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## Effects of Water Runoff on Fish Biodiversity: A Comprehensive Review

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### Abstract

*Water runoff encompassing agricultural, urban storm water, and forestry-related overland flow which represents one of the most pervasive non-point source pollutants threatening freshwater and coastal aquatic ecosystems globally. This comprehensive review synthesizes current evidence on the mechanisms through which various categories of water runoff impair fish biodiversity, examining sediment loading, nutrient enrichment, chemical contamination, and hydrological alteration as primary pathways of impact. Drawing on peer-reviewed literature published predominantly in recent times, this review documents how excess nutrients transported by runoff drive eutrophication and hypoxia, how suspended sediments impair fish sensory systems and reproductive success, and how heavy metals and pesticide residues elicit acute and sub lethal toxicological responses across trophic levels. The synergistic effects of multiple stressor, increasingly compounded by climate change, are found to accelerate community restructuring toward pollution-tolerant assemblages at the expense of sensitive endemic species. The review further evaluates landscape-scale and reach-level mitigation strategies, including riparian buffer restoration, constructed wetlands, low-impact development infrastructure, and integrated watershed management frameworks. The paper concludes by recommending critical knowledge gaps and research priorities essential for reversing the global decline of freshwater fish biodiversity in the hyper anthropogenic era.*

**Keywords:** Water runoff, Fish biodiversity, Eutrophication, Sedimentation, Non-point source pollution

## INTRODUCTION

Freshwater ecosystems, though covering less than one percent of the Earth's surface, sustain approximately ten percent of all described species and more than one-third of all vertebrate species (Dudgeon, 2024). Fish, as keystone components of these systems, serve critical ecological roles spanning nutrient cycling, energy transfer across trophic levels, and provision of ecosystem services of immense socioeconomic importance. Yet freshwater fish biodiversity is declining at rates far exceeding those observed in terrestrial or marine realms, with an estimated 30 percent of freshwater fish species currently classified as threatened, endangered, or extinct (Fortin-Hamel & Chapman, 2024; Collen *et al.*, 2014). A 2024 update to the Living Planet Index for Migratory Freshwater Fishes further documented an average 81 percent decline in monitored populations of 284 migratory species between 1970 and 2020 (Deinet *et al.*, 2024), underscoring the accelerating severity of freshwater biodiversity loss.

Among the numerous anthropogenic stressors responsible for this decline, water runoff stands out as a particularly diffuse and difficult-to-manage threat. Unlike point source pollution, which originates from discrete, identifiable locations, runoff-mediated pollution enters aquatic systems through complex, spatially distributed pathways shaped by land use, precipitation intensity, soil type, topography, and seasonal dynamics. The three principal categories of water runoff—agricultural runoff, urban storm water, and forestry-related overland flow—each carry distinct suites of contaminants and exert context-dependent effects on fish communities.

Agricultural runoff, driven by the application of fertilizers, pesticides, and the management of animal waste on approximately 52 percent of land area in the United States alone, delivers massive loads of nitrogen, phosphorus, and biocidal compounds into receiving water bodies (Hollingsworth *et al.*, 2022). Urban storm water, channelled from impervious surfaces such as roads, parking lots, and rooftops, transports heavy metals, polycyclic aromatic hydrocarbons (PAHs), pharmaceutical residues, and microplastics directly into streams and rivers, largely bypassing natural filtration processes (Schäfer *et al.*, 2024). Forestry practices, including clear-cutting and road construction, mobilize fine sediments and alter hydrological regimes in ways that further degrade fish habitat quality.

The consequences for fish communities range from acute mortality during acute pollution events to chronic, sub-lethal effects that progressively erode species richness, abundance, and reproductive output. Critically, these impacts are increasingly co-occurring with climate change, which amplifies flood and drought frequency, intensifies runoff events, and reduces the thermal tolerance of many fish species, creating compound stressors that challenge both individual fitness and community resilience (Dudgeon, 2025).

This review synthesizes current scientific understanding of the effects of water runoff on fish biodiversity across freshwater and coastal ecosystems. It examines the principal mechanisms of impact, evaluates evidence for community-level responses, explores synergistic interactions with other stressors and critically assesses the efficacy of available mitigation strategies. The paper is intended to serve researchers, resource managers, and policymakers engaged in the conservation and sustainable management of aquatic biodiversity.

