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Integrated Water Quality Assessment and Ecological Risk Evaluation of Freshwater Ecosystems Under Multiple Anthropogenic Stressors

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Abstract: The threats to the condition of freshwater systems from the impacts of agriculture, sewage, and industry have been increasing, but water quality and ecological risk have usually been evaluated independently of each other. In this study, an assessment was conducted for both water quality and ecological risk at 24 sites, which were reference sites, agricultural sites, and urban and industrial sites in a freshwater system where multiple land uses are observed. The samples were taken in three seasons and were assessed using physical, chemical, nutrient, metal, and biological parameters. Water quality score and four-tiered ecological risk categorization were combined, and the data were analyzed to find their correlations with pollution sources. Reference sites were still healthy, while industrial and urban sites had poor and very poor water quality conditions with the highest levels of ecological risk. Agricultural sites had the highest level of nutrient enrichment, and runoff in the wet season caused poor water quality at all human-impacted sites. Only 5 out of 24 sites were in the good category, and 11 sites were at considerable or high ecological risk levels. There was an extremely high correlation (correlation coefficient = 0.94) between stressor intensity and ecological risk. It is evident from the findings that using both the status of water quality and ecological risk will create a better platform to prioritize pollution abatement and restoration efforts.

Keywords: Freshwater Ecosystems; Water Quality; Ecological Risk; Anthropogenic Stressors; Nutrient Enrichment; Pollution Sources.

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I. Introduction

Background of Freshwater Ecosystem Degradation

Freshwater ecosystems like rivers, lakes, reservoirs, and wetlands provide water for drinking, agriculture, fisheries, and flood regulation, and are home to a significant proportion of global biodiversity. However, despite their importance, freshwater ecosystems have become one of the most transformed environments on Earth. Population growth, urbanization, and human land use have been progressively increasing the influx of nutrients, organic matter, metals, and other substances into the water bodies. Consequently, this leads to a gradual decrease in water transparency, oxygen levels, and water quality, and the loss of sensitive aquatic species and ecosystem functions provided to the communities by clean water.

Major Anthropogenic Stressors

There are several human activities acting together on freshwater ecosystems. For example, the use of fertilizers and pesticides on agricultural lands leads to increased amounts of nitrogen and phosphorus in streams and rivers due to their transport in rainwater and return flow of irrigation water. Domestic sewage leads to increased levels of organic matter, nutrients, and pathogenic microorganisms in water. Industries cause an increase in dissolved salts, metals, and artificial compounds in the form of constant effluent flow. Finally, stormwater and informal garbage dumps cause increased sedimentation and pollution by litter.

Importance of Integrated Water Quality and Ecological Risk Assessment

Typical monitoring usually compares individual parameter values with permissible thresholds. It serves the purpose of being in compliance with the rules but fails to characterize the state of water in its entirety. A composite score of water quality reduces several measurements to a single value, which is more

communicable. Ecological risk analysis takes it even further by answering the question of whether or not the state of pollution could affect the aquatic organisms and functioning of ecosystems. Together, the two methods will allow us to characterize the state of pollution as well as its potential consequences and prioritize management efforts according to the need for them.

Research Gap

Most of the literature considers only a particular water body, only particular groups of pollutants, and only a particular season of the year. The assessments of water quality status are often provided without estimation of their ecological consequences. Comparative analysis of various land uses in the same watershed is rather rare, as is the relationship between the degree of anthropogenic influence and the level of ecological risk in a form that would be easy for managers to interpret.

Aim and Objectives of the Study

The goal of this study project is to conduct a comprehensive assessment of water quality and ecological risks of freshwater ecosystems exposed to several anthropogenic stressors. Specific goals of the research include:

1. Determination of the water quality of reference, agricultural, urban, and industrial freshwater ecosystems in three different seasons.
2. Identification of main anthropogenic stressors for each sample site.
3. Determination of the water quality state of the selected freshwater ecosystems.
4. Determination of the ecological risks related to the identified state of water quality and pollutant concentrations.
5. Establishing the connection between pollution and the ecological state of the water body.

Section 1 introduces the background, anthropogenic stressors, research gap, aim, and objectives of the study. Section 2 reviews the previous studies on freshwater water quality, pollution sources, ecological impacts, and assessment approaches. Section 3 describes the study design, sampling, water quality analysis, stressor identification, ecological risk assessment, and statistical methods. Section 4 presents the main findings on water quality, pollution sources, seasonal variation, and ecological risk. Sections 5 and 6 are devoted to findings and management implications, primary findings, and recommendations and directions for future research.

