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Fish as sentinel species for riverine ecosystem health assessment and conservation management

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Abstract

Freshwater ecosystems are increasingly threatened by anthropogenic activities, including pollution, habitat fragmentation, hydrological alterations, climate change, and others, especially in the case of rivers. Fish occupy a range of trophic levels and possess varied sensitivities to environmental stressors, making them excellent sentinels for evaluating and monitoring the health of these dynamic ecosystems. In this context, we review the current knowledge on the integration of fish-based biomonitoring, ecotoxicological approaches, and conservation strategies, to provide a holistic framework for river ecosystem management. The paper reviews existing and emerging biomonitoring techniques, from traditional indices such as the Index of Biotic Integrity (IBI) and multimetric assessments to advanced molecular and omics tools (e.g., transcriptomics, metabolomics, and eDNA metabarcoding) that allow early detection of sublethal effects and community-level shifts. Reviews are provided on ecotoxicological perspectives, including bioaccumulation of contaminants (heavy metals, pesticides, pharmaceuticals and microplastics), biomarker responses (histopathological, physiological and genetic) and complex interactions of multiple stressors. The ways in which these data contribute to causal diagnosis of ecosystem degradation and risk assessment are considered. Moreover, the review connects monitoring science to on-the-ground conservation by showcasing successful case studies where fish sentinel data have resulted in policy changes, habitat restoration, protected area establishment and species recovery programs. Critical discussions of challenges including data standardization, integration of big data analytics, climate-induced range shifts, and the need for interdisciplinary approaches. The paper argues for a “One Health” paradigm that connects fish health, ecosystem integrity and human well-being, and suggests an integrated framework for adaptive management of river basins globally.

This review highlights the importance of fish as key indicators in the transfer of scientific knowledge to successful conservation results, ultimately leading to the sustainable management and restoration of threatened freshwater ecosystems.

Keywords: Fish sentinels, Freshwater biomonitoring, River ecosystem health, Ecotoxicology, Bioindicators, Index of Biotic Integrity, Invasive species, Climate adaptation, eDNA, Conservation strategies, Environmental biomarkers, Aquatic toxicology, Sustainable fisheries, River restoration

1. Introduction

Rivers and freshwater streams are among the most biodiverse and ecologically important ecosystems on the planet, covering less than 1% of Earth's surface but supporting about 10% of all known species and over one-third of all vertebrate species (Reid *et al.*, 2019) ^[41]. Freshwater biodiversity is declining at a rate two to three times faster than terrestrial or marine biodiversity (WWF, 2022) ^[53] due to habitat fragmentation, diffuse and point-source pollution, overextraction, invasive species and climate change. These interacting stresses pose serious risks to freshwater biota, as well as to the billions of humans who depend on river systems for food, water, and livelihoods. Fish within freshwater assemblages span trophic levels and ecological guilds and are therefore particularly sensitive to environmental change. Fish have been the backbone of biological assessment programs around the world (Pont *et al.*, 2021) ^[36] due to their sensitivity to physicochemical perturbations, visibility, ecological diversity and policy relevance. Karr (1981) ^[24] formalised the use of fish community structure as a means of inferring water quality through the development of the Index of Biotic Integrity (IBI), which has since been developed into dozens of regional variants and forms the basis for legislative bioassessment frameworks such as the European Union's Water Framework Directive (WFD 2000/60/EC).

At the same time, advances in ecotoxicology have resulted in a range of molecular, cellular and physiological biomarkers in fish that allow the detection of specific pollutant classes at sublethal concentrations, providing mechanistic insights into cause-effect relationships (Sumpter, 2020) ^[45]. Fish biomonitoring is currently undergoing a revolution thanks to environmental DNA (eDNA) and metabarcoding approaches, which allow for rapid and non-invasive assessments of biodiversity at an unprecedented taxonomic resolution (Deiner *et al.*, 2017; Jerde, 2021) ^[10, 22].

This review provides an extensive synthesis of fish as bio-indicators at various levels of biological organization, from molecular biomarkers to assemblage-level indices, and critically discusses the major stressors threatening freshwater fish biodiversity. We evaluate the strengths and weaknesses of existing biomonitoring frameworks, discuss emerging methodological frontiers, and propose evidence-based conservation and management practices. We place our synthesis in the context of achieving the Kunming-Montreal Global Biodiversity Framework targets for freshwater ecosystems by 2030 (CBD, 2022) ^[7].

2. Ecological Functions of Fish in River Ecosystem

Fish are not passive players in aquatic ecosystems but are active agents that fundamentally influence ecosystem structure, function and resilience across temporal and spatial scales. Ecologically, they contribute to nutrient cycling, energy flow, habitat modification, seed and propagule dispersal, and top-down regulation of food webs.