## AIM AND OBJECTIVES OF THE REVIEW

### Aim of the Review

The aim of this review is to consider the effects of water runoff on fish biodiversity in the ecosystem.

### Objectives of the Review

The objectives of this review are to:

- Review the sources and composition of water runoff.
- Review the mechanisms of impacts on fish biodiversity.
- Review the community-level responses to runoff-mediated stressor.

## SOURCES AND COMPOSITION OF WATER RUNOFF

### • Agricultural Runoff

Agricultural runoff constitutes the dominant source of non-point source pollution in most developed and rapidly industrializing nations. The primary constituents include nitrogen and phosphorus compounds derived from synthetic fertilizers and animal manure, pesticide residues from herbicide and insecticide applications, and suspended sediments mobilized during tillage and precipitation events. Studies conducted across North American agricultural watersheds have documented nitrogen concentrations in runoff reaching several-fold above background levels, while phosphorus loading from row-crop agriculture has been consistently identified as a driver of lacustrine and riverine eutrophication (Hollingsworth *et al.*, 2022). Globally, an estimated 15 million tonnes of phosphorus and 21 kg of nitrogen per hectare are lost annually from croplands through leaching and surface runoff, with much of this load accumulating in downstream aquatic systems (Zhou *et al.*, 2024).

Pesticide transport via surface runoff is particularly concerning given the diversity of active compounds entering aquatic systems. Organophosphate insecticides, neonicotinoids, fungicides, and herbicides have all been detected in surface water at concentrations biologically active to non-target aquatic organisms. Yamamuro *et al.* (2019) provided compelling field-scale evidence of food-web-mediated impacts, demonstrating that neonicotinoid applications to surrounding watersheds coincided with an 83 percent reduction in zooplankton biomass and the subsequent collapse of commercially harvested fish populations in a Japanese lake. Environmental DNA studies of fish assemblages near agricultural zones in the Great Barrier Reef catchment have demonstrated significant reductions in species richness during wet seasons, when runoff loads are highest, compared to dry-season baseline conditions—with pesticide and nutrient concentrations explaining a substantial proportion of community compositional variance (Chapman *et al.*, 2024).

### • Urban Storm water Runoff

Urban storm water runoff represents a chemically complex and ecotoxicologically significant pollution source, particularly as global urbanization accelerates. Impervious surfaces in cities generate approximately five times the runoff volume of equivalent woodland areas, fundamentally altering watershed hydrology and solute transport dynamics. Storm water collected from urban catchments routinely contains a mixture of heavy metals (zinc, copper, lead, cadmium), PAHs from combustion and petroleum products, chlorophenols, microplastics, and pharmaceutical compounds (Schäfer *et al.*, 2024). A bibliometric analysis of

emerging contaminants in storm water-mediated urban waters spanning 1994–2024 identified a marked post-2020 shift in research priority toward microplastics and per- and polyfluoroalkyl substances (PFAS) as contaminants of concern (Liu *et al.*, 2025), reflecting the evolving chemical landscape of urban runoff.

The 'first flush' phenomenon, whereby the initial portion of a runoff event carries disproportionately high contaminant loads following a dry antecedent period, means that even brief storm events can deliver toxic pulses to receiving streams. Research has demonstrated that urban storm water exhibits toxicity to a wide range of aquatic organisms, with highest risks associated with metals, PAHs, pesticides, and phthalate (Schäfer *et al.*, 2024; Robinson *et al.*, 2026). The lateral line sensory system of larval fish are critical for predator avoidance, schooling behavior, and prey detection has been shown to suffer structural damage from storm water exposure even at sub-lethal concentrations, with consequences extending to individual fitness and population viability.

- **Forestry and Peri-Urban Runoff**

Forestry operations, particularly clear-cutting and the construction of unpaved logging roads, substantially elevate suspended sediment delivery to streams by removing vegetation that stabilizes soils and intercepts precipitation. Deforestation of riparian zones additionally increases solar radiation reaching the water surface, elevating water temperatures and exacerbating the stress imposed by sedimentary turbidity on temperature-sensitive fish species. Fortin-Hamel and Chapman (2024) demonstrated that the combined exposure of a threatened freshwater fish (*Miniellus anogenus*) to elevated turbidity and increased water temperature produced interactive physiological and behavioral impairments exceeding the effects of either stressor alone or illustrating the compounding risks of forestry-driven runoff in the context of climate warming.