II. Literature Review

Water Quality Changes in Freshwater Ecosystems

The quality of water in rivers and lakes is influenced by natural processes, such as geology, precipitation, and temperature, as well as anthropogenic factors that have become dominant over these natural ones (Akhtar et al., 2021). According to global assessments of large river basins, there is a general trend towards degradation of organic matter, nutrient, and microbial contamination, with the worst situation observed in fast-growing regions with poor wastewater treatment infrastructure (Giri, 2021). The effect of climate change exacerbates this process, as a comprehensive analysis of hundreds of case studies demonstrates that the water quality of rivers deteriorates in conditions of droughts, heat waves, precipitation, and floods (Van Vliet et al., 2023). The oxygen content in lakes is also decreasing in temperate regions, which negatively affects the ecosystem and its biogeochemical cycle (Jane et al., 2021). The poor water quality causes health problems, as contaminated water leads to a variety of diseases with a non-uniform burden on the population (Lin et al., 2022).

Influence of Agricultural, Industrial and Urban Activities

Agricultural activities constitute a major contributor to diffuse pollution. According to a global study on pesticide residue pollution, a significant amount of land used for agriculture is exposed to a potential threat of pollution from more than one active substance, thus posing a threat to the water bodies receiving effluent (Tang et al., 2021). Wastewater is closely associated with urban and domestic pollutant sources, and according to global statistics, almost half of the total wastewater gets discharged untreated (Jones et al., 2021). Seasonal variations have been observed in urban rivers in terms of physical and chemical properties based on changes in discharge and precipitation (Rahman et al., 2021). Industry-related and road-related activities lead to increased salt and ion load, which can cause metal and nutrient mobilization from soils and sediments (Kaushal et al., 2021). Reviews of degrading factors have highlighted the importance of agricultural, urban, and industrial impacts being often found overlapping in the same watershed (Akhtar et al., 2021).

Ecological Impacts of Multiple Pollutants

The aquatic organisms encounter chemical cocktails rather than isolated substances. A global study on pharmaceuticals revealed that the concentration levels of pharmaceuticals, at the level of concern, were observed in about one-quarter of the river sites that had been studied, thus indicating that the emerging chemicals are now reaching ecosystems, which are away from their known sources (Wilkinson et al., 2022). Wider studies have pointed out that freshwater biodiversity faces an imminent crisis due to pollution, habitat modification, water flow changes, etc. (Albert et al., 2021; Maasri et al., 2022). The long-term study in Europe revealed that the earlier progress made in freshwater communities because of better wastewater management had stopped in recent times, and this is because the remaining stress factors are limiting further progress (Haase et al., 2023).

Existing Water Quality and Ecological Risk Assessment Approaches

The use of water quality indices is the most common way of synthesizing monitoring data. As explained by the review of index models, almost all of the models use the same four-step process that includes choosing parameters, making comparable scores out of measurements, determining significance, and combining scores, and each step brings some uncertainties (Uddin et al., 2021). In a more general review of water quality indices development and comparison of a large number of models, it was found that the outcome depends both on parameter choice and on the combining procedure (Chidiac et al., 2023). Basin-wide analyses usually combine index models with pollution source surveys in order to explain the outcomes (Giri, 2021). Water quality indices show only the state of water, while ecological risk classification provides an additional perspective on the same data set (Uddin et al., 2021; Chidiac et al., 2023).

Research Gap

The study demonstrates that there is substantial evidence of degradation; however, there are a number of lacunae that can be identified in this regard. Water index assessments provide data on water quality status but usually do not interpret their implications for aquatic organisms. Pollution sources research and biodiversity research are rarely related to each other despite being very close to one another. Moreover, seasonal variability, which may affect both load and pollution exposure, is frequently not taken into account, and the comparison of land uses in the same basin is rare.

