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A multiple-stressor syndrome approach to aquatic ecosystem management and restoration

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ABSTRACT

Aquatic ecosystems are increasingly exposed to interacting anthropogenic and climatic pressures that jointly alter water quality, biodiversity, hydrological regimes, habitat structure, and ecosystem functioning. Although single-stressor approaches remain useful for regulatory monitoring and experimental control, they are insufficient for explaining real-world degradation, where pollution, flow alteration, habitat simplification, biological invasions, and climate extremes often co-occur. This narrative review synthesizes recent evidence on multiple stressors in aquatic ecosystems and proposes the concept of multiple-stressor syndromes as a framework for diagnosing recurrent clusters of interacting pressures across rivers, lakes, reservoirs, wetlands, floodplains, estuaries, and tropical freshwater systems. The review argues that stressor syndromes are not merely additive combinations of pressures; rather, they are context-dependent configurations shaped by land use, hydrological connectivity, geomorphology, climatic exposure, governance, and legacy disturbance. By advancing a syndrome-based framework, this review contributes to multiple-stressor research by shifting the focus from classifying interaction types alone toward diagnosing recurring stressor clusters, their dominant drivers, ecological mechanisms, response pathways, and management leverage points. This diagnostic framing complements existing work on additive, synergistic, and antagonistic effects by making multiple-stressor science more directly applicable to water-quality assessment, restoration prioritization, ecological risk analysis, and adaptive water governance. The review highlights four key needs for future research and management: greater attention to underrepresented tropical and low-income regions, stronger integration of biological and functional indicators into water-quality monitoring, improved understanding of stressor timing and lag effects, and field-scale evidence on which stressor reductions generate measurable ecological recovery.

Keywords: Multiple stressors, Aquatic ecosystems, Water quality, Freshwater biodiversity, hydrological alteration, Habitat degradation, climate change, Ecological resilience

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Introduction

Aquatic ecosystems are increasingly shaped by interacting pressures rather than isolated disturbances. Rivers, lakes, reservoirs, wetlands, floodplains, estuaries, and coastal transition zones receive pollutants from entire catchments while simultaneously experiencing habitat degradation, altered flow regimes, biological invasions, overexploitation, and climate extremes. These pressures affect water quality, biodiversity, hydrological connectivity, ecosystem functioning, and the services that aquatic systems provide to society [1,2]. Yet many monitoring and management systems still evaluate stressors separately, using parameters such as nutrients, dissolved oxygen, turbidity, conductivity, contaminants, or biological indices as discrete indicators of condition.

Single-stressor assessment remains useful for regulation and experimental clarity, but it is insufficient for explaining real-world aquatic degradation. Freshwater biodiversity decline is driven by interacting pressures, including pollution, habitat loss, flow modification, invasive species, overexploitation, and climate change [3,4]. Similarly, meta-analyses and cross-ecosystem syntheses show that combined stressor effects may be additive, synergistic, antagonistic, opposing, or dominated by one pressure, making ecological responses difficult to predict from individual stressors alone [5,6]. A river may meet nutrient targets but remain biologically impaired because channel structure, riparian cover, baseflow, thermal refugia, and source populations have been lost [7]. A reservoir may experience harmful algal blooms not only because of external nutrient loading, but because warming, stratification, long residence time, internal phosphorus release, hypoxia, and food-web change reinforce one another [8].

This review advances the concept of multiple-stressor syndromes as a diagnostic framework for aquatic ecosystems. A multiple-stressor syndrome is defined here as a recurrent, context-specific cluster of interacting physical, chemical, biological, hydrological, and climatic pressures that produces recognizable water-quality and ecological outcomes. The concept builds on established examples such as urban stream degradation but extends the logic across broader aquatic settings, including agricultural catchments, reservoirs, wetlands, regulated rivers, tropical freshwaters, and estuarine receiving waters. The value of the syndrome perspective is that it asks not only which stressors are present, but which stressors repeatedly co-occur, what drivers generate them, how they interact mechanistically, what ecological outcomes they produce, and which management actions are most likely to weaken them.

Existing multiple-stressor frameworks have primarily addressed three related questions: whether combined effects depart from an additive expectation; how effects vary among taxa, endpoints and spatial scales; and how drivers, pressures and ecological responses may be linked in management frameworks. Interaction-based approaches classify joint responses as additive, synergistic, antagonistic, dominant, opposing or reversal effects, and remain essential for hypothesis testing and ecological risk assessment. However, the statistical form of an interaction does not by itself explain why particular pressures repeatedly co-occur, which landscape or institutional drivers generate them, how legacy conditions maintain degradation, or which combination of interventions is most likely to produce recovery. The syndrome-based approach proposed here complements interaction analysis by treating recurrent stressor configurations as diagnostic units that link drivers, co-occurring pressures, mechanisms, ecological outcomes, indicators and management leverage points across ecosystem types. To clarify how the proposed framework relates to established approaches, **Table 1** summarizes how the proposed syndrome-based framework differs from, and complements, established multiple-stressor assessment approaches.

The original contribution of this review is threefold. First, it reframes multiple-stressor research from a primary focus on interaction categories, such as additive, synergistic, and antagonistic effects, toward a comparative framework based on recurring stressor clusters and ecological response pathways. Second, it organizes these clusters across ecosystem types, showing how urbanization, agricultural intensification, hydrological regulation, wetland drainage, tropical land-use change, and coastal development generate distinct but overlapping syndromes. Third, it links each syndrome to management leverage points, thereby connecting multiple-stressor ecology with practical decisions about water-quality monitoring, restoration prioritization, ecological risk assessment, and adaptive catchment governance. This responds to calls for more realistic, cross-scale, and management-relevant multiple-stressor research (9,10).

The aim of this narrative review is therefore to synthesize current understanding of multiple-stressor syndromes in aquatic ecosystems and to propose a framework for integrating water quality, ecological mechanisms, and management responses. Specifically, the review seeks to: (i) identify major stressor domains affecting aquatic ecosystems; (ii) describe recurrent stressor syndromes across ecosystem types; (iii) explain key mechanisms through which stressors interact; (iv) evaluate implications for monitoring, modelling, restoration, and governance; and (v) highlight research gaps and priorities for syndrome-based aquatic ecology and water management.

