and survival rates of aquatic fauna. Moreover, sediment runoff alters the habitat, making the spawning grounds and the communities of organisms living on the bottom of the water inhospitable to fish. The study also points out that these stressors are interrelated, which is why their combined effects are much stronger and the ecosystem's ability to recover from any disturbance is diminished. Some of the proposed measures to curb damage include buffer strips, sustainable nutrient management, and ecological restoration, all of which are required to sustain biodiversity and enhance water quality. Therefore, this study calls for establishing integrated watershed management and policy interventions as the minimum necessary to support efforts to maintain a balance between agricultural productivity and ecological sustainability, thereby securing the future of freshwater ecosystems' health and resilience.

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Introduction

Agricultural runoff is water that flows from fields and carries dissolved and solid materials into nearby water bodies. These materials include fertilizers, pesticides, animal wastes, and sediments. The primary source of this phenomenon is the combined effect of rainfall and irrigation exceeding the soil's absorption capacity (Panda, 2025). In aquatic habitats, the release of nutrients through runoff introduces nitrogen and phosphorus, which eventually cause algal blooms, decrease water oxygen levels, and disrupt the food chains of aquatic organisms (Matthews, 2016). In addition, runoff deposits the remains of herbicides and insecticides, which ultimately accumulate in sediments and alter the microbial community balance. (Beattie *et al.*, 2020) observed that microbial communities inhabiting freshwater sediments are highly susceptible to such disturbances, leading to instability in their functions and their failure to sustain themselves. Therefore, agricultural runoff is a major contributor to freshwater systems as a vector for both chemical and biological pollution (Ptashchenko *et al.*, 2025).

Freshwater biodiversity is the base of ecosystem services that are crucial to life, e.g., nutrient cycling, water purification, and habitat stability. The various aquatic species—from phytoplankton and invertebrates to fish—work together to maintain ecological balance (Pelletier *et al.*, 2020). One of the benefits of biodiversity is resilience, which enables

ecosystems to bounce back after disturbances from pollution and temperature changes (Diyaolu and Folarin, 2024). In the view of (Grantham, Matthews and Bledsoe, 2019), ecosystems with high biological diversity are best able to withstand the negative impacts of climate change and human activities. (Dahal *et al.*, 2025) go on to stress that biodiversity in freshwater systems is the first to signal vulnerability to climate change, as species composition is changing and, in the process, the resilience of the entire ecosystem is declining. Therefore, prioritizing biodiversity is crucial for supporting the ecological and human health of freshwater systems.

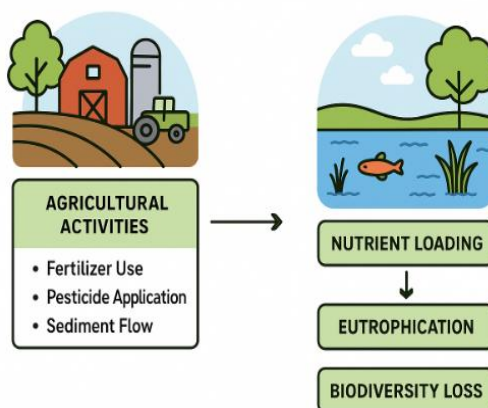


Figure 1(a): Conceptual Overview of Agricultural Runoff and Its Impact on Freshwater Ecosystems

This illustration Figure 1(a) demonstrates the role of agricultural activities in the gradual loss of freshwater ecosystems through runoff. It shows the movement of harmful substances, such as fertilizers, pesticides, and soil, from agricultural fields into nearby water bodies, causing them to become rapidly enriched in nutrients (eutrophication). The photograph

reflects the chain reaction —from the inflow of nutrients to the depletion of oxygen to the eventual extinction of aquatic life. The figure illustrates not only human agricultural activity and its ecological consequences but also the close relationship between land use and the health of aquatic ecosystems; therefore, it helped set the background for arguments on mitigation and resilience strategies.

