



Aquatic Environment Management and Sustainability

*Sana Kausar Mainoddin Patel and Syed Hamza Syed Saidoddin

Assistant Fisheries Development Officer, Government of Maharashtra, India

*Corresponding Author's email: sanapatelfish@gmail.com

Aquatic environments, including rivers, lakes, wetlands, estuaries and marine ecosystems, are essential for biodiversity conservation, ecosystem functioning and the sustainable provision of water and other natural resources. However, increasing pollution, habitat degradation, nutrient enrichment, wastewater discharge, over-extraction and climate change are placing considerable pressure on aquatic ecosystems. A 2024 UNEP assessment reported that one or more types of freshwater ecosystems are degraded in about half of the world's countries, with declining river flows, shrinking surface-water bodies and increasing water pollution being major concerns. Globally, approximately 80% of marine pollution originates from land-based activities, including untreated wastewater, agricultural runoff and other pollutants (Wang and Liting, 2024). Nutrient enrichment by nitrogen and phosphorus can further promote harmful algal blooms, oxygen depletion and biodiversity loss in freshwater and coastal ecosystems. These pressures highlight the need for integrated aquatic environment management based on regular water-quality monitoring, pollution prevention, wastewater treatment, habitat restoration and sustainable resource utilization. Effective management can help maintain ecological integrity, improve water quality and strengthen the resilience of aquatic ecosystems under increasing environmental pressures.

Aquatic environment: Importance and major components

Aquatic environments encompass freshwater and marine ecosystems, including rivers, lakes, reservoirs, wetlands, estuaries, coastal waters and oceans, which collectively support diverse biological communities and sustain fisheries and aquaculture activities. Their ecological condition is determined by interactions among physicochemical factors, such as temperature, pH, dissolved oxygen, salinity, turbidity, nutrients and organic matter, and biological components, including phytoplankton, zooplankton, macrophytes, benthic organisms, microorganisms and fish. These components regulate primary productivity, nutrient cycling, decomposition, food-web dynamics and habitat quality. Healthy aquatic ecosystems provide important ecosystem services, including food production, water purification, nutrient cycling, carbon sequestration, habitat provision and livelihood support. From an aquaculture perspective, the quality and carrying capacity of surrounding aquatic environments directly influence water availability, fish health, disease dynamics and production sustainability. Therefore, maintaining the ecological integrity of freshwater and marine ecosystems is essential for balancing aquatic resource utilization with long-term fisheries and aquaculture development (Walker et al., 2016).

Major threats to aquatic environments

Aquatic ecosystems are exposed to increasing pressures from anthropogenic activities and climate change, which can alter water quality, habitat structure, biodiversity and ecosystem functioning. Water pollution and eutrophication caused by excessive nutrient inputs, organic matter and other pollutants can promote algal blooms, reduce dissolved oxygen and create hypoxic conditions that adversely affect fish and other aquatic organisms. Industrial and domestic wastewater may introduce heavy metals, toxic chemicals, organic pollutants,

pathogens and excess nutrients, while agricultural runoff transports fertilizers, pesticides, sediments and animal wastes into freshwater and coastal systems (Mazur et al., 2024). Habitat degradation through wetland loss, shoreline modification, aquatic vegetation removal and other land-use changes can reduce spawning, nursery and feeding habitats, contributing to biodiversity decline. Climate change further intensifies these pressures through increasing water temperature, altered rainfall, droughts, floods, ocean warming and acidification. At the same time, emerging contaminants such as microplastics, pharmaceuticals, personal-care products and antibiotic residues are receiving increasing attention because of their persistence and potential ecological effects. Collectively, these stressors can reduce aquatic ecosystem resilience and negatively influence fisheries resources, aquaculture water quality, fish health and long-term environmental sustainability.

Water quality monitoring and assessment

Water quality monitoring is a fundamental component of aquatic environmental management because changes in water chemistry and biological conditions directly influence ecosystem health, fisheries resources and aquaculture productivity. Key physicochemical parameters, including temperature, pH, dissolved oxygen, salinity, turbidity, electrical conductivity, ammonia, nitrite, nitrate and phosphate, are routinely assessed to evaluate environmental conditions and identify potential pollution or stress. Biological indicators, such as phytoplankton, zooplankton, benthic macroinvertebrates, microbial communities and fish assemblages, provide complementary information on ecological condition and longer-term environmental changes. Conventional laboratory analysis provides reliable measurements, while sensor-based and real-time monitoring systems enable continuous assessment of important parameters, particularly in intensive aquaculture systems. Integration of sensors with the Internet of Things (IoT), automated data transmission and artificial intelligence can facilitate early detection of undesirable changes and support timely management interventions. Such integrated monitoring approaches can improve environmental decision-making, maintain suitable culture conditions and contribute to sustainable aquatic resource management.