2.1 Food web dynamics and food chain regulation

Fish in river food webs often play roles of primary consumers (algivores, detritivores), secondary consumers (invertivores) and top predators within a single ecosystem, with the capacity to occupy multiple trophic levels simultaneously. This trophic versatility allows fish to play a role as mediators in the transfer of energy from primary producers to higher vertebrates such as waterbirds and riparian mammals (Holmlund & Hammer, 1999) ^[18]. Apex predatory fish such as pike (*Esox lucius*) and salmonids exert top-down cascading effects in regulating prey population dynamics, maintaining species diversity via trophic cascade mechanisms and can indirectly promote primary productivity by controlling herbivore populations (Post *et al.*, 2019) ^[37].

Removal or addition of key fish species cause trophic cascades that have ecosystem-wide consequences. Layman *et al.* (2021) ^[25] experimentally removed piscivorous fish in Bahamian tidal creeks, and observed dramatic increases in biomass of small fish and invertebrates, and subsequent destabilization of benthic algal communities. Cascades like these illustrate the keystone roles that some fish species play in maintaining ecological balance.

2.2. Cycling of nutrients and productivity of ecosystems

Fish are mobile nutrient vectors within and between ecosystems, actively transporting nitrogen, phosphorus and carbon across spatial gradients that would otherwise be biologically unavailable (Capps *et al.*, 2018) ^[6]. In nutrient-limited systems fish excrete and egest dissolved inorganic nitrogen and phosphorus at rates that can equal or exceed

allochthonous inputs (McIntyre *et al.*, 2008) ^[29]. Migratory anadromous species, such as Pacific salmon (*Oncorhynchus* spp.), provide large amounts of nitrogen and phosphorus accumulated during oceanic feeding phases to subsidize oligotrophic headwater streams with marine-derived nutrients. The carcasses of spawned salmon support riparian plant communities, invertebrate assemblages and dozens of vertebrate scavengers (Quezada-Romegialli *et al.*, 2023) ^[39]. Feeding fish like common carp (*Cyprinus carpio*) and catfish (*Siluriformes*) bioturbate sediments, making nutrients available in the water column and boosting phytoplankton productivity, but in nutrient-enriched systems this can also mean faster eutrophication (Andreassen *et al.*, 2021) ^[1]. This dual ecological role underlines the context-dependency of fish-mediated nutrient cycling.

2.3 Habitat modification

Many fish species are ecosystem engineers, physically modifying substrates and creating structural complexity that provides benefits to a broader suite of organisms. Salmon redd (nest) construction assists in aerating gravels, flushing fine sediments and enhancing hyporheic water exchange that maintains dissolved oxygen for egg incubation (Hassan *et al.*, 2008) ^[16]. Burrowing catfish and freshwater eels influence sediment structure and porosity, creating refugia for macroinvertebrates and stimulating denitrification rates in streambed sediments (O'Connor *et al.*, 2020) ^[34]. Herbivorous fish (e.g. suckers, Catostomidae) graze epilithic biofilms, preventing periphyton from becoming overly abundant and maintaining diversity in benthic algal communities (Power 1990) ^[38].

3. Fish as Biological Indicators: Mechanisms and Models

Fish are useful as biological indicators because they integrate physicochemical and biological stressors over long temporal and spatial scales. Water chemistry measurements are point-in-time snapshots, whereas fish assemblages and biomarker profiles reflect cumulative exposure histories, and thus offer temporally integrated assessments of ecosystem condition (Pont *et al.*, 2021) ^[36].

3.1 Biomonitoring Indices at the Community Level

The Index of Biotic Integrity was initially proposed by Karr (1981) ^[24] and incorporates 12 metrics of species richness, composition, trophic structure, and fish abundance to evaluate ecological condition relative to reference site benchmarks. The IBI and its many regional variants are the most commonly used fish-based bioassessment tool globally and underpin water quality legislation in the United States, the European Union and increasingly in Asia and Latin America (Minns *et al.*, 2022; Li *et al.*, 2021) ^[30].

The European FAME (Fish-Based Assessment Method for the Ecological Status of European Rivers) framework, revised under WFD guidance in 2022, is based on guild-based metrics calibrated to each of the major river types within pan-European reference networks. Pont *et al.* (2021) ^[36] evaluated 23 national fish-based indices and showed convergent validity with WFD ecological status classifications, in support of harmonized crossborder monitoring. Table 1 Comparative overview of major biomonitoring indices currently in use.