This article is a narrative review designed to synthesize concepts, mechanisms, and management implications rather than estimate pooled effect sizes. A narrative approach is appropriate because multiple-stressor research in aquatic ecosystems spans freshwater ecology, limnology, hydrology, ecotoxicology, restoration ecology, conservation science, water-quality management, and climate-impact research. Because this was not a systematic review, the search was not designed to provide an exhaustive study inventory or formal risk-of-bias assessment. The Scale for the Assessment of Narrative Review Articles (SANRA) criteria were used to improve the clarity of the review's aims, literature-search description, referencing, scientific reasoning and presentation [14]. The review prioritizes peer-reviewed literature from 2015–2026, while retaining selected foundational and high-impact studies where needed to define concepts or support synthesis. Searches were conducted in Scopus and Google Scholar. Searches were last updated on July 16, 2026. Literature was identified using combinations of terms including "multiple stressors," "freshwater ecosystems," "aquatic ecosystems," "water quality," "hydrological alteration," "habitat degradation," "pollution," "climate change," "eutrophication," "salinization," "urban stream syndrome," "wetland degradation," "environmental flows," "ecological resilience," and "adaptive water management."

Studies were considered most relevant when they addressed interacting stressors, cross-scale ecological responses, aquatic biodiversity, water-quality deterioration, restoration constraints, or management frameworks. The review focuses on inland and transitional aquatic systems, including streams, rivers, lakes, reservoirs, wetlands, floodplains, estuaries, and coastal receiving waters. Purely marine studies were considered only where they related directly to riverine inputs, estuarine processes, or coastal receiving-water impacts. Reference lists of relevant reviews and primary studies were also screened.

A multiple-stressor syndrome is defined here as a recurrent, context-specific cluster of interacting physical, chemical, biological, hydrological, and climatic pressures that produces recognizable water-quality and ecological outcomes. This concept complements, but does not replace, existing interaction typologies such as additive, synergistic, antagonistic, opposing, and dominant-stressor effects [5,6]. Its value lies in shifting the analytical question from "What is the statistical form of interaction?" to "Which stressors repeatedly co-occur, why do they co-occur, how do they affect ecological mechanisms, and which management actions can weaken the syndrome?"

The review is organized around a diagnostic framework linking drivers, stressor syndromes, mechanisms, ecological responses, and management leverage points. To guide the synthesis, the review applies the framework shown in **Figure 1**. The framework links upstream drivers to recurrent stressor syndromes, then traces how these syndromes operate through shared ecological mechanisms to produce characteristic ecosystem responses. The final stage identifies management interventions that can weaken stressor clusters or interrupt the mechanisms that sustain degradation. This framework responds to calls for multiple-stressor research that is more realistic, mechanistic, temporally explicit, and useful for prediction and management [9,10]

Major Stressor Domains in Aquatic Ecosystems

Aquatic stressor syndromes usually arise from the interaction of five broad stressor domains: chemical pollution, habitat degradation, hydrological alteration, climate-related stress, and biological disturbance. These domains are analytically separable but ecologically interdependent.

3.1 Chemical pollution and contaminant mixtures

Chemical pollution remains one of the most visible and persistent stressor domains in aquatic ecosystems. Chemical pollution includes nutrients, organic matter, pesticides, metals, hydrocarbons, pharmaceuticals, personal-care products, PFAS, microplastics, road salts, and wastewater-derived contaminants [15]. The ecological risk of these pollutants is modified by flow, temperature, dissolved oxygen, pH, salinity, sediment, organic carbon, and biological sensitivity [16]. Thus, pollutant concentration alone rarely explains ecological response. For example, low flows may increase contaminant exposure by reducing dilution, whereas floods may remobilize sediment-bound nutrients, metals, pathogens, and organic pollutants.

Chemical stressors also interact with ecological feedbacks. Nutrient enrichment can trigger algal blooms, which increase diurnal oxygen variability and may generate hypoxia during decomposition [17]. Hypoxia can release phosphorus from sediments, reinforcing eutrophication [18]. Salinization can alter ion balance, mobilize metals, affect microbial processes, and reduce the survival of sensitive freshwater taxa [19]. Microplastic surfaces can support distinct microbial biofilms, collectively termed the plastisphere, whose composition and ecological functions may differ from those of surrounding-water communities; plastics may also harbour or transport some microbial pathogens, although these effects depend on polymer properties and environmental context (20,21). A syndrome-based approach therefore treats chemical pollution as part of a wider stressor matrix rather than as an isolated water-quality category.

3.2 Physical habitat degradation

Physical habitat provides the template on which aquatic communities assemble and ecosystem processes occur. Habitat degradation reduces the capacity of aquatic systems to buffer other stressors. Riparian clearing increases light, temperature, bank erosion, and runoff delivery [22]. Channel simplification reduces refugia during floods, droughts, heatwaves, and pollution pulses [23]. Fine sediment fills interstitial habitats, impairs benthic communities, reduces spawning success, and transports phosphorus and contaminants [24]. Wetland drainage weakens water retention, nutrient transformation, flood buffering, and carbon storage [25]. Consequently, habitat degradation often converts moderate chemical or climatic stress into stronger ecological impairment.

In management terms, habitat restoration may fail when water quality or flow regimes remain unsuitable, but water-quality improvements may also fail when habitat remains physically simplified. This reciprocal dependency is central to the syndrome perspective. Effective restoration requires diagnosing whether biological impairment is driven primarily by pollutant exposure, habitat limitation, hydrological alteration, lack of colonist sources, or interacting constraints.

3.3 Hydrological alteration

Hydrology is a master variable in aquatic ecosystems because it regulates connectivity, dilution, sediment transport, oxygen dynamics, nutrient cycling, thermal regimes, habitat availability, and life-history cues [26]. Hydrological alteration modifies the timing, magnitude, duration, and connectivity of water flows. Dams, abstraction, drainage, urban stormwater systems, groundwater depletion, and irrigation return flows alter dilution, residence time, sediment transport, oxygen dynamics, temperature, habitat availability, and life-history cues [27]. Flow alteration is therefore not only a physical stressor but also a mediator of chemical exposure, habitat condition, and biological recovery [28].

Hydrological alteration is often difficult to manage because it is linked to energy production, irrigation, flood control, navigation, urban drainage, and water supply (29). Nevertheless, environmental flows, dam re-operation, reconnection of floodplains, wetland rewetting, stormwater retention, groundwater protection, and abstraction limits are central tools for reducing multiple-stressor risk. In a syndrome framework, hydrological restoration is not treated as a separate objective but as a lever that can modify water quality, habitat condition, contaminant exposure, and biological recovery.

