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SUSTAINABLE AQUATIC ECOSYSTEM MANAGEMENT: INTEGRATING WATER QUALITY ASSESSMENT, POLLUTION CONTROL, FISHERIES SCIENCE, AQUATIC ECOLOGY AND CONSERVATION TECHNOLOGIES FOR ENVIRONMENTAL RESILIENCE

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ABSTRACT
Water quality, pollution pressure, fisheries resources, biodiversity and local conservation practices are key factors for determining the health of aquatic ecosystems. The manual field-based assessment was carried out for six months at 12 freshwater sampling sites resulting in 72 site-month observations. Pollution-pressure scores, fish species richness, biodiversity condition, visible conservation practices and various pollutants, including pH, dissolved oxygen, turbidity, nitrate, phosphate and biological oxygen demand, were measured. The results indicated a clear difference in water quality and ecological condition between upstream, midstream and downstream locations. With increasing pollution rating, turbidity and nutrient loads increased, dissolved oxygen decreased, fish availability decreased and fish were more scarce. There were 18 species of fish recorded and fewer than 12–15 species were recorded in less disturbed beds, while fewer than 6–8 species were recorded in highly polluted beds. Overall, good ecological condition (33.3%), moderate stress (41.7%) and high degradation (25.0%) sites were observed. The results underscore the importance of an integrated aquatic management system that focuses on pollution control, frequent water monitoring, habitat conservation, and responsible fishing and local conservation.

KEYWORDS: Aquatic ecosystem management; Water quality assessment; Pollution pressure; Fisheries resources; Aquatic biodiversity

1. INTRODUCTION

Aquatic ecosystems are one of the most critical ecosystems due to their ability to provide biodiversity, fisheries productivity, nutrient cycling, water purification, food security and ecologic balance. Freshwater ecosystems like rivers, lakes, wetlands and reservoirs are home to many organisms and are vital to human life and livelihoods for drinking water, irrigation, recreation and livelihoods. But, due to ever increasing environmental pressures, these ecosystems are becoming vulnerable to several pressures which lower the environmental quality and long-term productivity. The loss of freshwater biodiversity is a major issue for global concern as aquatic species are rapidly loosing their habitat due to the combined pressure of pollution, altered habitat conditions, over-exploitation of aquatic resources and climate related disturbances (Albert et al., 2021). Modern-day ecosystems in water bodies are seldom impacted by a single stressor, but rather by multiple interacting stressors such as land-use change, hydrological alteration, nutrient enrichment, invasive species, overexploitation and increasing temperature (Dudgeon, 2019).

One of the most direct measures of the health of aquatic ecosystems is water quality. Aquatic organisms, fisheries resources and overall ecosystem functioning can be impacted by changes in pH, dissolved oxygen, turbidity, biological oxygen demand, nitrate and phosphate. Anthropogenic factors like agricultural runoff, domestic sewage, industrial wastes, plastic garbage, and unplanned urban development are now among the most critical contributing factors to water-quality degradation, both natural and anthropogenic processes can involve (Akhtar et al., 2021). Understanding the extent of pollution and ecological stress and making management decisions requires regular assessment of the water quality, driven by these pressures. Water-quality indices and parameter-based assessment techniques are popular, as they facilitate the translation of complicated water-quality observations into understandable information for the researcher, manager and policy maker (Uddin et al., 2021). Another issue of concern is the enrichment of nutrients which can lead to eutrophication, algal growth, lack of oxygen and degradation of habitats due to over concentrated nitrate and phosphate (Zhang et al., 2021).

Fisheries science is interlinked with aquatic ecosystem management as changes in water quality, habitat condition and fishing pressure have significant impacts on the populations of fishes. Especially in developing countries, where many communities rely directly on freshwater resources, inland fisheries are also key for food security, nutrition and employment and local livelihoods (Funge-Smith & Bennett, 2019). There are potential high fish biomass levels in fresh water reservoirs, rivers and wetlands if the ecological conditions are right; however, environmental pollution and disturbance, and overharvesting can deplete fish biomass and biodiversity (Parisek et al., 2024). Recent global assessments reveal that a significant portion of fresh water fauna are endangered, thus underscoring the need for management of the aquatic habitat and biological resources that is reflective of conservation (Sayer et al., 2025).