## MECHANISMS OF IMPACT ON FISH BIODIVERSITY

- **Eutrophication and Hypoxia**

The most extensively studied pathway by which water runoff degrades fish biodiversity is eutrophication, the process by which excessive nutrient loading stimulates explosive algal growth that ultimately depletes dissolved oxygen and disrupts aquatic food webs. Nitrogen and phosphorus introduced via agricultural and urban runoff stimulate the proliferation of phytoplankton and cyanobacteria, leading to algal blooms that shade submerged aquatic vegetation, consume dissolved oxygen during nocturnal respiration and decomposition, and release potent biotoxins such as microcystins (Lan *et al.*, 2024). The resulting hypoxic or anoxic conditions and so-called 'dead zones' are physiologically lethal to most fish species and represent a direct mechanism of population collapse. The scale of this phenomenon is illustrated by the Gulf of Mexico hypoxic zone, which reached 6,705 square miles in summer 2024, fuelled by agricultural runoff delivering over 70 percent of excess nitrogen loads from the Mississippi-Atchafalaya River Basin (Organic Farming Research Foundation, 2024).

The relationship between nutrient runoff and fish biodiversity loss is not linear; threshold effects have been documented whereby once nutrient loading crosses critical tipping points, rapid state shifts from clear-water, macrophyte-dominated systems to turbid, phytoplankton-dominated systems occur with severe consequences for fish assemblage diversity and composition. Species adapted to

clear-water conditions like many rheophilic and visually oriented predatory fishes are systematically replaced by eutrophy-tolerant cyprinids and other generalists, reducing overall biodiversity indices and undermining ecosystem function (Wang *et al.*, 2024).

- **Sedimentation and Turbidity**

Fine sediment loading from surface runoff is widely recognized as among the most damaging physical stressors for freshwater fish biodiversity. Suspended sediments elevate turbidity, reducing light penetration and curtailing the productivity of primary producers that underpin aquatic food webs. Benthic deposition of fine particles smothers gravel substrates critical for spawning by salmonids and other lithophilic species; infilling of interstitial spaces prevents gas exchange across egg membranes, causing embryonic asphyxiation and trapping sac fry (U.S. EPA, 2026). Species dependent on coarse gravel habitat throughout their life cycles such as darters, lampreys, and unionid mussels suffers disproportionate declines when substrates are embedded with fine sediments.

High turbidity additionally impairs the visual foraging efficiency of piscivorous and insectivorous fishes, disrupts mate recognition and courtship signals in species relying on visual cues, and reduces the detection range for predator avoidance. Studies has established differential effects between sedimentary turbidity (inorganic suspended particles from runoff and erosion) and algal turbidity (organic particulates from eutrophication), with the former tending to scatter light more broadly across the visible spectrum and the latter absorbing light particularly in the blue and ultraviolet ranges, yielding distinct ecophysiological impacts depending on the primary runoff source (Utne-Palm *et al.*, 2018).

- **Chemical Contamination: Heavy Metals**

Heavy metals transported by urban and industrial runoff exert a range of physiological and behavioral toxicological effects on fish. Zinc, copper, lead, and cadmium were consistently detected in storm water across urban watersheds and accumulate in gill tissues and internal organs, impairing osmoregulatory function, enzyme activity, and immune competence. A systematic review of heavy metal toxicity across freshwater fish species confirmed that these metals consistently impair growth, behavior, reproduction, and immune function across taxonomically diverse species (Sharma *et al.*, 2024). Sub lethal metal exposures documented in field and laboratory studies include reduced growth rates, impaired reproductive success, disrupted endocrine signalling, and behavioural alterations such as reduced anti-predator responsiveness (Schäfer *et al.*, 2024). The phenomenon of bioaccumulation and biomagnification ensures that even moderate contamination of lower trophic levels translates into substantially elevated metal burdens in top predatory fish, with implications for both species conservation and human food safety.