Table 1: Major Fish-Based Biomonitoring Indices — Comparative Overview

Index Name	Origin / Reference	Key Metrics	Strengths / Limitations
Index of Biotic Integrity (IBI)	Karr (1981); updated Minns <i>et al.</i> 2022 [24, 30]	Species richness, trophic guilds, fish abundance metrics	Widely used; needs regional calibration
Fish-Based Biotic Integrity (FBI)	Hughes <i>et al.</i> 2002	Guild-based assessment of fish assemblage	Effective in large river systems
Multi-Metric Index (MMI)	Pont <i>et al.</i> 2021 [36]	Combines taxonomic, functional, abundance metrics	Comprehensive; computationally intensive
Fish Assemblage Index (FAI)	Li <i>et al.</i> 2021	Assemblage response to gradient stressors	Good for gradient studies
FAME (Fish Assessment for European rivers)	Pont <i>et al.</i> 2006; revised 2022	EU Water Framework Directive compliance	Pan-European standardization
Ecological Status Ratio (ESR)	WFD 2022 revisions	Ratio of observed to expected fish fauna	Policy-aligned, regulation driven

3.2 Physiological and Biochemical Markers

Biomarkers in fish provide mechanistic connections between classes of pollutants and biological effects, enabling source-directed remediation and supporting ecological risk assessment. Fish ecotoxicology has developed a hierarchy of biomarkers at the molecular, cellular, and organ levels, each with different temporal sensitivity to chemical exposure (van der Oost *et al.*, 2003; Sumpter, 2020) [45]. The cytochrome P450 enzyme EROD (ethoxyresorufin-O-deethylase) is highly upregulated in liver tissue after exposure to polycyclic aromatic hydrocarbons (PAHs), dioxins, and PCBs, providing sensitive biomarker evidence of aromatic hydrocarbon contamination at concentrations below acute toxicity

thresholds (Whyte *et al.*, 2000) [52]. Inhibition of acetylcholinesterase (AChE) in both brain and muscle tissue is a diagnostic biomarker of organophosphate and carbamate pesticide exposure, with significant sublethal effects on swimming performance and predator avoidance behavior (Faria *et al.*, 2022) [13]. Expression of the female-specific egg yolk precursor protein vitellogenin in male fish has become the canonical biomarker for estrogenic endocrine-disrupting chemicals (EDCs), with its occurrence documented in rivers receiving municipal wastewater effluents in Europe, North America, and Asia (Sumpter, 2020; He *et al.*, 2023) [45, 17]. Table 2 represents systematic review of biomarkers used in fish ecotoxicology.

Table 2: Biomarkers in Fish-Based Ecotoxicological Assessment

Category	Biomarker	Tissue / Matrix	Contaminant / Stress Detected
Enzymatic	AChE (Acetylcholinesterase)	Brain, muscle tissue	Organophosphate & carbamate pesticide exposure
Enzymatic	EROD (Ethoxyresorufin-O-deethylase)	Liver microsomes	PAH & dioxin contamination (CYP1A induction)
Genotoxic	Micronucleus frequency	Erythrocytes	Genotoxic pollutants, clastogenic agents
Genotoxic	DNA strand breaks (Comet assay)	Gill, liver cells	Heavy metals, oxidative stress
Oxidative Stress	MDA (Malondialdehyde)	Liver, gill tissue	Lipid peroxidation from ROS-generating pollutants
Oxidative Stress	SOD / CAT / GPx activities	Liver	General oxidative stress from pollutants
Endocrine	Vitellogenin (VTG)	Plasma (males)	Estrogenic compounds, EDCs
Histopathological	Gill lamellar fusion, liver necrosis	Tissue sections	Chronic exposure to effluents, metals
Behavioral	Altered swimming, avoidance response	Behavioral assays	Sublethal toxicant concentrations

3.3. Biomarkers of Behavior

Fish behavior is a sensitive and ecologically relevant indicator of sublethal stress that bridges the gap between molecular effects and population level consequences. Pesticides, heavy metals, pharmaceuticals and microplastics have been shown to cause altered swimming kinematics, reduced antipredator responses, disordered shoaling behaviour and modified olfaction-mediated homing navigation in fish (Brodin *et al.*, 2013) [5]. Brodin *et al.* (2013) [5] showed that brown trout (*Salmo trutta*) exposed to environmentally relevant concentrations of the anxiolytic drug oxazepam showed reduced sociality, increased risk-taking and faster feeding rates - behavioural changes with direct fitness consequences in natural systems. Behavioral bioassays associated with eDNA are emerging as non-invasive complements to traditional collection-based biomarker studies (Jerde, 2021) [22].