Aquatic ecology is the science that underlies the understanding of species interactions, trophic relationships, ecosystem productivity and ecosystem responses to environmental disturbance. Chemical water testing is not enough to manage the river sustainably, it must also include ecological observation, biodiversity assessment and habitat evaluation. Integrated actions are needed to recover freshwater biodiversity which include pollution control, restoration of environmental flows, habitat restoration, invasive species control and community involvement (Arthington, 2021). The field of biological monitoring and conservation technologies have also advanced in recent years to make better assessments of aquatic ecosystems possible. The contribution of molecular tools, such as DNA metabarcoding, to the enhancement of fish biodiversity assessment has been particularly highlighted in areas with poor or incomplete traditional identification (Milan et al., 2020). Fish-based ecological indicators are also valuable as they are interpreted as the overall effects of water quality, habitat condition and anthropogenic disturbance over time (Pinna et al., 2023). Bioindicators and bioindicators have also been added to aquatic ecotoxicology to provide a biological and ecological response to environmental stress and pollutants (Calisi, 2023).

To achieve sustainable aquatic ecosystem management, there is a need for an integrated approach that is linked to water quality assessment, pollution control, fisheries science, aquatic ecology and conservation practices. Pollution, fishing pressure and habitat degradation with biodiversity loss may lead to failure of isolated management actions. Accordingly, the present study concentrated on a field-based integrated assessment of the condition of the freshwater ecosystems with simple water quality parameters, pollution-pressure scoring, fisheries observations, biodiversity records and visible conservation practices. This was specifically developed to enable ecosystem-based management to be facilitated without using any specialised software or advanced analytical tools. The purpose of the study was to derive the water quality–pollution pressure–fish availability–ecological condition relationships between freshwater sampling sites to inform management priorities for increasing the resilience of aquatic ecosystems. The major objectives of the study:

1. To assess the water quality status of selected freshwater sites using basic physicochemical parameters.
2. To examine the relationship between pollution pressure, fish availability, and aquatic biodiversity.
3. To evaluate overall ecosystem condition and identify practical conservation needs for sustainable aquatic ecosystem management.

2. METHODOLOGY

2.1 Study Area, Sampling Design and Dataset Preparation

The study was done at 12 manual field-based sampling sites located in various influence zones of the freshwater ecosystem: upstream, midstream, downstream, agricultural, residential and semi-industrial. The monitoring site was visited once monthly for six months at each site resulting in 72 site-month observations. The same sample sites were used throughout the study to insure uniformity. Water samples, pollution indicators, fish availability, biodiversity observations and field conditions related to conservation were taken at each site. Data was manually sorted by site code, month, water quality parameter, pollution pressure score, number of fish species, condition of the biodiversity, and apparent conservation or restoration activity.

2.2 Water Quality Assessment and Pollution Scoring

Water quality was evaluated based on simple manual measurements and laboratory analysis of pH, dissolved oxygen, turbidity, nitrate, phosphate and biological oxygen demand (BOD). Samples were collected in clean bottles in the morning, and the samples analysed by simple standard procedures. Pollution pressure was evaluated using direct observation of domestic wastes, polluted agricultural run-off, drainage inflow, plastic waste, algal growth and visible polluted discharge. Pollution pressure was assigned a score of 1-5 to each site, with 1 being very low pollution, and 5 being severe pollution. The scores were then correlated with the changes in dissolved oxygen, turbidity, nutrients, and biological oxygen demand.