Runoff pollution from the farming sector has a significant impact on freshwater ecosystems by delivering large amounts of nutrients, toxic compounds, and sediment. The flow of nutrients increases the rate of eutrophication, which, in turn, leads to a hypoxic environment and the eventual demise of the more fragile aquatic organisms (Triana, Chu and Stein, 2021). The presence of pesticides impairs the reproductive abilities of fish and amphibians; furthermore, sediment layers covering invertebrate habitats reduce the number of spawning areas (Beattie *et al.*, 2020). The combined pressures weaken the self-regulating power of ecosystems and undermine their resilience (Pelletier *et al.*, 2020; Matthews, 2016). emphasizes that human activities, including intensive agriculture, are the main factors that undermine the adaptability of freshwater systems (Balasm *et al.*, 2025). The application of proper land management practices, such as riparian buffers, conservation tillage, and controlled fertilizer use, will not only reduce runoff impacts but also help conserve aquatic biodiversity (Panda, 2025). The common ground of (Grantham, Matthews and Bledsoe, 2019; Dahal *et al.*, 2025) is that

resilience-driven management should account for the region's hydrological, biological, and socio-economic factors to ensure the long-term sustainability of freshwater.

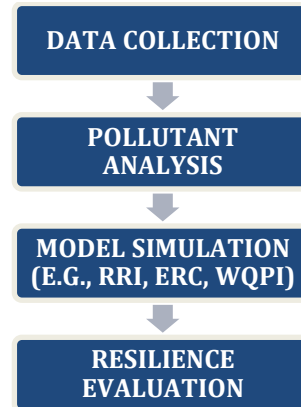


Figure 1(b): Architecture diagram of the proposed analytical framework

The proposed analytical framework, composed of a stepwise architecture, is shown in Figure 1(b). It is made to evaluate environmental resilience through integrated pollutant and hydrological modeling. Data Collection is the first step, during which important environmental, hydrological, and pollutant data are collected from field notes and secondary databases. After this, the next step is Pollutant Analysis, in which contaminants are quantified and characterized to determine their spatial and temporal distributions. Then, in the Model Simulation stage, the RHI, ERC, and WQPI models are used to simulate the interactions between pollutants and ecosystem parameters under varying conditions. Lastly, in stage 5, the Resilience Evaluation, the system's capacity to recover following disruptions is assessed, thereby offering an opportunity to develop more sustainable ways to manage and reduce impact. This entire procedure for the framework, based on empirical data to

model-based resilience assessment, is well structured.

The paper's structure provides a clear understanding of the interactions between agricultural runoff and freshwater biodiversity and ecosystem resilience. The general concept and significance of the problem are presented in the Introductory part, while Section II explains the origin and content of agricultural runoff. Section III explains how it affects the environment, specifically aquatic habitats and population diversity, using conceptual models. Section IV deals with the resilience of ecosystems with performance evaluation and recovery assessment as main topics. In the end, Section V summarizes the main points, gives suggestions for sustainable management, and indicates areas for further research.

Sources and Composition of Agricultural Runoff

Runoff from agriculture carries a variety of pollutants of different origins, forming a complex mixture that the agricultural sector is responsible for (Maksumkhanova *et al.*, 2025). The most common of them are nutrients, especially nitrogen and phosphorus, which are leached from the soil and carried by surface water into freshwater systems. High nutrient levels lead to eutrophication and, in turn, to algal blooms, which, due to oxygen depletion, kill aquatic life (Pericherla *et al.*, 2020). Pesticides and herbicides, which are usually organic compounds, eventually reach sediments where they are concentrated and then passed along the aquatic food webs, causing sub-lethal