3.4 Environmental DNA and Genomic Methods

Environmental DNA (eDNA) metabarcoding, the sequencing of genetic material shed into water by fish, is a paradigm shift in aquatic biomonitoring, allowing the detection of rare, cryptic, and invasive species with sensitivity greater than traditional netting approaches

(Deiner *et al.*, 2017; Jerde, 2021) [10, 22]. eDNA-based fish assessments have been validated against conventional electrofishing surveys in rivers across Europe, North America and Asia, providing comparable species richness estimates with substantially reduced sampling effort and without the physical impacts of active sampling. Near-real-time biodiversity monitoring of remote river systems is now being enabled by the combination of eDNA approaches with long-read nanopore sequencing and portable field laboratories (Deiner *et al.*, 2017) [10]. Transcriptomic and metabolomic profiling of fish tissues allows for the comprehensive and unbiased assessment of cellular stress responses and mechanism-of-action characterization of pollutants in fish tissues. These ‘omics’ approaches are increasingly being validated as regulatory biomarker tools, though challenges of data standardization, reference database completeness and cost remain for routine monitoring applications (Santos *et al.*, 2020) [42].

4. Indicator Fish Species and Their Ecological Importance

Different species of fish have different tolerances to environmental stressors, which allows the use of biotic integrity frameworks that weight species by their ecological

sensitivity or tolerance. For example, salmonids sit at one end of the sensitivity spectrum, requiring cool, well-oxygenated, unpolluted waters, whereas cyprinids such as

carp are broadly plastic and tolerant of degraded conditions. Table 3 Representative indicator species used in freshwater bioassessment programs of different biogeographic regions.

Table 3: Key Indicator Fish Species, Ecological Significance, and Associated Threats

Species (Common Name)	Family	Indicator Value	Primary Threats
<i>Oncorhynchus spp.</i> (Salmon)	Salmonidae	Clean, cold, oxygen-rich water	Habitat degradation, dam construction
<i>Salmo trutta</i> (Brown Trout)	Salmonidae	Sensitive to heavy metals, thermal stress	Acidification, pollution
<i>Micropterus salmoides</i> (Largemouth Bass)	Centrarchidae	Trophic balance, apex predator status	Eutrophication, invasive species
<i>Cyprinus carpio</i> (Common Carp)	Cyprinidae	Tolerant; elevated abundance = degraded water	Exotic introductions
<i>Labeo rohita</i> (Rohu)	Cyprinidae	Indian riverine health indicator	Overfishing, siltation
<i>Catla catla</i> (Catla)	Cyprinidae	Surface feeder; reflects plankton availability	Pollution, habitat loss
<i>Gambusia affinis</i> (Mosquitofish)	Poeciliidae	Tolerates hypoxia; signals low water quality	Invasive, displaces natives
<i>Danio rerio</i> (Zebrafish)	Cyprinidae	Lab model; bio-sentinel for endocrine disruptors	Laboratory-derived data limitations

5. Threats to Biodiversity of Freshwater Fish

Freshwater fish diversity is subject to a multitude of often interacting stressors operating at local, catchment and global scales. A recent global analysis estimated that 80% of the world's river systems are under moderate-to-severe threat to freshwater biodiversity (Vörösmarty *et al.*, 2010) ^[49], with conditions further deteriorating in the intervening decade. Table 4 summarizes the main threat categories, their key drivers, ecological impacts and associated management responses.

5.1 Habitat Loss and Fragmentation

Physical habitat alteration by dam construction, river channelization, floodplain drainage, and riparian land clearance is the most widespread threat to riverine fish worldwide. Dams and diversions fragment > 60% of the world's large river systems to a moderate or severe extent (Nilsson *et al.*, 2005) and the Global Dam Watch database shows that > 60,000 large dams were in operation by 2024.

Table 4: Major Threats to River Ecosystems and Integrated Management Responses

Threat Category	Primary Drivers	Ecological Impact	Management Response
Habitat Loss	Dam construction, channelization, floodplain encroachment	Fish passage obstruction, spawning ground loss, thermal alteration	Fish passes & ladders; environmental flow regimes; riparian buffer restoration
Water Pollution	Agricultural runoff (N, P), industrial effluents, pharmaceuticals, microplastics	Eutrophication, hypoxic dead zones, bioaccumulation, endocrine disruption	Constructed wetlands; effluent standards; green chemistry initiatives
Overfishing	Commercial fleets, illegal fishing, by-catch	Stock depletion, genetic diversity loss, trophic cascades	Total Allowable Catch (TAC), size limits, seasonal closures, MPAs
Climate Change	Temperature rise, altered precipitation, extreme events	Thermal stress, poleward range shifts, mismatched phenology	Assisted migration corridors; thermal refugia protection; emission reduction
Invasive Species	Ballast water, aquaculture escapes, intentional introductions	Competitive exclusion, predation on natives, disease vectors	Biosecurity regulations; rapid response eradication; public awareness
Microplastic Pollution	Urban runoff, synthetic textile fibers, plastic degradation	Gut blockage, endocrine disruption, trophic transfer	Extended Producer Responsibility laws; wastewater filtration upgrades

Dams hinder the migration of fish, change thermal regimes, remove flood pulses needed for spawning on floodplains, and convert lotic (flowing water) communities into lentic (still water) communities (Poff *et al.*, 1997; Grill *et al.*, 2019) ^[15]. In India, dam construction over the Ganga, Brahmaputra and Mahanadi river systems over the last four decades and more, has led to a > 50% reduction in populations of hilsa (*Tenualosa ilisha*) and mahseer (Tor spp.) (Molur *et al.*, 2011) ^[31].