III. Methodology

Study Design and Sampling Framework

A comparative field design was employed in a freshwater river system having a heterogeneous land-use pattern comprising forest headwaters, irrigated agricultural land, towns and industry. Twenty-four sampling points were identified corresponding to four different scenarios: reference (4 sites), agriculture (8 sites),

urban (6 sites) and industry (6 sites). The reference sites were chosen from areas where there was little human interference and acted as the control. The samples were collected from the rivers, lakes and connecting canals and each sample point was situated below the main land use under investigation. Sampling was conducted during dry season, wet season and post-wet season. Table 1 describes the sampling design used, and figure 1 shows the general experimental design of the experiment.

Table 1: Sampling framework of the study

Setting	Sites	Dominant Influence in Drainage Area	Samples Collected
Reference	4	Forest and Natural Vegetation, Very Few Settlements	12
Agricultural	8	Irrigated Cropland with Fertiliser and Pesticide Use	24
Urban	6	Dense Housing, Markets and Sewage Discharge Points	18
Industrial	6	Manufacturing Clusters and Effluent Channels	18
Total	24	Mixed Land Use Basin	72

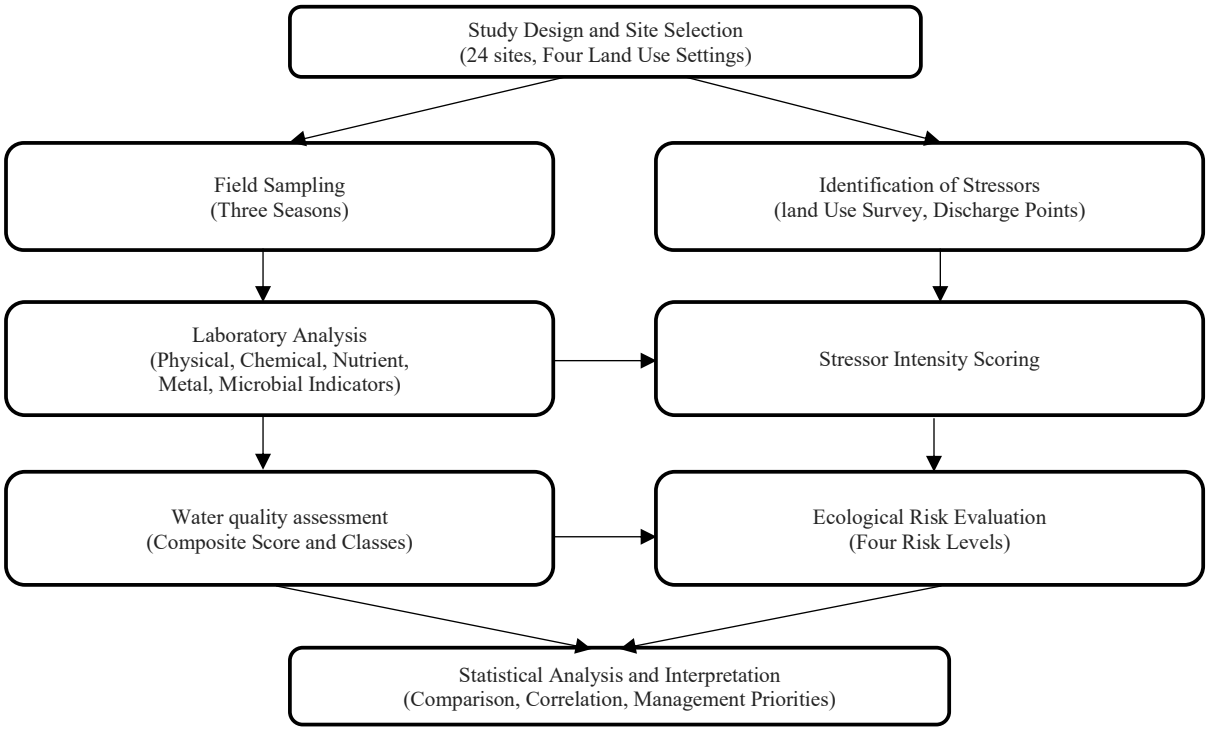


Figure 1: Methodological Workflow of the Integrated Assessment

Water Quality Sampling and Analysis

Samples of surface water were collected from the mid-flow point at a depth of 30 cm using cleaned sample containers. The samples were cooled and taken to the laboratory within 24 hours. Temperature, pH, dissolved oxygen and conductivity were measured on-site using field calibrated meters. Analyzed parameters included turbidity, total dissolved solids, biochemical oxygen demand, nitrates, phosphates, heavy metals (lead, cadmium and chromium) and fecal coliform bacteria. Standard methods for water testing were employed and quality control involved duplicates and field blanks. Replicates were carried out where results exhibited unacceptable variance.