- **Pesticide and Agrochemical Contamination**

Agricultural and urban runoff introduces a diverse array of pesticidal compounds into aquatic environments at concentrations frequently exceeding ecological threshold values. Organophosphate insecticides such as chlorpyrifos, malathion, and diazinon inhibit acetylcholinesterase activity in fish, disrupting neuromuscular transmission and producing characteristic toxicological syndromes. Neonicotinoids, though primarily targeted at insects, affect invertebrate prey populations upon which many fish depend, resulting in food web-mediated trophic cascades

that reduce fish condition and recruitment; neonicotinoids currently account for approximately 24 percent of the global insecticide market and are registered for use in over 120 countries (Zhang *et al.*, 2025). Yamamuro *et al.* (2019) provided landmark field evidence that neonicotinoid-driven zooplankton collapse triggered the commercial collapse of fish populations in a Japanese lake, demonstrating that indirect trophic pathways can produce community-level outcomes as severe as direct chemical toxicity. Herbicides such as atrazine and glyphosate alter aquatic primary productivity and have been shown to disrupt endocrine function in fish at environmentally relevant concentrations.

Researchers have detected pesticides such as organochlorides and pyrethroid compounds in urban runoff samples at levels sufficient to harm aquatic life in the majority of samples collected across broad geographic surveys (Chesapeake Bay Foundation, 2025). The interactive effects of pesticide mixtures, frequently present simultaneously in runoff, remain poorly characterized but likely represent greater ecotoxicological risks than assessments of individual compounds suggest.

- **Hydrological Alteration**

Beyond chemical loading, water runoff alters the hydrological regimes of receiving watercourses in ways that fundamentally restructure fish habitat. The conversion of permeable natural surfaces to impervious urban cover amplifies peak flood discharge and reduces base flow, creating 'flashy' hydrological regimes characterized by rapid, high-magnitude flow events followed by extended low-flow periods. Fish assemblages adapted to natural, seasonally predictable flow regimes are disrupted by these altered patterns; spawning migrations triggered by specific flow cues are mistimed, spawning substrates are scoured or deposited at inopportune times, and habitat connectivity along river corridors is periodically interrupted by extreme flows (Dudgeon, 2025). Agricultural drainage networks similarly accelerate the delivery of water from the landscape to streams, reducing the transit time available for natural attenuation of pollutants.

## COMMUNITY-LEVEL RESPONSES TO RUNOFF-MEDIATED STRESSOR

- **Species Richness and Compositional Shifts**

Empirical studies conducted across diverse geographic contexts consistently demonstrate that increasing intensity of runoff-associated pollution is negatively correlated with fish species richness. Zhong *et al.* (2025), in a study of montane fish assemblages in China, documented significant reductions in fish diversity along water quality gradients shaped by land use intensification, with landscape-scale anthropogenic activity mediating biodiversity through multiple water quality pathways.

The directionality of compositional change is consistent across studies: pollution-sensitive species including native salmonids, cyprinids with restricted environmental tolerances, and diadromous fishes are displaced, while tolerant species such as common carp, channel catfish, and introduced centrarchids come to dominate degraded assemblages. These shifts in community composition carry functional consequences, as declining species diversity typically accompanies reduced functional diversity like narrowing the range of ecological roles fulfilled within the system and diminishing resilience to further perturbation.

- **Synergistic Effects of Multiple Stressor**

A critical finding emerging from recent research is that runoff-mediated stressor rarely act in isolation; their co-occurrence with other anthropogenic and environmental factors produces synergistic or antagonistic interactions that cannot be predicted from single-stressor experiments alone. The interaction between elevated water temperature from climate change and sedimentary turbidity from runoff provides a well-documented example: Fortin-Hamel and Chapman (2024) showed that their combined exposure produced greater impairment of fish physiology and behavior than the additive effects of each stressor, a finding with important implications for conservation under future climate scenarios.

Similarly, Zhong *et al.* (2021) demonstrated through analysis of long-term, globally distributed fish community datasets that the effects of climate-driven temperature change on community thermal index were significantly exacerbated in catchments with high levels of land use, indicating that runoff-mediated water quality degradation reduces community resilience to thermal stress. These synergistic relationships underscore the inadequacy of single-stressor management approaches and highlight the necessity of integrated, landscape-scale conservation strategies.