3.4 Climate-related stressors

Climate-related stressors increasingly amplify existing syndromes. Warming, droughts, floods, heatwaves, evaporation, salinization, and altered rainfall affect pollutant transport, dilution capacity, stratification, oxygen availability, and organism tolerance. River water quality often deteriorates during droughts, heatwaves, rainstorms, floods, and long-term climatic change, although responses vary by constituent and setting [30]. Climate change should therefore be treated not as a separate pressure, but as a multiplier of local and regional stressor interactions. Climate change is especially important for multiple-stressor research because it changes background conditions under which local stressors operate. A nutrient concentration that previously produced moderate algal growth may become more problematic under warmer temperatures and longer residence times [31]. A pesticide pulse may have stronger effects when organisms are already physiologically stressed by heat, low oxygen, or salinity [32]. A restored reach may fail to recover if drought reduces connectivity to source populations. Conversely, reducing local stressors such as nutrient loading, riparian loss, and water abstraction can increase climate resilience [33]. This creates an important management implication: climate adaptation in aquatic ecosystems cannot rely only on climate-specific interventions; it also requires reducing non-climatic stressors that erode resilience.

3.5 Biological stressors and ecological feedbacks

Biological stressors include invasive species, harmful algal blooms, pathogens, disease, altered trophic interactions, and biodiversity loss. These stressors are both outcomes and drivers of degradation (34). Eutrophication can promote cyanobacterial blooms, but blooms can further degrade oxygen conditions and food webs (35). Habitat disturbance can facilitate invasions, while invasions can reinforce habitat simplification and native biodiversity loss (36). Therefore, biological responses should not be treated only as endpoints; they can also mediate the trajectory of stressor syndromes.

1. Multiple-Stressor Syndromes Across Aquatic Ecosystem Types

Stressor syndromes vary across ecosystem types because land use, hydrology, geomorphology, climate, connectivity, and governance generate different stressor clusters. The categories below are not rigid; many systems express hybrid syndromes. Their purpose is diagnostic: to identify dominant drivers, stressor combinations, mechanisms, outcomes, and management leverage points. The syndrome categories discussed below are intended as a comparative diagnostic framework rather than a fixed classification. Many aquatic ecosystems express overlapping or hybrid syndromes, particularly where urbanization, agriculture, flow regulation, mining, wetland loss, and climate extremes coincide. **Table 2** summarizes the major syndrome types reviewed in this section by linking ecosystem type, dominant drivers, stressor clusters, ecological outcomes, monitoring indicators, priority interventions, and key supporting references.

4.1 Urban river syndrome

Urban rivers are shaped by impervious surfaces, stormwater runoff, wastewater discharge, channel engineering, riparian loss, thermal pollution, contaminants, salinization, and flashy hydrology (41). The key mechanism is the coupling of hydrological pulses with chemical and physical disturbance. Storm events deliver sediments, nutrients, metals, hydrocarbons, microplastics, pathogens, and organic matter while also increasing shear stress and turbidity (42). During dry periods, wastewater dominance and reduced baseflow may elevate nutrients, conductivity, temperature, and organic enrichment. Ecological outcomes include loss of sensitive macroinvertebrates, simplified fish assemblages, altered microbial communities, reduced habitat quality, and impaired ecosystem functioning (43). Management should prioritize stormwater retention, sewer overflow control, riparian restoration, green infrastructure, thermal buffering, and channel complexity rather than relying only on pollutant compliance.

4.2 Agricultural catchment syndrome

Agricultural catchments commonly combine nutrient enrichment, pesticide exposure, fine sediment, livestock waste, pathogens, riparian clearing, drainage, irrigation return flows, and seasonal low flows. These stressors are often synchronized by rainfall, fertilizer application, pesticide use, soil disturbance, and crop cycles (44). As noted in previous section, sediment functions as both a physical stressor and a vector for phosphorus, pathogens, and contaminants. Nutrients stimulate eutrophication, pesticides affect algae and invertebrates, and low flows increase exposure. Recovery may be delayed by legacy nutrients stored in soils, groundwater, wetlands, and sediments. Management should combine riparian buffers, nutrient budgeting, pesticide reduction, soil conservation, livestock exclusion, constructed wetlands, and catchment-scale land-use planning.

4.3 Lake and reservoir eutrophication–stratification syndrome

Lakes and reservoirs are vulnerable to nutrient loading, long residence time, thermal stratification, internal phosphorus release, hypoxia, harmful algal blooms, and food-web alteration. Warming can intensify stratification, extend bloom seasons, reduce oxygen solubility, and reinforce internal nutrient cycling. Cyanobacterial blooms threaten drinking water, recreation, fisheries, and ecosystem health (37). Management must address both external nutrient loading and internal feedbacks. Catchment nutrient control remains fundamental, but some systems may also require oxygenation, mixing, sediment management, selective withdrawal, or food-web restoration. Monitoring should integrate nutrients, temperature profiles, dissolved oxygen, chlorophyll-a, cyanotoxins, residence time, and biological indicators.

4.4 Wetland degradation syndrome

Wetland syndromes typically involve drainage, reduced hydroperiod, hydrological disconnection, nutrient enrichment, sedimentation, invasive plants, peat oxidation, agricultural encroachment, and climate-driven drying. Hydrology is the central control: altered inundation changes vegetation, decomposition, denitrification, carbon storage, fire risk, and invasion potential. Degraded wetlands also export stress downstream by losing their capacity to retain sediments, transform nutrients, buffer floods, and support biodiversity (45). Management should prioritize rewetting, floodplain reconnection, drainage control, nutrient reduction, invasive-species management, buffer protection, and early conservation of intact wetlands.

4.5 Regulated river and dam-impact syndrome

Dams and flow regulation generate altered flow seasonality, reduced flood pulses, sediment trapping, thermal alteration, fragmentation, blocked migration, modified nutrient transport, and reduced floodplain connectivity. Global mapping shows that free-flowing rivers have been substantially reduced by fragmentation and regulation (38). The key mechanism is disruption of flow as an ecological signal and transport process. Many organisms depend on flood timing, temperature cues, sediment dynamics, and connectivity for migration, spawning, recruitment, and dispersal. Management options include environmental flows, dam re-operation, sediment management, fish passage, selective withdrawal, floodplain reconnection, and strategic barrier removal. These actions should be evaluated together because restoring flow alone may fail if sediment supply, temperature, habitat, or connectivity remain impaired.