Identification of Anthropogenic Stressors

The stresses were determined using a land use survey in the catchment area of the site under investigation, visual inspection of discharge sites, and review of the records of farm inputs, sewer connections, and industrial permits in the area. A score from 0 to 100 was determined for the degree of

stressors based on the percentage of farmland, built up areas and industrial areas within the catchment area, the number and magnitude of discharge points, and dumping of wastes. The pollution level of the basin was then distributed among four pollution sources.

Water Quality Assessment

The values recorded were normalized to a standard scale and averaged into one composite water quality index value between 0 and 100, whereby higher index values imply better quality of the water body. Priority was accorded to the oxygen content, organic matter, nutrients and metal ions since these factors directly affect the aquatic life. The scores were classified into five categories: excellent (90-100), good (70-89), medium (50-69), poor (25-49) and very poor (<25).

Ecological Risk Evaluation

The risk at each site was determined using the ratio of measured values of nutrients, oxygen-demanding compounds, and metals to safe limit levels for aquatic organisms, which was then combined to give a final risk index between 0 to 10. The sites were classified into four categories based on the risk level – low (less than 3), moderate (3-5), considerable (5-7), and high (more than 7).

Statistical Analysis

The mean values were compared for the four scenarios and for the three seasons by means of the standard tests for differences between groups at the 5 % significance level. Correlation coefficient was used to assess the association between the intensity of stressor and the ecological risk value, while the linear trend line was drawn for illustration purposes. The number and proportion of sites within each water quality category and risk level were estimated for every scenario. All the analysis was done by using standard statistical software.

IV. Results

Characteristics of Sampled Freshwater Environments

The sampled sites exhibited a clear gradient in terms of human activity. The reference sites were drained from areas that had forests and no human habitation while the agricultural sites were located next to irrigated farmlands. The urban sites had water from densely populated areas, with markets while the industrial sites were next to manufacturing centers and effluent discharge. The total number of samples was 72. Water in reference sites was clean and oxygen rich while in urban and industrial sites there was murky color and odor.

Variation in Major Water Quality Parameters

The mean dissolved oxygen content decreased from 7.8 mg/L in reference sites to 5.9, 4.6, and 4.1 mg/L in agricultural, urban, and industrial sites, respectively shown in table 2 and figure 2. The biochemical oxygen demand increased from 1.8 mg/L in reference sites to 6.8 mg/L in urban sites, the maximum observed. Nitrate concentration was the maximum in agricultural sites (7.8 mg/L), over six times the reference value, while phosphate concentration was the maximum in urban sites (0.42 mg/L). Total dissolved solids reached the level of 690 mg/L in industrial sites, nearly five times the reference mean. Lead, cadmium, or chromium exceeded the protection standards in four of the six industrial sites at least once during the study period. Differences among the four sites were significant for all the parameters at 5% level.

Table 2: Mean Values of Major Water Quality Parameters By Setting

Setting	Dissolved oxygen (mg/L)	Oxygen demand (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Turbidity (NTU)	Dissolved solids (mg/L)
Reference	7.8	1.8	1.2	0.04	6	140
Agricultural	5.9	3.9	7.8	0.31	21	310
Urban	4.6	6.8	5.2	0.42	28	420
Industrial	4.1	6.1	4.4	0.28	34	690

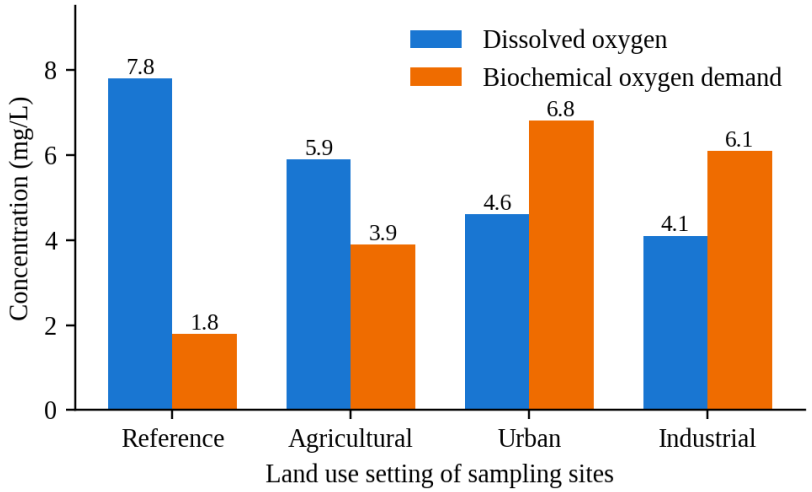


Figure 2: Mean Dissolved Oxygen and Biochemical Oxygen Demand at the Four Settings