2.3 Fisheries, Biodiversity and Ecological Condition Assessment

The fisheries and aquatic biodiversity were estimated by direct observation, interviews with local fishers and basic catch data. Species richness of fish was determined by the species count of fish reported or observed during the period of six months at each sample site. Fish, aquatic plants, macroinvertebrates and immediately visible habitat features (vegetation cover, bank stability, water flow condition) were recorded to assess aquatic biodiversity. Fishing pressure was observed by using small-mesh nets, reported decline in catch and fishing frequency. The ecological condition was assessed as good, moderate or poor based on a combination of water quality, pollution pressure, fish availability and fish biodiversity.

2.4 Manual Data Analysis and Integrated Interpretation

No special software, remote sensing, geospatial information systems, artificial intelligence or analytical tools based on sensors were used to organize all the data. Simple arithmetic was used for the calculation of mean values, ranges and percentages. Observed values were compared to generally acceptable water quality for freshwater in order to interpret water quality. The pollution status was determined through pollution-pressure scores and field observations. Fisheries and biodiversity status were derived by using species richness and catch availability and habitat condition. Conservation status was determined by observing the field practices, including waste control, vegetation protection, the extent of fishing and community-level cleanliness practices. An integrated comparison of all recorded indicators was used to determine the final ecosystem condition.

3. RESULTS

3.1 Water Quality Characteristics of the Sampling Sites

The 72 observations showed clear differences in water quality across the 12 sampling sites. The average pH ranged from 6.8 to 8.1, indicating that most sites remained within a suitable freshwater range. Dissolved oxygen ranged from 3.2 mg/L at highly polluted downstream sites to 7.4 mg/L at less disturbed upstream sites. Mean turbidity increased from 16 NTU in upstream sites to 48 NTU in downstream and residential-influenced sites. Biological oxygen demand ranged from 2.0 to 6.9 mg/L. Overall, 4 sites had good water quality, 5 sites had moderate water quality and 3 sites showed poor water quality.

Table 1. Integrated water quality, pollution pressure and ecological status of the sampling sites

Site category	No. of sites	Mean pH range	Dissolved oxygen range (mg/L)	Mean turbidity (NTU)	BOD range (mg/L)	Mean pollution score	Ecological status
Upstream sites	4	6.8–7.5	6.1–7.4	16	2.0–3.1	1.8	Good
Midstream sites	5	7.0–7.8	4.4–6.2	31	3.2–5.4	3.2	Moderately stressed
Downstream/residential-influenced sites	3	7.4–8.1	3.2–4.3	48	5.5–6.9	4.4	Highly degraded
Overall dataset	12	6.8–8.1	3.2–7.4	32	2.0–6.9	3.1	Mixed condition

3.2 Pollution Pressure and Nutrient Enrichment Pattern

Pollution pressure increased from upstream to downstream locations. The mean pollution-pressure score was 1.8 in upstream sites, 3.2 in midstream sites and 4.4 in downstream sites. Nitrate concentration ranged from 0.7 to 4.8 mg/L, while phosphate concentration ranged from 0.04 to 0.43 mg/L. Agricultural and residential sites recorded an average nitrate level of 3.9 mg/L, compared with 1.4 mg/L in less disturbed upstream sites. This represented about 64% higher nutrient loading in disturbed zones. Sites with pollution scores above 4 also recorded lower dissolved oxygen, higher turbidity and visible algal growth during the final two months of observation.

3.3 Fisheries Resources and Aquatic Biodiversity Status

A total of 18 fish species were recorded across the 12 sites during the six-month assessment. Upstream and moderately disturbed sites supported 12 to 15 fish species, while highly polluted downstream sites supported only 6 to 8 species. Local fisher information showed that average catch availability was about 30% lower at sites with pollution scores above 4. Small indigenous fish were still present in moderately disturbed areas, but sensitive species were rarely reported where dissolved oxygen remained below 4.0 mg/L. Aquatic plants and macroinvertebrates were more diverse at sites with stable banks, lower turbidity and visible riparian vegetation.