4.6 Tropical freshwater degradation syndrome

Tropical freshwaters often combine deforestation, agriculture, mining, hydropower development, urbanization, untreated wastewater, high sediment yield, pathogen contamination, riparian loss, and climate variability (1). These systems are highly biodiverse but underrepresented in long-term monitoring and multiple-stressor research. Dudgeon (39) emphasized that tropical freshwaters face both immediate anthropogenic pressures and climate-related risks. Management should avoid uncritical transfer of temperate thresholds and instead develop regionally appropriate indicators, low-cost monitoring, community-based assessment, riparian restoration, wastewater improvement, mining regulation, and protection of ecological refugia.

4.7 Coastal and estuarine receiving-water syndrome

Estuaries and coastal receiving waters integrate upstream catchment pressures with marine and climatic processes. Their syndromes include riverine nutrient export, organic loading, sediment delivery, hypoxia, harmful algal blooms, plastic pollution, industrial contaminants, habitat loss, salinity shifts, dredging, overfishing, warming, and sea-level rise (46). Nutrient enrichment, stratification, warming, and organic matter decomposition interact to reduce oxygen availability; declining oxygen in coastal waters has major consequences for animal diversity, productivity, and biogeochemical cycling (40). Management requires integrated river-basin and coastal-zone governance, including upstream nutrient reduction, wastewater treatment, wetland and mangrove restoration, fisheries regulation, protected areas, and climate-adaptive coastal planning.

4.8 Case studies from selected regions

Tropical freshwater degradation is not a single uniform syndrome. Its expression varies according to catchment development, hydrology, extractive activity, wastewater infrastructure and climatic seasonality. In the Mara River basin of Kenya and Tanzania, for example, agricultural expansion, soil erosion, nutrient and organic-matter inputs, livestock and wildlife effects, excessive water withdrawal, human settlements and artisanal gold mining occur within the same transboundary river system (47). Biological assessment demonstrated that macroinvertebrate responses differed across land-use and disturbance categories and were strongly affected by seasonality, illustrating the need to combine physicochemical monitoring with regionally calibrated biological indicators (48).

In tropical agricultural streams in Panama, pesticide toxicity, nutrient enrichment and habitat alteration jointly influenced macroinvertebrate communities (44). This example demonstrates that riparian condition and physical habitat can modify the ecological expression of chemical exposure, and that tropical catchments should not be assessed through nutrient concentrations alone.

In tropical South America more broadly, alluvial mining, deforestation, dams, agricultural expansion and urban discharge frequently create overlapping sediment, contaminant, fragmentation and flow-alteration pressures (49). Satellite evidence indicates that mining-related sediment increases are widespread in tropical rivers, although the ecological consequences vary among catchments and should be assessed locally (50).

Southeast Asian rivers and wetlands similarly experience combinations of dam construction, sand or mineral extraction, urban wastewater, agricultural runoff, riparian conversion, invasive species and climatic extremes (51). The syndrome framework should therefore be applied through regionally specific diagnosis rather than by transferring thresholds or biological expectations directly from temperate systems. Across these regions, priorities include protection of riparian refugia, wastewater and mining controls, environmental-flow protection, low-cost sensor networks, regionally calibrated biomonitoring, and community participation.

4.9 Cross-system critical synthesis

Across systems, three principles emerge. First, stressor syndromes are structured by dominant drivers such as urbanization, agriculture, flow regulation, drainage, mining, and climate change. Second, the same stressor can produce different outcomes depending on the syndrome in which it occurs; nutrient enrichment in a shaded stream differs from nutrient enrichment in a stratified reservoir or estuary. Third, management succeeds when it targets the mechanisms that maintain the syndrome. The diagnostic question is therefore not only “Which stressors are present?” but “Which stressor cluster is operating, what mechanism sustains it, and which intervention can most effectively weaken it?”

2. Ecological Mechanisms and Response Pathways

Multiple-stressor syndromes affect aquatic ecosystems through recurring mechanisms that connect exposure, organism response, habitat condition, food webs, and resilience.

5.1 Exposure modification

One of the most important mechanisms in multiple-stressor syndromes is exposure modification, where one stressor changes the intensity, duration, timing, or bioavailability of another (12). Hydrology is especially important in this regard. Low-flow conditions reduce dilution capacity and can increase concentrations of nutrients, salts, wastewater-derived contaminants, pesticides, and organic matter. They also increase residence time, allowing algal biomass to accumulate and water temperature to rise. Conversely, high-flow events may dilute dissolved contaminants but can also mobilize sediment-bound phosphorus, metals, pathogens, microplastics, organic matter, and pesticides from soils, drains, floodplains, and riverbeds (52).

This dual role of flow explains why water-quality responses to climate extremes can be complex. Droughts may intensify chronic exposure, whereas storms and floods may produce acute pulses. The ecological outcome depends on whether organisms experience repeated sublethal stress, short toxic pulses, habitat displacement, oxygen depletion, or post-event resource subsidies (53). A syndrome-based perspective is useful because it links exposure to the timing of land-use activities, rainfall, wastewater discharge, dam operation, and biological sensitivity. For example, pesticide runoff following application may have different ecological consequences if it coincides with low dissolved oxygen, high temperature, larval emergence, or reduced habitat refugia.

Sediments also modify exposure. Fine sediments can act as both a physical habitat stressor and a carrier of phosphorus, organic contaminants, pathogens, and metals. In agricultural and mining-affected systems, sediment deposition may prolong exposure long after the initial runoff event (54). In reservoirs, wetlands, and estuaries, sediments can become long-term stores of nutrients and contaminants that are later released under anoxia, salinity change, pH shifts, or disturbance (55). Thus, sediments provide a pathway through which historical stressors become contemporary ecological constraints.

5.2 Physiological stress and tolerance thresholds

Aquatic organisms respond to multiple stressors through physiological limits. Temperature, dissolved oxygen, salinity, and contaminants can alter organismal energy budgets, metabolism, growth, and survival. When these stressors occur together, one stressor may reduce the physiological capacity to tolerate another, thereby narrowing the range of conditions under which sensitive organisms can persist (56–58). Warming is particularly influential because it increases metabolic demand while often reducing oxygen availability. When warming coincides with hypoxia, salinity, pesticides, or nutrient-driven algal blooms, sensitive organisms may be pushed beyond tolerance thresholds even if each individual stressor remains below a conventional guideline (31).