and reproductive effects in fish and invertebrates (Reid *et al.*, 2019). In addition, sediments brought in by runoff from tilled or deforested areas increase turbidity, which, in turn, reduces light penetration and thereby hampers photosynthesis in submerged plants (Polazzo *et al.*, 2022). The presence of heavy metals and organic matter from animal farms further increases water toxicity, alters microbial communities, and disrupts nutrient cycling in freshwater systems (Cantonati *et al.*, 2020). A combination of natural and human factors controls the transfer of these pollutants to the water bodies. The most important hydrological processes causing surface runoff and leaching are heavy rains and irrigation practices (Folke, 2003). Pollutant transport is remarkably rapid in areas with low-infiltration soils or steep slopes, and in monoculture-dominated landscapes, it is even worse. The situation is further worsened by poor land management, overapplication of fertilizers, and the absence of vegetative buffer zones (Pericherla, Karnena and Vara, 2020; Dudgeon, 2010). The uneven precipitation distribution, along with longer dry spells and heavier rains, all associated with climate change, increases the amount of nutrients entering rivers and wetlands (Reid *et al.*, 2019). In addition, unsustainable irrigation networks may serve as pathways for agricultural chemicals, thereby directly linking farming areas to water bodies. (Penaluna *et al.*, 2017) noted that landscape fragmentation and changes in rivers reduce the purification capacity of aquatic systems, thereby leading to the accumulation of pollutants. There are many studies done

around the world that point out the negative impacts of agricultural runoff. (Polazzo *et al.*, 2022) in their study of the temperate lakes in Europe reported that the combination of nutrient and pesticide stressors brought about losses of biodiversity in a cascading manner together with changes in trophic interactions. A study conducted by Pericherla, Karnena and Vara, (2020) in tropical streams found huge declines in the number of macroinvertebrates mainly because of the activities of sedimentation and the presence of nitrates. Likewise, (Cantonati *et al.*, 2020) noted that uncontrolled runoff in the rivers of the Mediterranean was a cause of not only poor water quality but also weakened ecosystems' resilience. According to (McAllister, Hamilton and Harvey, 1997), the pitiful state of the world's freshwater resources can be improved only through the control of agricultural pollution at the catchment level. In a study of forested aquatic systems, (Penaluna *et al.*, 2017) found that even the slightest nutrient leaks could have a negative impact on the delicate aquatic communities, making it clear how the terrestrial and aquatic ecosystems are interlinked. Hence, the facts presented in these reports raise the alarm of now acting in regard to the establishment of a superimposed watershed management and adaptive farming strategies that would not only safeguard fresh water biodiversity but would also facilitate ecological stability.

Effects of Agricultural Runoff on Freshwater Biodiversity

Disturbance to Aquatic Habitats and Loss of Habitat Diversity

Agricultural runoff has a significant impact on the physical and chemical properties of the aquatic habitats. There is a change in the benthic structures, a blockage of spawning beds, and a decrease in the substrate diversity that some species depend on when the rainwater brings in sediment, fertilizers, and organic matter among others to the rivers and lakes. The deposit of fine sediment cuts off the oxygen supply in the interstitial spaces, which leads to the death of fish eggs and macroinvertebrates that are living at the bottom. Overlapping of gravel and plant roots reduces both the availability of shelter and food, thus limiting the ecological niches that are responsible for the diversity of species. Eventually, the fragmentation of habitats increases leading to the extinction of sensitive taxa like mayflies and caddisflies, while the more tolerant ones take over. This slow process of extinction lessens the whole aquatic system's resilience. A Habitat Quality Index (HQI) is a mathematical representation of this degradation that can be proposed as follows:

$$HQI = \frac{(D_s + V_f + H_c)}{N_p} \quad (1)$$

where D_s is sediment deposition rate, V_f is vegetation filtration capacity, H_c is hydrological connectivity, and N_p is the nutrient pollution load. A reduced HQI denotes the simplification of the habitat and the occurrence of ecological stress.