5.2 Degradation of Water Quality and Emerging Contaminants

Agricultural non-point source pollution, mainly nitrogen and phosphorus from fertilizer use and livestock waste, is the main cause of eutrophication in rivers and reservoirs across the globe, resulting in algal blooms, hypoxic dead zones, and fish kills (Diaz & Rosenberg, 2008) ^[11]. However, a complex mixture of emerging contaminants of concern (CECs), including pharmaceuticals, personal care products, microplastics and per- and polyfluoroalkyl substances

(PFAS) that are not removed by conventional wastewater treatment are increasingly co-occurring with conventional nutrient and heavy metal pollutants (Baho *et al.*, 2022) ^[3]. Microplastic pollution has been reported in freshwater fish on all continents and the reported effects include physical gut blockage, inflammatory responses, endocrine disruption and oxidative stress at ecologically relevant concentrations (Horton *et al.*, 2018; Limonta *et al.*, 2022) ^[19, 27].

5.3 Impacts of Climate Change

Climate change exacerbates the threat to freshwater fish through altered thermal regimes, seasonal flows, increased frequency of extreme events and the geographic distribution of invasive species. As water temperatures warm, coldwater specialists, including salmonids, are being forced to find thermal refugia at higher elevations and latitudes, with model projections showing 20-40% range contractions under RCP 4.5 and RCP 8.5 scenarios by 2100 (Comte & Olden, 2017; Myers *et al.*, 2022) ^[8, 32]. Changes in precipitation regimes are exacerbating hydrological

variability, with predictions of increased frequency and severity of droughts in river systems with exceptional fish endemism under Mediterranean, semi-arid and monsoon influences (Markovic *et al.*, 2023) ^[28]. Phenological mismatches - in terms of fish spawning, insect emergence and flood pulse timing - are emerging as mechanistic pathways through which climate change reduces recruitment success even in the absence of direct thermal lethality (Jonsson & Jonsson, 2022) ^[23].

5.4 Unsustainable Harvesting and Overfishing

Overexploitation of inland fisheries is a major cause of declines in freshwater fish populations worldwide, even if it is less visible than the collapse of marine fisheries. More than 600 million people obtain nutrition security from inland fisheries, especially in South and Southeast Asia, Sub-Saharan Africa and the Amazon basin where subsistence and small-scale commercial fisheries are essential for rural livelihoods (FAO, 2022). Illegal, unreported and unregulated (IUU) fishing practices, including the use of destructive gear such as electrofishing, poison fishing and fine-meshed nets, remove immature fish before they have had a chance to reproduce, weakening population resilience and genetic diversity (Pinder *et al.*, 2019) ^[35]. Rapid introduction of commercial fishing pressure on previously unexploited lake and river systems is being driven by urban market expansion and refrigeration technology, resulting in the depletion of stocks in areas with limited monitoring capabilities (FAO, 2022).

5.5 Water Plants Invaders

Invasive fish are one of the most difficult-to-reverse threats to freshwater biodiversity with pathways including deliberate releases for aquaculture or sport fishing, accidental releases from the aquarium trade, and transport in ballast water (Gozlan *et al.*, 2010) ^[14]. The European native brown trout (*Salmo trutta*) has been introduced to highland streams in Australia, New Zealand, South Africa and the Himalayas, and has been implicated in the local extinction of over 30 native fish species through competitive exclusion and predation (Townsend, 1996) ^[47]. Bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*H. molitrix*) were introduced into North American river systems as an aquaculture species and for water quality management and have rapidly invaded the Mississippi River basin, outcompeting native filter feeders and altering zooplankton communities (Irons *et al.*, 2007; Brandner *et al.*, 2023) ^[21, 4].

6. Strategies of conservation and management

Conservation of freshwater fish biodiversity will need multi-scale adaptive management frameworks that address the proximate drivers of decline as well as the underlying socio-economic and governance factors that enable overexploitation and environmental degradation. The following sections present evidence-based strategies in line with the Kunming-Montreal Global Biodiversity Framework's 2030 targets and the UN Sustainable Development Goals (SDGs 6, 14, 15).

6.1 Protected Area Networks and Freshwater Reserves

Freshwater protected areas lag far behind their terrestrial and marine counterparts with only about 17% of the world's

river networks within protected area boundaries and even fewer with effective management for aquatic biodiversity (IUCN, 2022). Research on freshwater protected areas in the Amazon basin, the Mekong River, and the Congo River demonstrates that well-managed reserves increase fish species richness by 20-40%, increase recruitment of commercially important species and provide resilience to climate change stressors (Arthington *et al.*, 2018; FAO, 2022) ^[2, 7]. The Kunming-Montreal targets (CBD, 2022) emphasize the identification of 'freshwater Key Biodiversity Areas' (KBAs) containing endemic, threatened, and ecologically important fish assemblages.