Strategies for aquatic environment management

Effective aquatic environment management requires integrated strategies that reduce pollution, maintain ecological functions and improve the resilience of freshwater and marine ecosystems. Pollution prevention and wastewater treatment are essential for controlling the discharge of organic matter, nutrients, pathogens, heavy metals and other contaminants into receiving waters. In aquaculture, appropriate effluent treatment, sediment management and water reuse can reduce nutrient loading and minimize environmental impacts. Bioremediation and phytoremediation provide environmentally compatible approaches in which microorganisms, algae and aquatic plants are used to degrade, transform or remove pollutants and excess nutrients from contaminated water and sediments (Pandey et al., 2023). Habitat restoration and conservation, including the protection and restoration of wetlands, mangroves, seagrass beds, riparian vegetation and other critical habitats, can improve water quality, provide nursery and spawning grounds and support aquatic biodiversity. In addition, integrated watershed and coastal management promotes coordinated management of land, water and aquatic resources by addressing pollution sources and resource-use pressures across connected ecosystems. These approaches, when supported by regular monitoring, stakeholder participation and science-based management, can help maintain aquatic ecosystem health while supporting sustainable fisheries and aquaculture development.

Sustainable aquaculture and aquatic environment

Sustainable aquaculture requires efficient use of water, feed and other resources while minimizing the release of pollutants and nutrients into surrounding aquatic environments. Effluent and nutrient management are essential for reducing organic matter, suspended solids, nitrogen and phosphorus discharge from intensive farming systems. Appropriate settling, filtration, biofiltration and treatment of culture effluents can reduce environmental loading

before water is released or reused. Water recycling and reuse can substantially reduce freshwater demand and support more controlled culture conditions, particularly in intensive and water-limited production systems. Technologies such as biofloc technology (BFT), recirculating aquaculture systems (RAS), aquaponics and integrated multitrophic aquaculture (IMTA) can improve resource-use efficiency by promoting nutrient recovery, water conservation and waste utilization. In addition, good aquaculture management practices involving appropriate stocking density, efficient feeding, biosecurity, regular water-quality monitoring and responsible chemical use are important for maintaining fish health and reducing environmental impacts. The integration of these approaches can help reconcile aquaculture production with aquatic ecosystem protection and contribute to long-term environmental sustainability.

Emerging technologies for sustainable aquatic management

Artificial intelligence and the Internet of Things

Artificial intelligence (AI) and the Internet of Things (IoT) are increasingly being integrated into aquatic resource management and aquaculture to support real-time monitoring, prediction and automated decision-making. IoT-enabled sensors can continuously measure important environmental parameters such as temperature, dissolved oxygen, pH, salinity, turbidity and ammonia, while AI and machine-learning algorithms can analyse these datasets to identify patterns and predict potential environmental or production-related problems. In aquaculture systems, AI can assist in biomass estimation, fish behaviour analysis, disease detection and feeding management. Automated feeders and aeration systems can also be operated according to real-time environmental and biological information, thereby reducing unnecessary feed and energy consumption. The integration of AI, IoT and cloud-based data platforms therefore provides opportunities for more efficient, responsive and sustainable management of aquatic production systems (Miller et al., 2025).

Remote sensing and geographic information systems

Remote sensing and geographic information systems (GIS) provide important spatial tools for monitoring aquatic ecosystems and supporting resource management. Satellite-based observations can be used to assess changes in water bodies, wetlands, reservoirs, coastal areas and aquaculture landscapes over large geographical areas. Remote sensing techniques can also provide information on parameters such as surface temperature, turbidity, chlorophyll-a, algal blooms and changes in habitat characteristics. GIS enables the integration and spatial analysis of remote-sensing information with field observations, environmental variables, land-use patterns and aquaculture infrastructure. These technologies can support the identification of suitable locations for aquaculture development, assessment of habitat degradation and monitoring of changes in aquatic resources. Their application can consequently improve spatial planning, environmental assessment and long-term management of aquatic ecosystems.

Smart environmental monitoring

Smart environmental monitoring systems are transforming aquatic ecosystem management from periodic sampling towards continuous and real-time assessment. Networked sensors, automated monitoring stations and wireless communication technologies allow frequent or continuous measurement of key water-quality parameters. Such systems can detect sudden changes in dissolved oxygen, temperature, pH, salinity, turbidity and other environmental variables and generate alerts when conditions exceed predefined thresholds. The collected information can be transmitted to cloud-based platforms where it can be visualised and analysed for management decisions. In aquaculture, real-time monitoring can facilitate rapid responses to environmental stress and reduce the risk of production losses. At the ecosystem level, smart monitoring can strengthen the assessment of pollution, eutrophication and other environmental disturbances and provide timely information for aquatic resource management (Patra et al., 2024).

Conclusion

Aquatic environment management is essential for maintaining ecosystem health, conserving biodiversity and supporting sustainable fisheries and aquaculture production. Increasing pollution, eutrophication, habitat degradation, climate change and emerging contaminants require integrated approaches that combine pollution prevention, wastewater treatment, water-quality monitoring, habitat restoration and sustainable resource utilization. Sustainable aquaculture practices such as effluent treatment, water recycling, biofloc technology, recirculating aquaculture systems and integrated production approaches can reduce environmental pressures while improving resource-use efficiency. At the same time, artificial intelligence, IoT, remote sensing, GIS, smart monitoring and precision aquaculture are providing new opportunities for real-time assessment, early warning and data-driven management. The effective integration of conventional environmental management with these emerging technologies, supported by scientific monitoring, stakeholder participation and appropriate regulatory frameworks, can strengthen the resilience of aquatic ecosystems. Such integrated management is important for achieving a balance between aquatic resource conservation, environmental protection and the long-term development of sustainable fisheries and aquaculture.

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