Distribution of Anthropogenic Stressors

Runoff from agriculture formed the greatest percentage of the pollution load of 34%, while sewage from households came second with 27% and effluent from industries third with 24%. Storm water and solid waste made up the rest at 15%, as illustrated in figure 3 below. The stressor intensity index scores were 17 at reference sites, 48 at agricultural sites, 67 at urban sites and 77 at industrial sites. It is notable that many of the urban sites had overlapping sources of pollution due to agricultural return flows upstream and industrial sites downstream of towns.

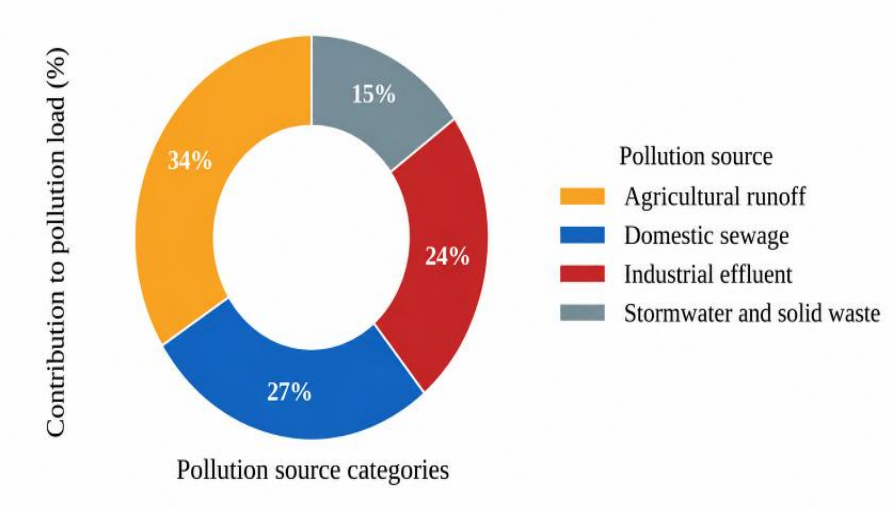


Figure 3: Share of Pollution Load Contributed by Each Source

Overall Water Quality Status

The mean water quality scores at reference sites, agricultural sites, urban sites, and industrial sites were 86, 62, 48, and 41 respectively. None of the sites fell into the excellent category. Out of a total of 24 sites, five (21 %) sites were found to be in good condition, nine (37.5 %, 38 % rounded) in medium condition, seven (29 %) in poor condition, and three (13 %) in very poor condition. All four reference sites and one agricultural site were in good condition, while all very poor sites were either urban or industrial. Scores declined at each site during the wet season and partially recovered during the post-wet season shown in figure 4.