6.2 Environmental Flow Regimes

Environmental flows (e-flows) — the volume, timing, duration and quality of water flows required to sustain freshwater ecosystems — are a key management tool to mitigate the impacts of dam regulation and water extraction on fish. Environmental flows are now a core part of water resource governance following the Brisbane Declaration and Global Action Agenda on Environmental Flows (2018) and implementation frameworks are now required in the European Union, South Africa, Australia and increasingly, India (Arthington *et al.*, 2018) ^[2]. Tennant *et al.* (2022) ^[46] showed that environmental flow releases in the Murray-Darling Basin restored breeding migrations of golden perch (*Macquaria ambigua*) and Murray cod (*Maccullochella peelii*) within two seasons of implementation.

6.3 Restoration of Habitat

Active restoration of habitats, including riparian revegetation, large wood recruitment, in-channel habitat enhancement, removal of obsolete dams, and reconnection of floodplains, results in measurable benefits to fish assemblages within 3-10 years. A meta-analysis of 189 stream restoration projects in North America and Europe showed significant increases in salmonid density after large wood addition and pool-riffle structure restoration (Radinger *et al.*, 2019) ^[40]. Dam removal has become a powerful restoration tool in Europe and North America, and there is evidence of fish passage recovery on the Elwha River (USA) after removal of two large dams, which allowed Chinook salmon to return to 90 km of habitat that had been inaccessible for five years (Warrick *et al.*, 2015) ^[51].

6.4 Sustainable Fisheries Stewardship

To ensure inland fishery productivity and ecosystem integrity, fisheries management needs to be evidence-based and includes science-based total allowable catch (TAC) limits, minimum mesh sizes, seasonal fishing closures and community-based co-management arrangements. The integrated fisheries assessment program of the Mekong River Commission that employs telemetry tracking, acoustic surveys and participatory fisheries monitoring offers a model for transboundary fisheries governance in large tropical river systems (Pinder *et al.*, 2019; FAO, 2022) ^[35]. Community-based approaches to fishery management, in which local fishing communities are vested with management authority with scientific support from government and NGO partners, have shown particular efficacy in South and Southeast Asian river systems where formal regulatory capacity is limited (Cooke *et al.*, 2021) ^[9].

6.5 Design of a Biomonitoring Program and the Biomonitoring Framework

Standardized sampling protocols, adequate reference site networks, statistically robust index calibration and clearly defined ecological quality objectives linked to regulatory

thresholds are all essential for effective fish-based biomonitoring. Figure 1 is a flowchart of the recommended seven-step framework for implementing a fish-based biomonitoring program from site selection to policy recommendations.