This mechanism is central to understanding climate-amplified water-quality degradation. Climate change does not simply add a new stressor to aquatic systems; it changes the physiological background against which all other stressors operate. Piggott et al. (11) showed that climate warming and agricultural stressors can interact to affect stream ecosystem functioning, including organic matter processing. This supports a broader point: functional processes may respond to multiple stressors even when structural community changes are less immediately visible. Similarly, meta-analytical evidence indicates that combined stressor effects in freshwater ecosystems are variable and often difficult to predict from single-stressor responses alone (5).

Tolerance thresholds also differ among taxa and life stages. Early life stages of fish, amphibians, and aquatic invertebrates are often more sensitive to temperature, hypoxia, contaminants, and sedimentation than adults. Sessile or low-mobility organisms may be unable to escape deteriorating conditions, while mobile species may track suitable habitats if connectivity remains intact (59). This means that the same stressor syndrome can restructure communities through selective loss of sensitive taxa, recruitment failure, altered dispersal, and competitive release of tolerant species. Over time, repeated threshold exceedance can lead to biological homogenization, where communities become dominated by generalist, tolerant, or invasive taxa.

5.3 Habitat-mediated vulnerability

Habitat condition mediates how organisms experience stressors. Structurally complex habitats provide refugia during floods, droughts, heatwaves, predation, and pollution pulses. Riparian vegetation moderates light and temperature, stabilizes banks, supplies organic matter, filters runoff, and supports terrestrial–aquatic food-web linkages (60). Substrate diversity supports benthic invertebrates, fish spawning, microbial processes, and hyporheic exchange. Wetland vegetation slows water, traps sediment, transforms nutrients, and provides habitat heterogeneity (61).

When habitat is degraded, organisms become more exposed to chemical and climatic stressors. Channelized streams often lack refugia during high-flow events and may warm rapidly because of reduced shading. Fine-sediment deposition reduces interstitial habitat and oxygen exchange, weakening benthic communities and fish recruitment (62). Loss of floodplain connectivity reduces access to spawning, nursery, and feeding habitats. Shoreline modification in lakes and reservoirs reduces littoral complexity, affecting macrophytes, invertebrates, and fish (63). Wetland drainage reduces hydroperiod diversity and exposes organisms to desiccation, predation, and invasive species.

Habitat-mediated vulnerability helps explain why water-quality improvements do not always produce rapid biological recovery. A stream may show reduced nutrient concentrations after management intervention, but if channel morphology remains simplified and riparian vegetation is absent, sensitive taxa may not return. Similarly, environmental flows may be less effective in regulated rivers if sediment deficits, thermal alteration, or migration barriers continue to constrain habitat suitability (64). For management, this means that water quality, physical habitat, and hydrology must be interpreted together rather than as independent restoration targets.

5.4 Food-web alteration and functional disruption

Multiple-stressor syndromes often propagate through food webs. Nutrient enrichment may increase primary production, but whether this supports higher trophic levels depends on algal composition, grazing pressure, oxygen dynamics, habitat condition, and toxic blooms (65). Pesticides may reduce sensitive invertebrates, weakening prey availability for fish and altering decomposition or grazing processes (66). Sedimentation may reduce benthic habitat and shift food webs toward tolerant collector-gatherers or microbial pathways (62). Invasive fish or plants may restructure trophic interactions, alter nutrient cycling, and reinforce degraded states.

Food-web alteration is important because ecosystem function may change before species losses are fully apparent. Multiple stressors can alter microbial community composition, organic-matter decomposition, ecosystem respiration, and elemental processing before conspicuous changes in higher trophic levels become apparent (67,68). Functional indicators can therefore provide early warning of ecological degradation. However, functional responses may be context-dependent. For example, moderate nutrient enrichment may stimulate microbial decomposition where oxygen and habitat remain suitable, but the same enrichment may contribute to hypoxia and reduced decomposition under warming, low-flow, or high organic loading conditions.

Food-web disruption can also create feedbacks. In eutrophic lakes, reduced grazing by zooplankton can facilitate phytoplankton dominance (35). Loss of macrophytes can increase sediment resuspension and reduce habitat for grazers and fish. Hypoxia can eliminate benthic fauna, reducing bioturbation and altering nutrient release (62). In estuaries, deoxygenation can compress habitat for mobile species and restructure predator–prey interactions (46). These feedbacks mean that recovery from stressor syndromes may require more than reducing external pressures; it may also require restoring biological interactions and habitat structures that maintain desirable ecosystem states.

5.5 Loss of resilience, ecological memory, and regime shifts

The most severe outcome of multiple-stressor syndromes is loss of resilience. Resilience refers to the capacity of an ecosystem to absorb disturbance, reorganize, and retain function, structure, and identity. Repeated exposure to stressor pulses can erode this capacity by reducing biodiversity, simplifying food webs, eliminating refugia, depleting seed or egg banks, disrupting dispersal pathways, and altering sediment or nutrient stores (69). Once resilience is reduced, ecosystems may shift abruptly or gradually into alternative states that are difficult to reverse (70). Examples include transitions from clear-water to turbid-water states in shallow lakes, macrophyte-dominated to phytoplankton-dominated systems, oxygenated to hypoxic bottom waters, diverse native fish assemblages to tolerant or invasive-dominated assemblages, and intact wetlands to drained or shrub-invaded states. These shifts often involve feedbacks that maintain degradation even after external stressor inputs decline. Internal phosphorus loading, sediment resuspension, invasive species dominance, altered hydrology, and loss of propagule sources can all delay or prevent recovery.

Ecological memory can either support or constrain recovery. Where remnant populations, intact riparian zones, seed banks, floodplain habitats, and hydrological connectivity remain, ecosystems may recover after stressor reduction (71). Where these memory components are lost, restoration may require active reintroduction, habitat reconstruction, reconnection, or long timeframes (71). This has important implications for management prioritization: protecting relatively intact systems and refugia may be more cost-effective than restoring heavily degraded systems that have crossed ecological thresholds.

3. Monitoring, Modelling, and Management Implications

Syndrome-based management requires moving from isolated parameter monitoring toward integrated ecological diagnosis. Conventional monitoring of nutrients, dissolved oxygen, pH, conductivity, temperature, turbidity, and selected contaminants remains essential, but it is insufficient when stressors interact through flow, habitat, climate, and biological feedbacks (72). A syndrome-based programme should combine physicochemical, hydrological, habitat, biological, functional, and land-use indicators (73).