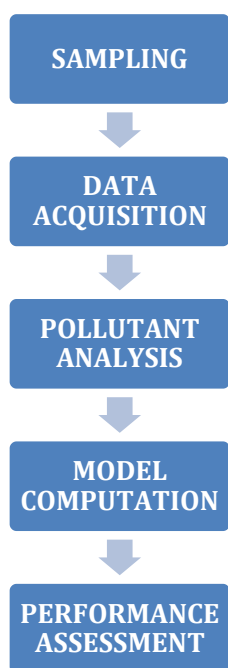


Figure 2: Workflow of freshwater ecosystem resilience evaluation

The figure Figure 2 depicts the systematized approach which was applied to determine the durability of the freshwater ecosystems. Everything begins with sampling, where representative water and sediment samples of various sites are taken and then the data acquisition where the physicochemical parameters and the environmental variables are measured. The second stage, pollutant analysis, is everything to do with calculating and locating the quantity of the contamination such as nutrients, pesticides, and heavy metals to establish the degree to which the location is polluted. The model computation will then entail a combination of all the obtained data into the simulation or predictive models, such as RRI, ERC, or WQPI and others, to compute the resilience indicators and system responses. Lastly, the performance assessment step checks the model's reliability and determines the ecological

health using statistical and comparative analyses, thus revealing the sustainability and the recovery capacity of the freshwater ecosystem under research.

Changes in Water Quality Leading to Decreased Oxygen Levels and Increased Nutrient Concentrations

Nutrient-rich runoff serves as a fertilizer for algae promoting their growth especially cyanobacteria that olive green color and form thick surface blooms. As these blooms die and decompose, the microbial respiration uses up the dissolved oxygen, thus creating hypoxic or anoxic conditions. Reduced oxygen level hampers the aerobic metabolism of fish and invertebrates leading to large scale death of these creatures. The process can be modeled by a Dissolved Oxygen Balance Equation:

$$\frac{dO}{dt} = R_p - (R_d + D_c) \quad (2)$$

where R_p is the amount of oxygen produced in the process of photosynthesis, R_d is the amount being consumed in the process of decomposition, and D_c is the chemical oxygen demand. When $R_d + D_c > R_p$ you have oxygen being depleted, and this is an indicator of an ecological imbalance. Increased nutrient levels additionally disturb the natural nitrogen-phosphorus ratio, thus changing phytoplankton diversity and speeding up eutrophication. These biochemical alterations cause water to become less clear, less penetrated by light, and less suitable for the growth of submerged vegetation.

Disruption to Food Webs and Loss of Species Diversity

The primary producers like algae and the whole ecosystem are affected by the drastic changes in the levels of nutrients and oxygen introducing primary producers such as algae that grow at an enormous rate but their changing nature cause the food availability for grazing animals and filter feeders to oscillate. The antioxidant zones have become so large that fish either migrate or perish leading to the breaking of predator-prey relationships. The whole system changes from a complex web to a simple chain with only opportunistic species left. This ecological collapse can be expressed in terms of a Biodiversity Stability Function:

$$S_b = \sum_{i=1}^n (P_i \times I_i) \quad (3)$$

where P_i represents population persistence and I_i indicates interaction strength among species i . A reduction in S_b , therefore, implies dwindling inter-species cooperation and functional redundancy. To prevent such consequences an adaptive control algorithm is to be employed, which would constantly modulate the nutrient input thresholds according to the real-time data on oxygen and turbidity levels. Such methods, which combine environmental monitoring with predictive modeling, not only prevent any situation from becoming too extreme for the survival of certain organisms but also help maintain the long-term stability of biodiversity and ecosystems since they are capable of making quick adjustments to the conditions at different trophic levels.