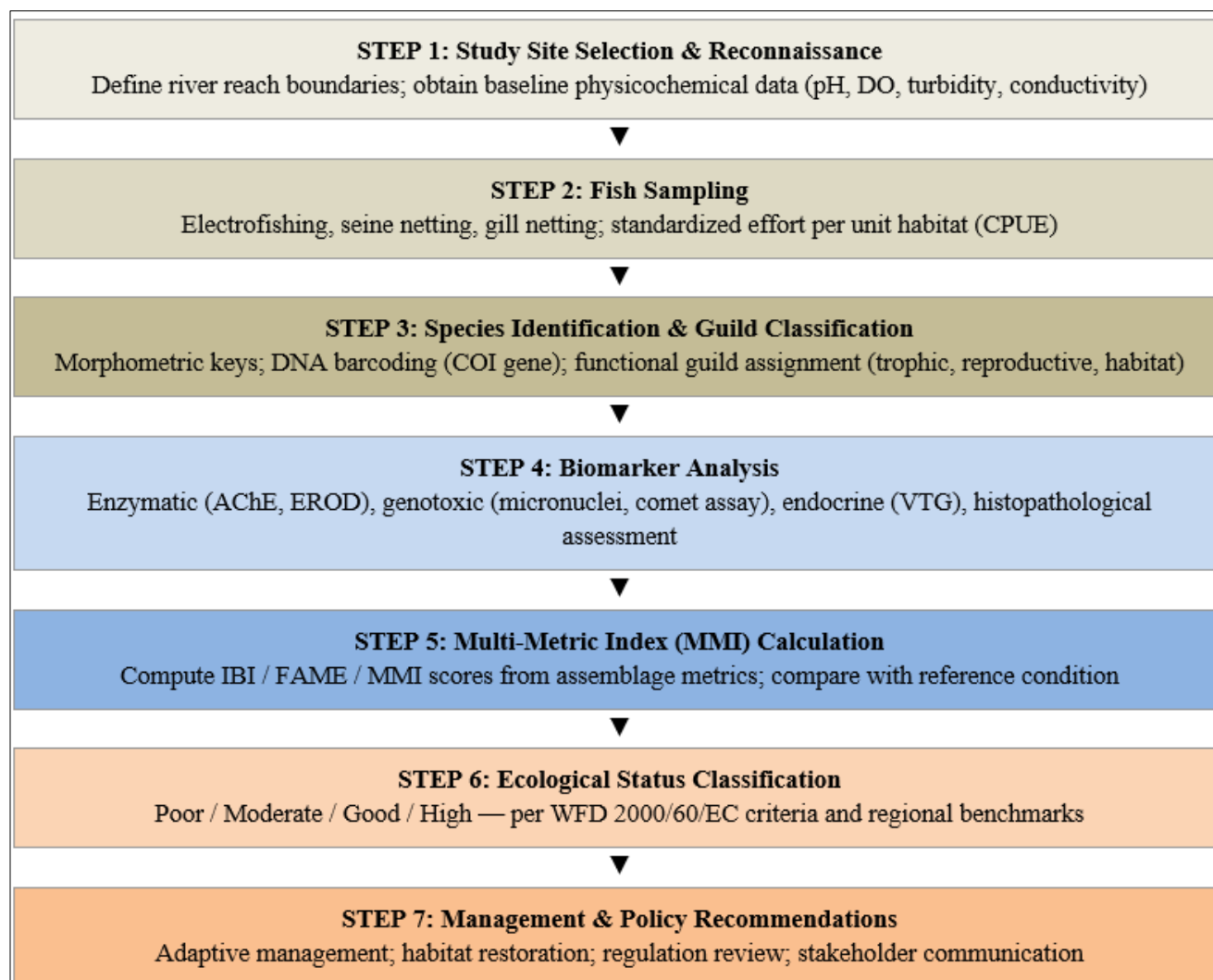


Fig 1: Fish-Based Biomonitoring Framework — Seven-Step Decision Process

Figure 2 presents a complete decision framework for conserving fish habitat based on identification and assessment of major ecological threats to freshwater ecosystems. The framework starts with an ecological risk assessment, which measures the severity and effect of different stressors, including habitat loss, pollution, overfishing, invasive species and climate change. To mitigate habitat loss and fragmentation, management strategies include installing fish passages, restoring riparian buffer zones and regulating environmental flows to preserve habitat connectivity and ecological integrity. Point source pollution is managed through strict effluent treatment standards, continuous monitoring using biomarkers and reducing pollutant discharges at source. Best management practices, construction of wetlands and establishment of vegetated filter strips reduce nutrient and sediment inflow into aquatic systems, mitigates non-point source pollution,

particularly from agricultural runoff. These regulatory measures include total allowable catch (TAC) quotas, seasonal fishing closures, gear restrictions, and community-based co-management, all of which are designed to help combat overfishing and maintain sustainable fish populations. Management of invasive species involves quick-response removal programs, enforcement of biosecurity regulations, and research into mechanisms of competitive exclusion. Further, climate change related stressors are addressed through protection of thermal refugia, assisted colonization of vulnerable species, and advocacy for emission reduction strategies. This framework results in an adaptive management plan that includes continuous monitoring, evaluation and review cycles every 3-5 years to ensure dynamic and science-based conservation of fish habitats and aquatic biodiversity.

Conservation Decision Framework for Fish Habitat Management	
THREAT IDENTIFIED	Ecological Risk Assessment
Habitat Loss / Fragmentation	→ Fish Passage Installation, Riparian Buffer Restoration, Environmental Flow Regulation
Pollution (Point Source)	→ Effluent Treatment Standards, Regular Biomarker Monitoring, Source Abatement
Pollution (Non-Point Source)	→ Agricultural Best Management Practices, Constructed Wetlands, Vegetated Filter Strips
Overfishing	→ TAC Quotas, Seasonal Closures, Gear Restrictions, Community Co-management
Invasive Species	→ Rapid Response Removal, Biosecurity Regulations, Competitive Exclusion Research
Climate Change Stressors	→ Thermal Refugia Protection, Assisted Colonization, Emission Reduction Advocacy
OUTCOME: Adaptive Management Plan → Monitoring → Review Cycle (3–5 years)	

Fig 2: Conservation Decision Framework for Fish Habitat Management

7. New Frontiers and Future Directions

7.1 Remote Sensing and Machine Learning Integration

Recent advances in satellite-based remote sensing, including hyperspectral water quality mapping, LiDAR-based floodplain topography, and synthetic aperture radar for river morphology, are enabling the quantification of landscape-scale drivers of fish assemblage change at an unprecedented spatial resolution (Wang *et al.*, 2022) ^[50]. Integrated remote sensing and biological datasets are being used to train machine learning algorithms, such as random forest classifiers and convolutional neural networks, to predict IBI scores across unsampled river segments, enabling whole-catchment ecological status mapping without proportional increases in field sampling cost (Radinger *et al.*, 2019; Myers *et al.*, 2022) ^[40, 32].