- **Impacts on Reproductive Biology and Recruitment**

Sub lethal effects of runoff pollution on fish reproduction and early life stages represent a key mechanism through which biodiversity is eroded over time even in the absence of acute mortality. Endocrine-disrupting compounds transported via runoff—including certain pesticides, pharmaceutical residues, and industrial chemicals—interfere with sex hormone synthesis and signalling in fish, producing intersex phenotypes, altered secondary sexual characteristics, and impaired gametogenesis documented across numerous field studies. Scott and Flick (2008) demonstrated gonadal intersex, skewed sex ratios, and vitellogenin induction in native fish populations downstream of estrogenic effluents, illustrating how feminizing compounds reaching waterways via runoff and wastewater pathways can reshape population reproductive structure. Sediment-mediated embryo asphyxiation and the disruption of spawning substrate availability further reduce recruitment success in lithophilic species, creating population sinks in heavily impacted reaches. The cumulative effect of these reproductive impairments on population viability can be substantial over ecologically relevant timescales, particularly in long-lived species with low intrinsic rates of population increase.

## MITIGATION STRATEGIES AND MANAGEMENT APPROACHES

- **Riparian Buffer Zones**

Riparian buffer zones are strips of native vegetation maintained along stream banks and watercourse margins which are among the most cost-effective and ecologically beneficial measures for intercepting runoff before it reaches watercourses. Well-designed buffers trap suspended sediments, promote nutrient uptake by terrestrial vegetation, and provide organic matter inputs to stream food webs, shade channels to moderate temperatures, and stabilize stream banks against erosion. Meta-analyses of buffer effectiveness consistently demonstrate substantial reductions in sediment and nutrient delivery to streams from adjacent agricultural fields, with wider and more structurally complex buffers providing greater filtration efficacy. Quantitative modelling indicates that a 15 m forested corridor retains approximately 67 percent of upland

pollutant inputs and supports around 79 percent of biodiversity compared to wider reference buffers (Bentrup *et al.*, 2025), while a global meta-analysis confirmed that forested riparian buffers support on average 32 percent more reference species than converted riparian zones in human-modified landscapes (Leal *et al.*, 2026). Restoration of riparian vegetation is therefore a primary recommendation in virtually all freshwater biodiversity conservation frameworks, including the Emergency Recovery Plan for global freshwater biodiversity (Dudgeon, 2024).

- **Constructed Wetlands and Retention Infrastructure**

Constructed wetlands designed for storm water treatment offer a multi-functional approach to reducing the impacts of urban and agricultural runoff. By detaining water and promoting sedimentation, plant uptake, and microbial degradation of contaminants, these systems can substantially reduce nutrient, metal, and pesticide loads before they reach natural watercourses. Research on bio-retention treatment of urban storm water has demonstrated its capacity to rescue lateral line developmental deficits in zebra fish exposed to storm water, providing direct evidence that engineered treatment infrastructure can protect sensitive fish physiological systems from runoff contamination (Upton *et al.*, 2018). However, the same study noted that coho salmon, as a more sensitive salmonid, showed persistent lateral line impairment even after bio-retention treatment, indicating that current treatment technologies may not fully protect all species.

- **Low-Impact Development and Green Infrastructure**

Low-impact development (LID) strategies seek to restore the hydrological functioning of developed landscapes by promoting infiltration, evapotranspiration, and on-site retention of storm water. Green roofs, permeable pavements, rain gardens, bioswales, and urban tree canopy expansion all reduce the volume and peak discharge of runoff entering drainage networks, attenuating the flashy hydrological regimes that destabilize stream channels and amplify pollutant loads. At the watershed scale, the systematic deployment of LID measures across urban catchments has been modelled and observed to produce measurable improvements in receiving water quality and biotic integrity, though the magnitude of benefit depends strongly on the spatial configuration and catchment-wide extent of implementation.