High-frequency sensors can capture short-term fluctuations in temperature, dissolved oxygen, conductivity, turbidity, chlorophyll-a, pH, and nitrate that routine sampling may miss (74). Remote sensing can support assessment of land cover, turbidity, chlorophyll-a, wetland extent, water temperature, shoreline change, and floodplain inundation (75). Environmental DNA can improve detection of rare, invasive, cryptic, or sensitive taxa. Coupled hydrological–water-quality models, Bayesian networks, trait-based models, and scenario tools can support prediction where they are field-validated and interpretable (76). However, advanced tools should not be treated as substitutes for ecological understanding. In data-limited regions, low-cost monitoring, community-based assessment, targeted biological indicators, and simple risk-screening frameworks may be more appropriate.

Management should prioritize locally controllable stressors that increase resilience to climatic uncertainty. Managers cannot control regional heatwaves or extreme rainfall, but they can reduce nutrient loads, improve wastewater treatment, restore riparian shade, reconnect wetlands and floodplains, protect baseflows, limit abstraction, improve habitat complexity, and reduce pollutant pulses. Intervention sequencing is critical: habitat restoration may fail if toxic contamination persists; nutrient reduction may be delayed by internal loading; environmental flows may be ineffective without connectivity or suitable habitat; and species recovery may fail if source populations are absent.

Syndrome-based governance also requires coordination across sectors. Agriculture, urban planning, wastewater management, hydropower, mining, fisheries, conservation, public health, and climate adaptation often operate under separate mandates, yet aquatic degradation emerges from their combined effects (77). Integrated catchment governance should identify dominant stressor clusters, responsible sectors, ecological thresholds, monitoring indicators, and priority interventions. This makes integrated water-resource management more operational by linking diagnosis to action.

4. Knowledge Gaps and Future Research Agenda

Despite rapid growth in multiple-stressor research, major knowledge gaps still limit prediction, monitoring, and management of aquatic ecosystem degradation. The central challenge is no longer whether multiple stressors matter, but how their effects vary across ecological contexts, spatial scales, timeframes, organism groups, and management settings. Future research should therefore move from documenting stressor co-occurrence toward identifying mechanisms, thresholds, and intervention points.

7.1 Geographic and ecosystem bias

Multiple-stressor evidence remains unevenly distributed across regions and ecosystem types. Temperate rivers and lakes are better represented than tropical freshwaters, temporary wetlands, floodplains, headwaters, urban ponds, groundwater-dependent systems, and small reservoirs. This bias is problematic because tropical and subtropical systems often experience rapid land-use change, high biodiversity, limited wastewater treatment, mining impacts, and climate variability, yet have weaker long-term monitoring coverage. Recent freshwater conservation assessments identify lack of biodiversity data, limited understanding of multiple stressors, and weak conservation planning as major barriers, especially in underrepresented regions (3,4,39). Future work should prioritize region-specific stressor syndromes rather than assuming that temperate models apply globally.

7.2 Weak evidence on timing, sequence, and legacy effects

Many studies examine simultaneous stressors, but real aquatic systems experience stressors sequentially, seasonally, and historically. Agricultural runoff may follow fertilizer or pesticide application; urban pollutant pulses may follow storms; reservoir hypoxia may develop seasonally; droughts may intensify contaminant exposure after long periods of nutrient accumulation. Legacy nutrients, contaminated sediments, altered channels, drained wetlands, and lost source populations can delay recovery long after current stressor inputs decline (78). Future studies should examine stressor timing, order of exposure, recovery windows, and lag effects using long-term monitoring, before–after-control–impact designs, palaeoecological records, and repeated field experiments.

7.3 Limited understanding of thresholds and recovery pathways

A major weakness in current evidence is the limited ability to identify when aquatic systems cross thresholds from reversible degradation to persistent altered states. Multiple stressors may produce nonlinear responses, but management often relies on linear assumptions. For example, reducing nutrient inputs may not restore a shallow lake if internal phosphorus loading, macrophyte loss, and food-web feedbacks maintain turbidity. Similarly, improving water chemistry may not restore a stream if habitat complexity, flow variability, and dispersal connectivity remain impaired. Future research should focus on ecological thresholds, early-warning indicators, recovery trajectories, and the conditions under which stressor reduction produces measurable biological improvement.

7.4 Need for biological and functional indicators

Water-quality assessment still relies heavily on physicochemical parameters, yet these may not capture ecological impairment or recovery. Biological and functional indicators are needed to detect how stressor syndromes affect ecosystem structure and processes. Macroinvertebrates, fish, algae, macrophytes, microbial communities, environmental DNA, decomposition, nutrient uptake, primary production, denitrification, and food-web metrics can provide more direct evidence of ecological condition (28). Birk et al. (6) highlighted that stressor effects vary across ecosystems and spatial scales, reinforcing the need for indicators that connect stressor exposure to biological response. Future monitoring should integrate chemical, hydrological, habitat, biological, and functional metrics within syndrome-based assessment frameworks.

7.5 Insufficient field-scale management experiments

There is still limited evidence on which management interventions most effectively weaken multiple-stressor syndromes. Many studies diagnose degradation, but fewer test recovery under real-world conditions. Restoration actions such as riparian reforestation, wetland reconnection, environmental flows, nutrient reduction, stormwater treatment, dam re-operation, and wastewater upgrades should be evaluated through field-scale experiments and adaptive management programmes. These studies should measure ecological recovery, not only pollutant reduction. Tickner et al. (3) emphasized that freshwater recovery requires coordinated action across flow management, habitat protection, pollution control, invasive species management, and connectivity restoration. Future work should therefore test combinations of interventions rather than isolated restoration measures.

7.6 Data integration and predictive modelling gaps

Although sensors, remote sensing, environmental DNA, and machine learning are expanding rapidly, many datasets remain fragmented across agencies, sectors, and spatial scales. Predictive models are often limited by poor integration of hydrology, chemistry, habitat, biological response, and governance variables. Orr et al. (10) argued that multiple-stressor research needs stronger cross-disciplinary integration to improve prediction and management relevance. Future research should develop models that are mechanistic enough to explain stressor pathways, but practical enough for decision-making. Bayesian networks, coupled hydrological–water-quality models, trait-based models, and scenario tools are promising when combined with field validation and stakeholder input.