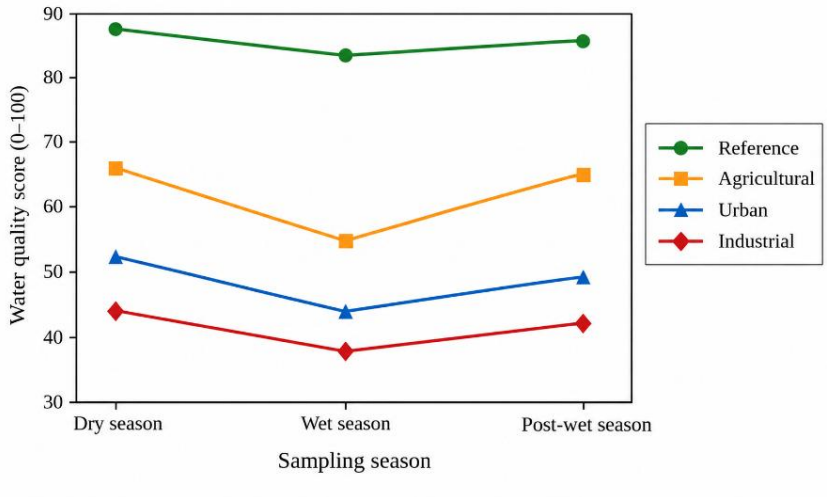


Figure 4: Seasonal Variation in Water Quality Score at the Four Settings

Ecological Risk Levels

Low risk was observed for all four reference sites. For agricultural sites, one site was low, five were moderate, and two were considerable. For urban sites, two were at moderate risk, three had considerable risks and one had high ecological risk. Industrial sites had more severe risks compared to others, where three sites were at high risks, two were considerable and one at moderate risk, as seen in figure 5. In total out of 24 sites, 5 (21%) were at low risk, 8 (33%) at moderate risk, 7 (29%) at considerable risk and 4 (17%) at high risk. Out of 24, 11 sites or almost half were considerable or high risks.

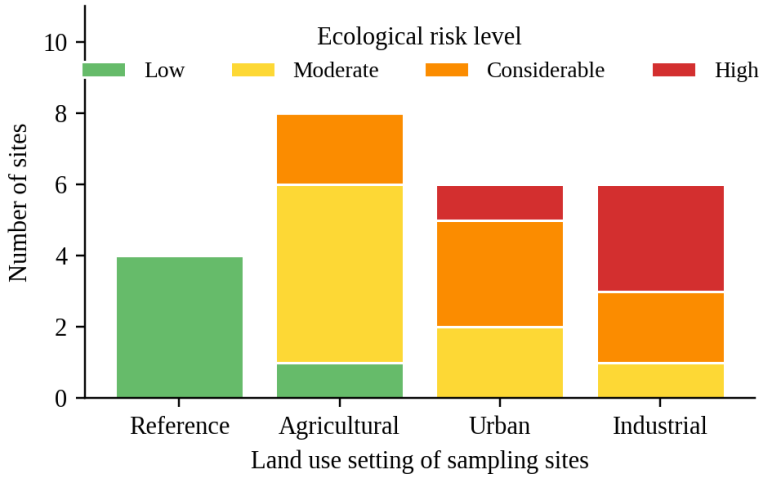


Figure 5: Number of Sites in Each Ecological Risk Level by Setting

Relationship Between Pollution Sources and Ecological Condition

There was an observed significant positive relationship between stressor intensity and ecological risk score with a correlation coefficient of 0.94, as seen in figure 6. As the stressor intensity increased, risk scores also increased continuously, and there was not a clear threshold observed, which suggests that even small increase in stressor caused the increase in risk. Reference sites were clustered in low intensity and risk; agricultural sites were in the middle ranges while urban and industrial sites were on the upper end of both scales.

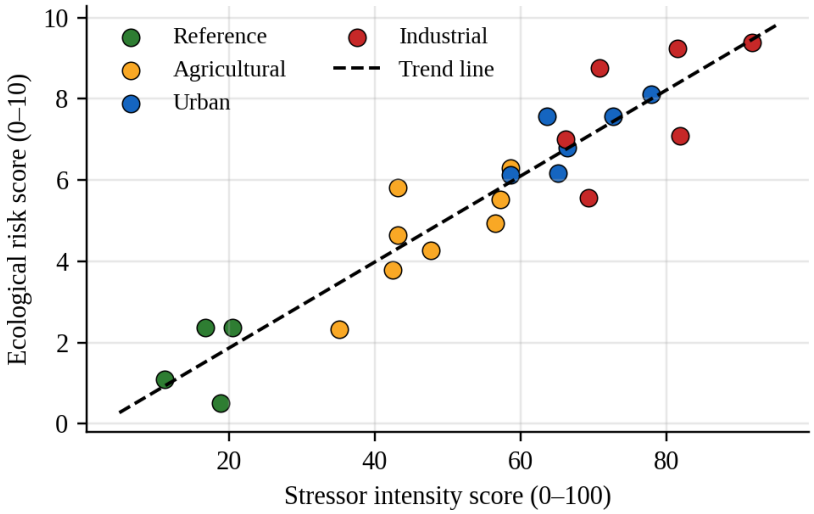


Figure 6: Relationship Between Stressor Intensity Score and Ecological Risk Score

V. Discussion

Interpretation of Water Quality Variations

Decline in oxygen content and increase in organic content from reference sites to urban and industrial sites indicate a trend observed when biodegradable wastes get into the water body faster than their breakdown occurs through natural processes. Low oxygen content in urban areas indicates that there is no proper treatment of the sewage; high nitrate levels in agricultural areas suggest fertilizer losses from agricultural land. The wet season decrease in all human-affected areas suggests that rainwater helps carry pollutants from agricultural lands, roads, and garbage dumps to the water bodies.