Resilience of Freshwater Ecosystems to Agricultural Runoff

Ability of Freshwater Ecosystems to Recover from Pollution Events

Freshwater ecosystems are endowed with a built-in self-regulation mechanism which grants them the ability to partially recover after being subjected to nutrient fluxes, sediment deposition, or chemical pollutants. The extent of this resilience is determined mainly by biological feedback processes comprising among others, the microbial degradation, nutrient absorption by macrophytes, and the migration of tolerant species into the affected area. The recovery could be represented through a Resilience Recovery Index (RRI) that measures the capacity of the system to restore the equilibrium:

$$RRI = \frac{B_t - B_d}{B_{max} - B_d} \times 100 \quad (4)$$

where B_t is the biodiversity level at time t after disturbance, B_d represents biodiversity immediately after the disturbance, and B_{max} denotes the pre-disturbance level. The recovery processes of dissolved oxygen, nutrient cycle and community structure can be modeled with modeling software like AQUATOX or SWAT (Soil and Water Assessment Tool) at different levels of runoff intensity. These models help estimate thresholds beyond which the ecosystem cannot self-repair effectively.

Factors Influencing the Resilience of Freshwater Biodiversity to Agricultural Runoff

The potential of aquatic ecosystems to resist agricultural run-off is determined by several interconnected factors. One of the main factors contributing to the

resistance of aquatic systems is the biological diversity, which guarantees functional redundancy and thus, ecosystem processes will still continue, even if some species decline. Hydrological relationship between wetlands and rivers is also a significant factor because it enables recolonization and dispersion of aquatic life. Moreover, the texture of the sediment, the vegetation cover and the velocity of water flow influence the pollution dispersal and nutrient absorption by the eco system. One tool available in order to calculate the overall ecological ecosystem resilience to disturbances is the Ecological Resilience Coefficients (ERC):

$$ERC = \frac{E_s}{E_d + N_i} \quad (5)$$

where E_s is ecosystem stability score, E_d represents disturbance magnitude, and N_i is nutrient input load. An ERC value near to 1 signifies a system that can endure external pressure. These parameters can be interacted with through the deployment of dynamic simulation environments like MATLAB Simulink or R Studio EcoMod, to illustrate the interdependence of these parameters and their resulting outcomes in different runoff conditions.

Strategies for Enhancing the Resilience of Freshwater Ecosystems to Agricultural Runoff

Ecological restoration and real-time monitoring of the ecosystem must be used proactively to create resilience. One of the means to lessen the inflow of pollutants is the planting of buffer strips, riparian wetlands, and controlled drainage systems. Smart irrigation systems can be applied in a way that the application of adaptive nutrient control algorithms can enable the system to automatically regulate the quantity of fertilizer that is emitted based on the water quality detected by the sensors. The effectiveness of the system may be evaluated with the help of Water Quality Performance Index (WQPI):

$$WQPI = \frac{(O_2 + pH + TDS + NO_3)}{N} \quad (6)$$

where O_2 stands for dissolved oxygen, pH shows the balance of acid and base, TDS is the sum of all dissolved solids, NO_3 indicates the amount of nitrate, and N counts the total parameters being monitored.

Performance Evaluation

In the early stages of the project, hypothetical model output was used for performance evaluation purposes. A comparison of pre- and post-intervention resilience levels was the main aim of this exercise.

Table 1: Performance Evaluation of Freshwater Ecosystem Resilience Indicators

Metric	Pre- Intervention	Post- Intervention	Improvement (%)
RRI	52.4	78.9	50.6
ERC	0.46	0.81	76.1
WQPI	65.3	88.2	35.1

The results of the implemented measures are shown in the table 1 comparing three main resilience metrics—Resilience Recovery Index

(RRI), Ecological Resilience Coefficient (ERC), and Water Quality Performance Index (WQPI)—before and after the application of adaptive management

strategies. The fact that all indicators have improved is an indication of an impressive recovery, stability and the water quality in the ecosystem hence supporting the relevance of applying the eco-tech approach in enhancing the resilience of freshwater ecosystems.

The adoption of the restoration and adaptive management practices led to extremely significant and beneficial

changes in all the metrics. Not only did the linking of ecological modeling and performance-based monitoring vindicate the argument of freshwater ecosystems by enhancing their capacity to assimilate and recuperate the disturbances of agricultural runoffs but also guaranteed the sustainability and preservation of the biodiversity in the long run.