- **Agricultural Best Management Practices**

Within agricultural watersheds, a suite of best management practices (BMPs) has been developed to reduce runoff volume, nutrient loading, and pesticide delivery. These include cover cropping, conservation tillage, precision fertilizer application, integrated pest management, vegetated drainage ditches, constructed wetland filters, and the management of tile drainage systems. Empirical evaluations of BMP effectiveness indicate variable and context-dependent reductions in nutrient and sediment export, with the greatest benefits achieved when multiple complementary practices are deployed at strategically prioritized locations within catchments. Integrated watershed management frameworks that combine spatial targeting of BMPs with adaptive monitoring and stakeholder engagement have demonstrated the most sustained improvements in receiving water quality and fish biodiversity metrics.

- **Policy and Regulatory Frameworks**

Technical mitigation measures alone are insufficient without supportive policy and institutional frameworks. The inclusion of

inland waters in Targets 2 and 3 of the 2022 Global Biodiversity Framework requires a protection of 30 percent of inland waters and restoration of 30 percent of degraded ecosystems by 2030 which represents a significant advance in the international policy landscape for freshwater biodiversity conservation (Dudgeon, 2024). National-level implementation through water quality regulations, land use planning instruments, agricultural subsidy reform, and incentive programs for conservation practice adoption is essential for translating these global commitments into watershed-scale outcomes that protect fish communities.

## CONCLUSION

Water runoff, in its agricultural, urban, and forestry-related forms, exerts profound and pervasive negative effects on fish biodiversity through a suite of interacting chemical, physical, and hydrological mechanisms. The scientific evidence reviewed here demonstrates that sediment loading, nutrient-driven eutrophication, chemical contamination, and hydrological alteration collectively restructure fish communities, replacing diverse assemblages of native species with impoverished, pollution-tolerant communities. These impacts are being amplified by climate change, which intensifies runoff events, elevates water temperatures, and reduces the capacity of fish communities to withstand additional anthropogenic stressors.

Effective conservation of freshwater fish biodiversity in the face of escalating runoff pollution demands a multi-scale response encompassing riparian restoration, engineered treatment infrastructure, low-impact development, agricultural best management practices, and coherent policy frameworks anchored in international biodiversity commitments. Critically, the translation of existing scientific knowledge into effective conservation action is a persistent weakness in freshwater management globally, and must be accelerated if the curve of fish biodiversity decline is to be meaningfully bent within the timeframe of the Global Biodiversity Framework's 2030 targets. This review underscores the urgency of that challenge and the breadth of scientific evidence now available to guide a more effective response.

## RECOMMENDATIONS

Despite substantial advances in understanding the effects of water runoff on fish biodiversity, significant knowledge gaps remain broad. Nevertheless, several priority areas merit focused research attention in coming years.

Firstly, the ecotoxicology of runoff-associated contaminant mixtures remains poorly characterized. Most regulatory thresholds and impact assessments are based on single-compound exposures, yet fish in real-world environments are concurrently exposed to complex mixtures of metals, pesticides, pharmaceuticals, and micro-plastics, the interactive toxicological effects of which remain largely unquantified. Mixture toxicity frameworks and high-throughput toxicological screening approaches represent promising methodological advances in this space.

Secondly, long-term monitoring datasets of sufficient spatial and temporal resolution to detect biodiversity trends attributable to runoff pollution, as distinct from climate variability and other co-occurring stressor remain rare outside of North America and Western Europe. Expanding freshwater biodiversity monitoring networks in rapidly developing regions of Asia, Africa, and Latin America where runoff pressures are intensifying alongside

accelerating land use change which is a critical priority for global conservation assessment.

Thirdly, the effectiveness of mitigation interventions for restoring fish biodiversity, as opposed to improving physicochemical water quality metrics, is frequently not evaluated with adequate rigor. Long-term, replicated, before-after-control-impact study designs that track fish community recovery following BMP implementation are needed to build an evidence base for adaptive management and to identify the conditions under which mitigation investments are most cost-effective.

Fourthly, the cumulative legacy effects of long-term contaminant accumulation in sediments such as persistent organic pollutants and heavy metals deposited over decades of agricultural and urban runoff on fish population genetics, epigenetics, and long-term evolutionary potential represent a poorly understood dimension of the runoff biodiversity problem with implications for the long-term recovery potential of impacted systems.

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