7.2 Environmental DNA on a Large Scale

The emergence of automated eDNA samplers and real-time metabarcoding using portable nanopore sequencers has the potential to transform fish biomonitoring from expensive episodic sampling campaigns to continuous high-frequency surveillance networks. One of the most direct practical uses of eDNA technology in freshwater management is the early-warning detection of invasive species prior to populations reaching detectable densities via traditional sampling (Jerde, 2021) ^[22]. Ongoing research topics are standardization challenges, matrix effects in turbid rivers and the conversion of species detection to ecological status classifications.

7.3 Microbiome-Fish Interactions as Indicators of Ecosystem

The gut and skin microbiome of freshwater fish is now recognized as a sensitive composite indicator of environmental condition, combining signals from multiple stressors, such as exposure to pollutants, temperature stress and pathogen pressure, into a measurable biological response (Sullam *et al.*, 2022) ^[44]. Antibiotic, herbicide, and heavy metal exposure at environmentally relevant

concentrations has been linked to immunosuppression, disease susceptibility, and altered behavior in fish and associated with dysbiosis of the fish microbiome. 16S rRNA amplicon sequencing based fish microbiome profiling is a scalable and cost-effective complement to traditional biomarker analysis in regulatory monitoring programs.

7.4 Transdisciplinary Approaches and Indigenous Knowledge

Long-term fish biomonitoring programs, which may involve decades of data collection across entire river systems, require transdisciplinary collaborations that integrate ecological science with social science, economics, governance, and traditional ecological knowledge (TEK). Indigenous and local community knowledge of historical fish abundance, seasonal migration patterns and habitat use is often the only long-term baseline available with which to compare contemporary surveys (Saunders & Dulvy, 2024) ^[43]. The Yukon River salmon monitoring program and Australian Indigenous Ranger fisheries programs are examples of co-designed monitoring programs that give communities meaningful roles in data collection, interpretation and management decision-making and have shown superior long-term data continuity and management compliance compared to purely government-administered approaches (Cooke *et al.*, 2021) ^[9].

8. Conclusion

As they integrate environmental changes across multiple trophic levels, temporal scales and habitat conditions, fish are one of the most reliable and scientifically robust indicators of freshwater ecosystem integrity. This review has illustrated how fish-based biomonitoring has evolved in four decades from single metric water quality proxies to complex multi-scale multi-metric frameworks to assess the condition of an ecosystem at molecular, physiological, assemblage and landscape scales. Fish are long lived organisms that occupy a wide variety of ecological niches

and are sensitive to changes in hydrology, water chemistry, habitat fragmentation, thermal stress, nutrient enrichment, toxic contamination and biological invasions. They are thus important socio-economic and cultural resources linking ecological sustainability with human well-being and environmental governance, as well as biological indicators of ecosystem health. Over the last 40 years, fish-based biomonitoring has advanced from conventional species richness surveys and simplistic water quality indicators to highly sophisticated multi-metric frameworks that encompass physiological biomarkers, histopathology, reproductive impairment, trophic dynamics, genetic diversity and landscape-scale ecological modelling. Recent technological advances are changing freshwater conservation science. Now environmental DNA (eDNA) metabarcoding enables rapid, non-invasive detection of rare, cryptic and invasive species with unprecedented sensitivity. At the same time, artificial intelligence and machine learning algorithms are becoming increasingly able to predict biodiversity loss, identify ecological thresholds and optimize conservation interventions in the context of climate uncertainty. Molecular ecotoxicology enhances monitoring capacity by delineating the sub-lethal effects of contaminants on gene expression, endocrine function, oxidative stress pathways and developmental processes prior to the emergence of visual signs of ecosystem collapse. Such innovations, however, cannot in themselves safeguard freshwater biodiversity. Effective conservation requires stronger institutional frameworks, standardized global monitoring protocols, equitable financial investment, and enhanced scientific capacity in developing nations where freshwater ecosystems are under the greatest anthropogenic pressures. Equally important is involving Indigenous peoples and local communities in participatory river governance and adaptive management strategies. Meeting the targets of the Kunming-Montreal Global Biodiversity Framework and restoring resilient “living rivers” by 2030 will require unprecedented international cooperation, policy integration and ecological stewardship. In the end, fish will remain the long-term ecological sentinels that will reveal whether or not humanity’s commitment to maintaining freshwater ecosystems has succeeded or failed in an era of accelerating environmental change.

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