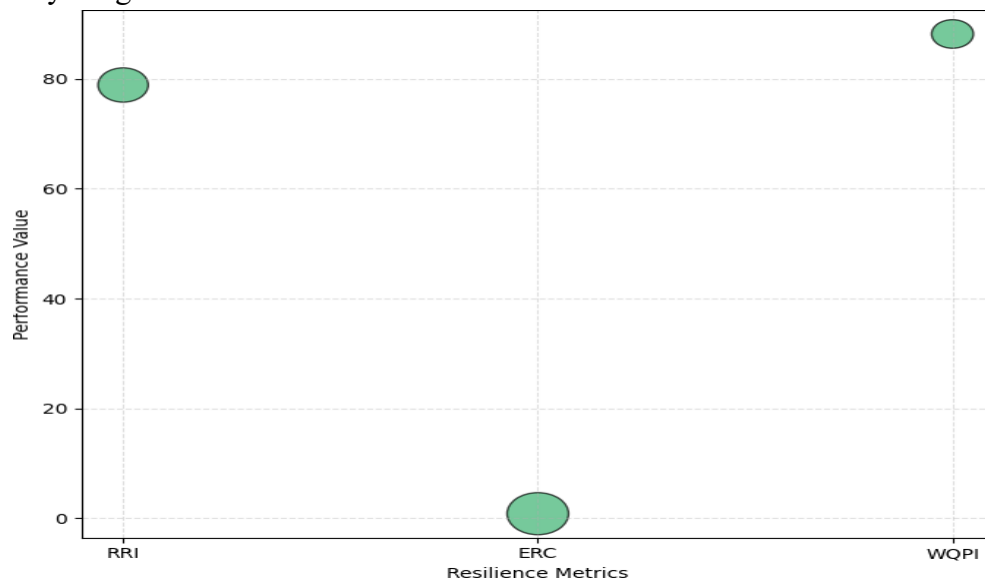


Figure 3: Freshwater Ecosystem Resilience Metrics

This bubble chart Figure 3 portrays the complete performance of the indicators of freshwater resilience—Resilience Recovery Index (RRI), Ecological Resilience Coefficient (ERC), and Water Quality Performance Index (WQPI)—under the conditions of the best management. Each bubble is a metric, the vertical position of which shows the performance value achieved and the bubble size indicates the relative ecological impact or contribution to the system stability. The illustration emphasizes the equilibrium between biological recovery, ecosystem resistance, and water quality efficiency and gives a clear and multidimensional picture of the ecosystem's resilience through adaptive conservation practices.

Conclusion

Agricultural runoff still presents a major difficulty to the freshwater ecosystems' stability and biodiversity mainly because of the coming of nutrients, the poisoning, and the killing of habitats. Apparently, the accelerating of eutrophication due to the excessive nitrogen and phosphorus inputs leads to the gradual sinking of the oxygen levels in the water and losing the most sensitive aquatic species. Besides, the inflow of this pesticide and sediment further deteriorates the quality of the habitat as well as disturbs the ecological balance. The freshwater systems experiencing those forces are, however, varying in levels of resiliency, which

relies on the biodiversity, hydrological connectivity, and the steering of the adaptive ecological functions. Some of the sustainable land-use strategies include the vegetated buffer zoning, the controlled use of fertilizers and the integrated watershed management strategies which have proven to be measurably successful in alleviating pollution and augmenting recovery. Future studies ought to concentrate on developing the predictive ecological models that combine the hydrological, biological, and climatic data to forecast the ecosystem responses to changing agricultural and climatic conditions. Enhancing the community-based surveillance system, policy application, and technological development will be the secret to maintaining the inherent resilience of the aquatic environments. Addressing the problem of agricultural runoff is not only an environmental issue but also a sustainable development global concern, which plays a substantial role in ensuring the conservation of freshwater biodiversity and the provision of ecosystem services as well as the ecological integrity, upon which natural systems and the livelihoods of human beings depend.

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