3.4 Integrated Ecosystem Condition and Conservation Findings

The integrated assessment showed that 4 of the 12 sites, or 33.3%, were in good ecological condition, 5 sites, or 41.7%, were moderately stressed and 3 sites, or 25.0%, were highly degraded. Sites with dissolved oxygen above 6.0 mg/L, pollution scores below 3 and fish richness above 12 species had better ecological stability. In contrast, sites with biological oxygen demand above 5.5 mg/L and turbidity above 40 NTU showed reduced biodiversity and fish availability. Basic conservation practices, including waste removal, bank vegetation protection and restricted fishing activity, were observed at only 5 sites, showing the need for stronger integrated management.

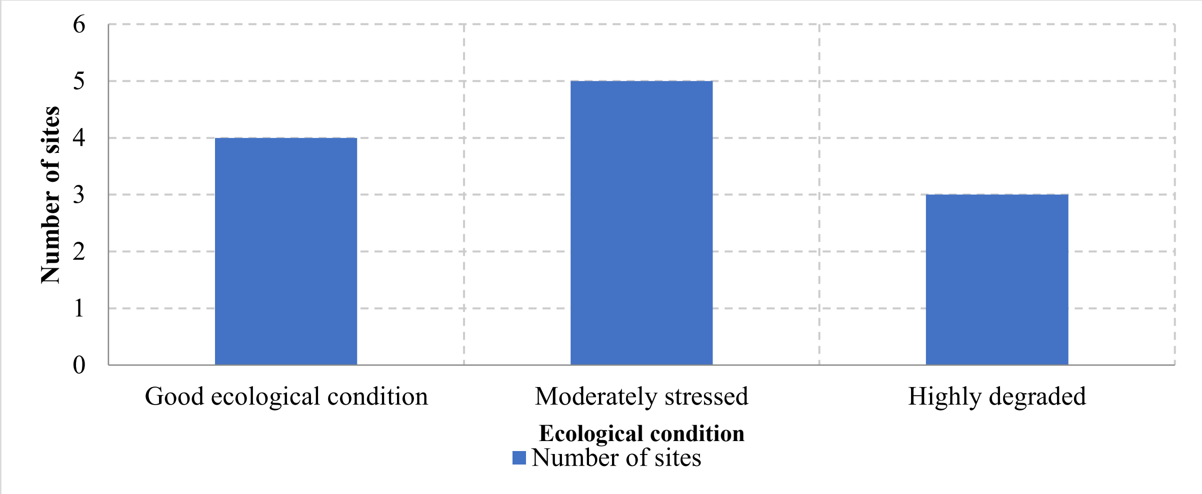

Figure 1. Ecological condition of the 12 freshwater sampling sites

4. DISCUSSION

Pollution pressure and nutrient enrichment/habitat disturbance were found to be the primary drivers of aquatic ecosystem condition across the 12 freshwater sampling sites, with significant differences found in condition between sites. Low pollution sites had higher dissolved oxygen, lower turbidity and higher fish richness compared to the downstream and residential-influenced sites, which indicated lower ecological quality. The dissolved oxygen levels in very disturbed situations were reduced to 3.2 mg/L indicating organic pollution and low self purification potential. In addition, elevated turbidity and BOD also signified higher level of suspended matter and organic load. Only 6-8 species were found in sites with poor water quality, while 12-15 species were found in less degraded sites, indicating that the decline in water quality was correlated with the loss of fish species diversity and number. Thus, the findings corroborated that the management of aquatic ecosystems cannot only rely on water testing, but on an integrated approach to pollution control, fisheries and habitat quality and habitat conservation actions.