7.7 Governance and implementation gaps

The greatest barrier may not be scientific knowledge alone, but implementation. Multiple-stressor syndromes are produced by interacting sectors, including agriculture, urban planning, wastewater management, hydropower, mining, fisheries, conservation, and climate adaptation (10). However, governance is often fragmented. Future research should therefore examine how institutions coordinate across catchments, how monitoring data influence policy, and how trade-offs among water supply, food production, energy, biodiversity, and public health are negotiated. Syndrome-based management will require integrated catchment governance, transparent prioritization, stakeholder participation, and long-term funding for monitoring and restoration.

5. Conclusion

The syndrome-based approach should be viewed as a testable diagnostic framework rather than a replacement for experimental interaction analysis, cumulative-risk assessment or existing water-governance models. Its practical value lies in integrating these approaches around recurrent combinations of drivers, stressors, mechanisms, ecological responses and recovery constraints. Future applications should validate proposed syndrome categories using long-term field observations, intervention studies and geographically representative evidence. Integration of conventional monitoring with eDNA, remote sensing, high-frequency sensors and carefully validated AI-assisted analyses may improve early detection and adaptive management, but effective restoration will still depend on reducing causal pressures, restoring hydrological and habitat processes, and evaluating biological recovery at catchment scale.

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LIST OF TABLES

Table 1. Comparison of established multiple-stressor assessment approaches and the proposed syndrome-based framework

Approach	Main focus	Typical output	Key strength	Main limitation	Management use	Key citations
Interaction-based assessment	Tests whether combined stressor effects differ from an expected additive response	Additive, synergistic, antagonistic, dominant, or opposing effects	Provides formal tests of joint effects	Results depend on the null model, endpoint, taxon, and scale	Identifies important stressor interactions	(5,6,11)
Cumulative-effects assessment	Estimates the combined burden of multiple pressures	Pressure indices, risk scores, or vulnerability maps	Supports spatial screening and prioritization	May obscure mechanisms and interaction types	Identifies high-risk areas and receptors	(10,12)
Driver–Pressure–State–Impact–Response and causal-chain frameworks	Links drivers, pressures, ecological change, impacts, and responses	Causal models and indicator sets	Connects ecological change with policy and governance	Can oversimplify feedbacks, legacy effects, and nonlinear responses	Supports reporting and broad policy planning	(10,13)
Integrated management frameworks	Organizes evidence for assessment and management	Decision workflows, monitoring priorities, and intervention options	Improves links between science and management	Often remains general and requires local validation	Guides monitoring, intervention selection, and adaptive management	(12,13)
Multiple-stressor syndrome approach	Identifies recurrent stressor clusters, mechanisms, outcomes, and leverage points	Syndrome profiles, indicators, recovery constraints, and intervention packages	Integrates context, co-occurrence, mechanisms, legacy effects, and management sequencing	Conceptual categories may overlap and require empirical validation	Supports ecosystem-specific diagnosis and coordinated restoration	This review

Established approaches and the proposed syndrome-based framework are complementary. Interaction-based methods classify joint effects; cumulative assessments estimate total pressure; causal frameworks connect drivers with ecological and policy responses; and integrated management frameworks guide decision-making.

The syndrome-based approach adds an ecosystem-specific diagnostic layer by linking recurrent stressor clusters with mechanisms, ecological outcomes, recovery constraints, and management actions.

Notes:

i. Interaction terms such as additive, synergistic, and antagonistic depend on the null model and response metric used.
ii. Syndrome categories are not mutually exclusive; aquatic systems may express overlapping or shifting syndromes.
iii. The proposed framework does not replace experimental, cumulative-risk, or causal-chain approaches. It integrates their evidence for diagnosis and management.

The syndrome-based framework requires validation through field studies, long-term monitoring, and restoration assessments.

Table 2. Cross-ecosystem comparison of multiple-stressor syndromes, mechanisms, ecological responses, recovery constraints, and management priorities

Ecosystem type	Dominant drivers	Defining diagnostic feature	Important modifier	Likely recovery constraint	Stressor cluster	Ecological outcomes	Monitoring indicators	Priority interventions	Key references
Urban rivers/streams	Urbanization, wastewater, stormwater, channel modification	Flashy runoff coupled with mixed pollutant pulses and channel alteration	Sewer leakage, imperviousness, baseflow contribution	Persistent channel simplification and repeated storm pulses	Flashy flow, nutrients, metals, hydrocarbons, microplastics, pathogens, heat, high conductivity	Sensitive taxa loss, simplified fish communities, altered microbes, poor habitat/function	Flow, conductivity, temperature, DO, nutrients, turbidity, metals, microbes, macroinvertebrates	Green infrastructure, stormwater control, sewer upgrades, riparian restoration, channel rehabilitation	(6,9,10)
Agricultural catchments	Fertilizer, pesticides, livestock, drainage, riparian clearing	Seasonal co-occurrence of nutrients, sediment and pesticides	Rainfall timing, crop cycle, soil type	Legacy nutrients and contaminated sediments	Nutrients, pesticides, fine sediment, pathogens, low flow, riparian loss	Eutrophication, benthic smothering, food-web simplification, delayed recovery	N, P, pesticides, turbidity, sediment, pathogens, DO, flow, biota	Buffers, nutrient budgeting, pesticide reduction, soil conservation, livestock exclusion, constructed wetlands	(5,11)
Lakes/reservoirs	Nutrient loading, warming, damming,	Nutrient enrichment reinforced by stratification	Residence time and warming	Internal phosphorus loading and	Nutrients, stratification, internal P release,	Blooms, cyanotoxins, fish kills, macrophyte	N, P, chlorophyll-a, cyanotoxins, temperature/DO	Nutrient reduction, internal loading control, oxygenation/mixing,	(6,30,37)