Effects of Major Anthropogenic Stressors

The following signatures were associated with each of the stressors. The agricultural pollution showed nutrient enrichment, which is a result of increased algae activity and may lead to drastic drops in oxygen levels during nighttime and post algae death. The urban pollution was characterized by an increased organic matter and phosphate levels, which are common indicators of sewage pollution, and also present the problem of human exposure to this water. The industrial pollution signature included high levels of dissolved solids, turbidity and metals – the pollutants are not fast to dilute, as metals are deposited in sediments and can be released back into the water at a later stage. Agriculture presented the biggest load of pollution, but industrial stressors carried the greatest risks.

Ecological Implications of Observed Pollution

The sites in the large category and the high-risk category may house fewer sensitive insect, snail, and fish, and the tolerant species may progressively replace sensitive species. The low oxygen hampers the

existence of fish and invertebrate, enrichment in nutrients stimulates the production of algae leading to shading and smothering of benthic habitats, and toxic metals are known to bioaccumulate through food chains. Since flowing water transports the pollutants downstream, an impact at one site may have an adverse effect on other stretches which would normally be healthier. The fact that almost half of the sites were categorized in the high-risk categories is a sign of threat to the ecology of the basin.

Comparison with Previous Studies

The occurrence of the poorest water quality at urban and industrial outfalls and enhanced nutrient concentrations in farmlands corroborates previous reports from numerous river catchments in various regions, which have consistently indicated that land use is the principal cause of variations in water quality. The seasonal decrease in water quality during the wet season also conforms to previous researches, although the magnitude of this decrease varies with the amount of rainfall. A departure from the previous studies is the existence of an explicit linear relationship between stressor intensity and risk, which usually gets concealed by sampling only a limited pressure intensity range in single-site surveys.

Implications for Freshwater Ecosystem Management

Management needs a selective approach based on the research results. Urban areas require development of sewage collection and treatment systems, while industrial sites should have effluent standards and constant monitoring. Agricultural areas will benefit from nutrient management, buffer strips of vegetation along the water bodies, and irrigation return flows. The rest of the pollution sources can be dealt with through stormwater management and solid waste collection. The monitoring process should cover the wet season when the pollutant input is at its peak. Combined water quality and risk classification can be used for ranking the sites so that scarce financial resources can be directed first at the most endangered ones.

VI. Conclusion

The integrated assessment of 24 sites, there was a significant degradation of water quality and increased ecological risk from reference to agricultural, urban and industrial sites. Mean water quality scores declined from 86 in reference sites to 41 in industrial sites, only five sites were categorized as good sites and eleven sites were at considerable or high ecological risk. Agricultural runoff is the greatest source of pollution loading whereas industrial and urban discharges were responsible for the worst conditions. Water quality declined at all human modified sites during the wet season and the ecological risk increased progressively with stressor intensity. Combined effects of multiple stressors are impacting freshwater conditions within the entire basin, which will affect the availability of oxygen, habitat conditions and survival of sensitive species. The close relationship between pressure and risk implies that ecological risk can be predicted based on land use and discharge data, providing an effective risk prediction system. It would be necessary to treat sewage in urban areas, control effluents in industrial areas, manage nutrients and buffer strips in agricultural fields and manage stormwater and wastes in the basin. Monitoring needs to be a part of regular programmes during the wet season, and the water quality and risk class should dictate the priority of restoration activities. Reference areas should be preserved for use as standards and refuges for species. For future monitoring, monitoring of water quality over several years is needed to distinguish between seasonal and long-term changes, and biological indicators like bottom-dwelling insect and fish fauna should be incorporated to verify the expected impacts on the ecosystem. Studies of extreme weather conditions, low-cost sensors and remote sensing from satellites, and community-based monitoring programs will improve early warnings and management of freshwater ecosystems.

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