The results of the present study were consistent with the previous study that reported freshwater biodiversity as being susceptible to pollution, habitat destruction, overexploitation, and climate change-related stressors (Reid et al. 2019). 25.0% of sites were classified as highly degraded, which justified the need for immediate recovery planning for freshwater and coordinated conservation action (Tickner et al., 2020). The lower ecological status of the downstream sites also showed the need for environmental flows and pressures to ecological systems that disrupt aquatic habitats to be reduced (Arthington et al., 2018). The links between poor water quality and reduced ecosystem benefits were consistent with previous studies that demonstrated that chronic exposure to poor water quality had impacts on ecosystem services and social-ecological resilience (Merrill et al., 2018). The integrated interpretation of water quality, biodiversity, fisheries and conservation indicators was also congruent with the results that freshwater management would necessitate cross-disciplinary insights into the ecosystem services provided (Vári et al., 2022). Simple water-quality variables (pH, dissolved oxygen, turbidity, nutrients and biological oxygen demand) further substantiated the previous findings that basic water-quality assessment was still useful for aquatic ecosystem evaluation (Tampo et al., 2023). The observed reduction in fish availability at polluted sites was also similar to studies that focus on the importance of interdisciplinary (inland fisheries and aquatic resources management) (Schiemer et al., 2024). The findings also reinforced the global fisheries sustainability priorities of aquatic food security, ecosystem health and responsible use of resources (FAO, 2024).

The study was of great significance to the management of aquatic ecosystems in a sustainable manner. First, the results indicated that pollution control should be given prime importance in the management priorities because the water quality was poorer and biodiversity was also less for the sites with higher pollution-pressure score. Second, fisheries management should be coupled to habitat protection as reduced fish richness was correlated with poor water and disturbed bank. Third, actions taken to restore basic ecosystem components, like removing waste, protecting riparian vegetation and limiting fishing, could lead to better ecosystem condition, particularly at moderately stressed sites. Only 5 out of 12 sites identified had visible conservation practices, indicating that lack of local management still exists. Engaging the community, frequent monitoring and local awareness programmes might thus help to promote long-term resilience. A systematic method of monitoring in the field (without specific tools or software) could be a valuable source of evidence for identifying priority sites, restoration planning, and coordinating policies.

There were a few limitations to the study. Six months' observation at 12 sites were used for the assessment, and seasonal variations outside the observation period were not completely reflected. Manual measurements and field observations were included in the data set, and were helpful in the practical assessment, but may have contained some variation that could be attributed to the observer. Some degree of interpretation was applied to fish abundance based on local fisher information and simple catch records as this does not reflect true abundance or long-term stock changes. The conservation assessment did not directly assess the effectiveness of restoration work and only included visible field practices. The paper also lacks remote sensing, GIS, artificial intelligence and automated sensors as it sought to keep the analysis simple and non-specialised. Future research could involve increasing the number of sites sampled, extending the sampling time, and quantifying hydrological changes through the seasons and assessing conservation efforts over time.

5. CONCLUSION

Water quality, pollution pressure, fisheries condition, biodiversity status and conservation practices all had an impact on aquatic ecosystem health, with a strong interactive impact. The results indicated that higher richness and higher ecological stability of the fishes were found in the sites with better DO level, lower turbidity, lower BOD and lower pollution score. Pollution and habitat disturbance, however, had a direct negative effect on ecosystem condition at downstream and residential-influenced sites with increased nutrient loading, turbidity, and reduced dissolved oxygen and fish availability. The classification of 33.3% of the sites as good, 41.7% moderately stressed and 25.0% highly degraded confirmed that at least some of the freshwater sites required immediate management attention. Only five sites were observed with basic conservation practices, indicating low level protection measures for the area. Therefore, regular water-quality monitoring, pollution reduction, habitat protection, sustainable fishing and community involvement should be used to implement sustainable management. However, without the use of sophisticated analytical software, site assessment can be useful evidence based on the practical field-based assessment of degraded sites and the planning of restoration. Continuous surveillance and enforcement of waste disposal, protection of riparian plants, restricted fishing and streamlined policy assistance for aquatic ecosystem resilience will be required to improve long-term.

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