	long residence time	and internal loading		food-web feedbacks	hypoxia, cyanobacteria	loss, regime shifts	profiles, Secchi depth	selective withdrawal, sediment management	
Wetlands/floodplains	Drainage, agriculture, disconnection, climate drying	Hydroperiod shortening combined with enrichment or invasion	Drainage intensity and climatic drying	Peat oxidation, altered elevation and propagule limitation	Short hydroperiod, nutrients, sediment, invasive plants, peat oxidation	Biodiversity loss, reduced purification, carbon loss, invasion, weaker flood buffering	Hydroperiod, water level, vegetation, nutrients, sediment, carbon, invasive cover	Rewetting, drainage control, reconnection, nutrient reduction, buffer protection, invasive control	(3,4,10)
Regulated rivers	Dams, abstraction, hydropower, flood control	Altered flow cues, sediment transport and connectivity	Dam operation and thermal release	Barriers, sediment deficit and absent source populations	Altered flow, sediment trapping, thermal change, fragmentation, blocked migration	Migratory fish loss, altered spawning, channel incision, floodplain decline	Flow regime, temperature, sediment, connectivity, fish migration, habitat	Environmental flows, dam re-operation, sediment management, fish passage, barrier removal	(3,38)
Tropical freshwaters	Deforestation, mining, agriculture, urbanization, weak wastewater treatment	Sediment, pollution, pathogens, riparian loss, and altered flow	Rainfall, mining, wastewater, and hydropower	Weak monitoring, poor treatment, fragmentation, and refugia loss	Sediment, metals, nutrients, pathogens, pesticides, riparian loss, altered flow	Turbidity, metal contamination, pathogen risk, fish decline, reduced water security	Turbidity, sediment, metals, nutrients, microbes, temperature, flow, fish, macroinvertebrates	Riparian restoration, wastewater improvement, mining regulation, low-cost/community monitoring, refugia protection	(4,39)
Estuaries/coastal waters	Riverine loads, wastewater, coastal development, climate change	Catchment loads, stratification, warming, and habitat loss	River flow, residence time, tides, and salinity	Upstream loading, internal recycling, wetland loss, and fragmented governance	Nutrients, organic matter, sediment, hypoxia, HABs, plastics,	Deoxygenation, blooms, habitat loss, food-web change, fisheries impacts	DO, nutrients, chlorophyll-a, salinity, temperature, turbidity, contaminants, benthos	Basin–coastal management, nutrient reduction, wastewater treatment, wetland/mangrove restoration, fisheries regulation	(3,30,40)

salinity shifts, warming

Note: The categories in this table are diagnostic rather than mutually exclusive. Individual aquatic systems may exhibit overlapping or hybrid syndromes, and their expression may vary with hydrology, climate, land use, connectivity, disturbance history, and governance. The mechanisms, responses, recovery constraints, and interventions listed represent dominant patterns identified in the reviewed literature and are not exhaustive or quantitatively ranked.

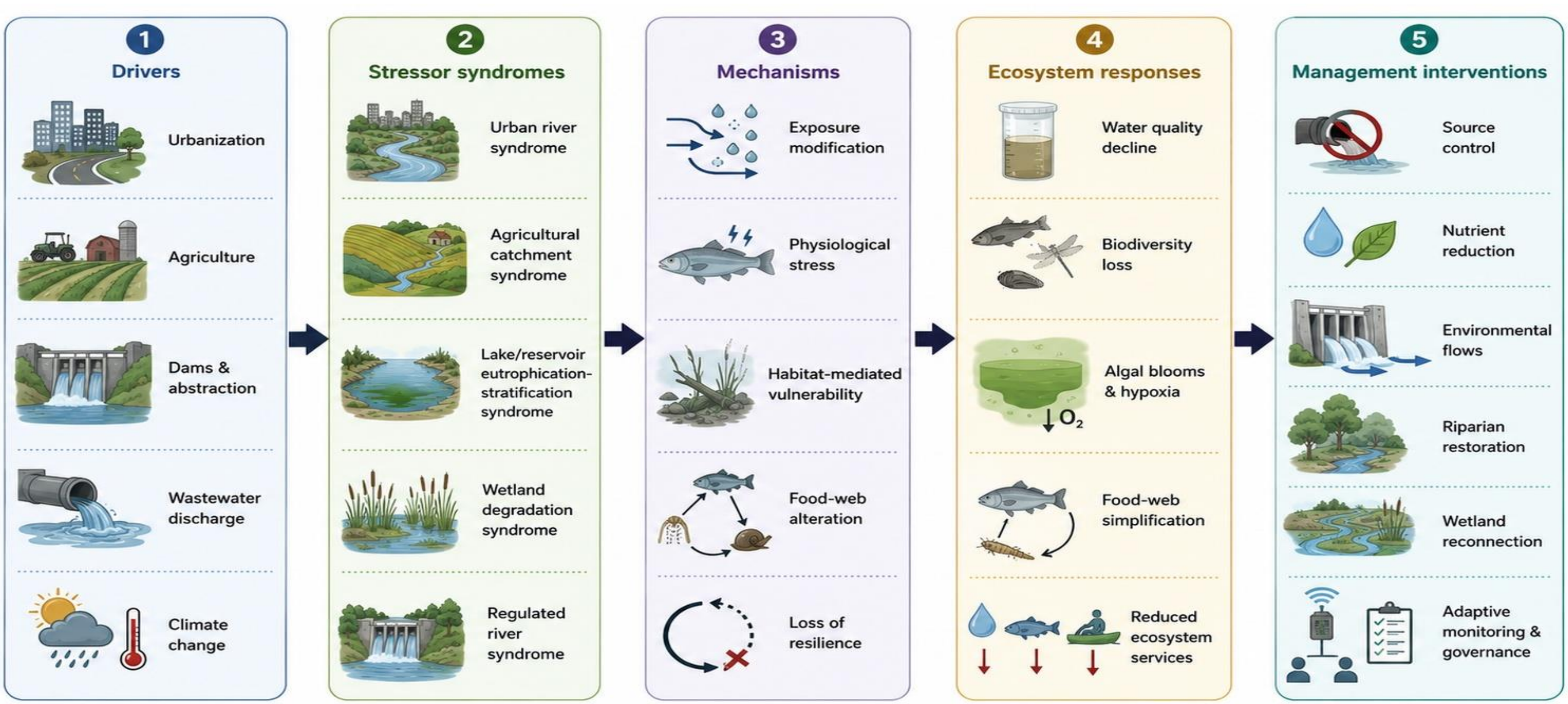

Figure 1 Conceptual framework of multiple-stressor syndromes in aquatic ecosystems

***Note*:** The framework illustrates how recurrent drivers, including urbanization, agriculture, dams and abstraction, wastewater discharge, and climate change, generate recognizable stressor syndromes across aquatic systems. These syndromes operate through mechanisms such as exposure modification, physiological stress, habitat-mediated vulnerability, food-web alteration, and loss of resilience. The resulting ecosystem responses include water-quality decline, biodiversity loss, algal blooms and hypoxia, food-web simplification, and reduced ecosystem services. Management interventions target different points in the framework, including source control, nutrient reduction, environmental flows, riparian restoration, wetland reconnection, and adaptive monitoring and governance.