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Measures for improving water quality to bend the curve of global freshwater biodiversity loss

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Abstract

The degradation of water quality is among the most pervasive, complex, and challenging problems that impact the world's freshwater ecosystems and their biodiversity. Contamination pathways vary globally and involve a diverse array of pollutants that include simple (e.g., road salt) to more complex (e.g., pharmaceuticals) chemicals, as well as non-natural sources of heat, light, noise, silt, plastics, and also pathogens from wastewater or livestock. These pollutants can cause significant harm on their own, in mixtures or in combination with other stressors. Over geographically extensive areas affecting most river systems and many standing waters, pollutants have been released either legally, illegally or incidentally over inter-decadal to centennial timescales. Some pollutants and pathogens also affect people through morbidity, mortality, and economic loss, so that there is synergy in protecting freshwater biodiversity against pollution while delivering human well-being through the global Sustainable Development, ecosystem services, and climate change agenda. Existing approaches aimed at reducing water pollution are insufficient and require a previously unmatched step-change in approach to address the major impacts from both conventional and emerging pollutants, such as pharmaceuticals, pesticides and microplastics. Success stories on measures that address freshwater pollution are relatively limited such that available examples are often "works in progress" or represent partial success. Here, we review both challenges and potential solutions to freshwater pollution, focusing on case studies that range across (i) informing action through monitoring and understanding pollutant trends and ecosystem impacts; (ii) regulation and enforcement nationally and internationally to reduce pollutant loads, substitute harmful substances, and ensure that polluters pay; (iii) improving the management and remediation of pollutants at source, *in situ*, and across catchments, including scalable, nature-based solutions, and (iv) addressing the systemic drivers of pollution through education, incentives, and market mechanisms. Significant challenges remain, but water quality restoration in freshwater ecosystems will bring manifold benefits for freshwater biodiversity and human well-being at all scales from local to global.

Key words: freshwater ecosystems, water pollution, response measures, restoration, case studies

1. Introduction

Rapidly declining biodiversity, decreasing species' populations, and disrupted ecological functions in freshwater ecosystems are now corroborated widely through a range of local and global data (Harrison et al. 2018; Tickner et al. 2020; Albert et al. 2021). In closely monitored regions such as North America and Europe, past biodiversity recovery that arose from regulatory legislation has now stalled or might even be reversing (Haase et al. 2023; Pharaoh et al. 2023; Rumschlag et al. 2023). Addressing biodiversity loss in freshwater systems is a complex problem due to the multitude of anthropogenic pressures that impact them, the disproportionally large species richness and diversity they support, and the wide array of practitioners, communities, and stakeholders that manage or rely on freshwater resources (Strayer and Dudgeon 2010; Stendera et al. 2012; Cooke et al. 2023). Understanding the role of degraded water quality, therefore, requires recognition that pollution acts both directly and alongside other impacts, most notably the physical modification of freshwater ecosystems and their catchments, reduced connectivity within and between freshwater environments, modified flow regimes, the over-exploitation of freshwater resources, the proliferation of invasive alien species, and variations in temperature or discharge due to climate change (Dudgeon et al. 2006; Durance and Ormerod 2007; Whitehead et al. 2009; Verberk et al. 2016; Reid et al. 2019; Cuthbert et al. 2022). As recognized by other contributors to this special issue, the need to implement solutions is urgent, multi-faceted, and requires actions at scale and in ways that are prioritized to have the greatest effect in bending the curve of biodiversity loss (Cooke et al. 2025; Tickner et al. 2025).

The degradation of water quality and consequences for freshwater biodiversity is a multiple stressor problem in its own right. First, because impairments to water quality are so widespread geographically that they interact with most other pressures, often exacerbating or facilitating their impacts (Verhoeven et al. 2006; Nõges et al. 2016; du Plessis 2022). Second, water quality impairment frequently reflects multiple substances, pathogens, or other nonchemical pollutants such as noise, radioactivity, and light pollution that cooccur in freshwaters, both intentionally or unintentionally, as a result of human activities (Spears et al. 2021). Water pollution is often the result of direct, point-source inputs (e.g., a sewage outflow, industrial discharge, and oils spills) involving contaminants that are traceable to a single-identifiable source (Holt 2000). Alternatively, it can reflect diffuse sources, for example, nutrient runoff from catchment-wide agriculture, road runoff, or the atmospheric transport of substances from distant emission sources (OECD 2017). The timescales involved also vary from episodic or event-related "pulses" (e.g., spillages or acid episodes reflecting snowmelt or rainstorms) to longer-term and near-continuous discharges over years to decades. These contrasting spatial and temporal scales mean that water quality is a local, regional, international, and transboundary issue, where responses can range from addressing pollution from local incidents to solving long-term, large-scale problems that require international cooperation. Moreover, changes in water quality bring risks not only for ecosystem structure and function (Feckler et al. 2025), but also for the subsequent human uses of water with associated effects on health, amenity, economy, and food production (Schwarzenbach et al. 2010; Damania et al. 2019). In combination, these circumstances mean that the need to address degraded water quality is among the most pressing of all issues in the protection of freshwater ecosystems and the management of water resources.

Here, we consider the response actions needed to protect and improve water quality for the benefit of freshwater biodiversity and people. To do so, first we outline and exemplify some of the principal sources and routes of water quality degradation under different circumstances around the world. These freshwater pollution sources, pressures, and responses can be incorporated into the DPSIR (Drivers-Pressures-State-Impact-Response) framework (Gari et al. 2018) as a conceptual lens throughout the study (Fig. 1). Furthermore, we present a series of evidence-informed, legislative, environmental, and incentive-oriented response measures that, if embraced, have the potential to improve water quality, as exemplified through case studies (Table 1). Finally, we consider how to overcome various challenges in implementing response measures to bend the curve of freshwater biodiversity loss. We acknowledge that water quality intersects with other pressures and threats facing freshwater biodiversity, so efforts that focus solely on water quality without considering other issues such as climate change or habitat impairment are unlikely to be fully effective.

One of the potential solutions to addressing water quality issues is through environmental flows (e-flows)—specifically the modification of the volumes, timing, and quality of river flows that can sustain aquatic ecosystems while also providing sustainable support for human cultures, livelihoods, and well-being (Arthington et al. 2018). As well as through their intrinsic quality, flow modifications have the potential to di-

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Fig. 1. DPSIR (Drivers-Pressures-State-Impacts-Responses) framework for freshwater pollution. Solid lines represent direct causal relationships, where one component affects another. Dashed lines represent feedback relationships, where one component can influence the state of another. Together, this framework employs a systems approach to the complex problem of freshwater pollution.

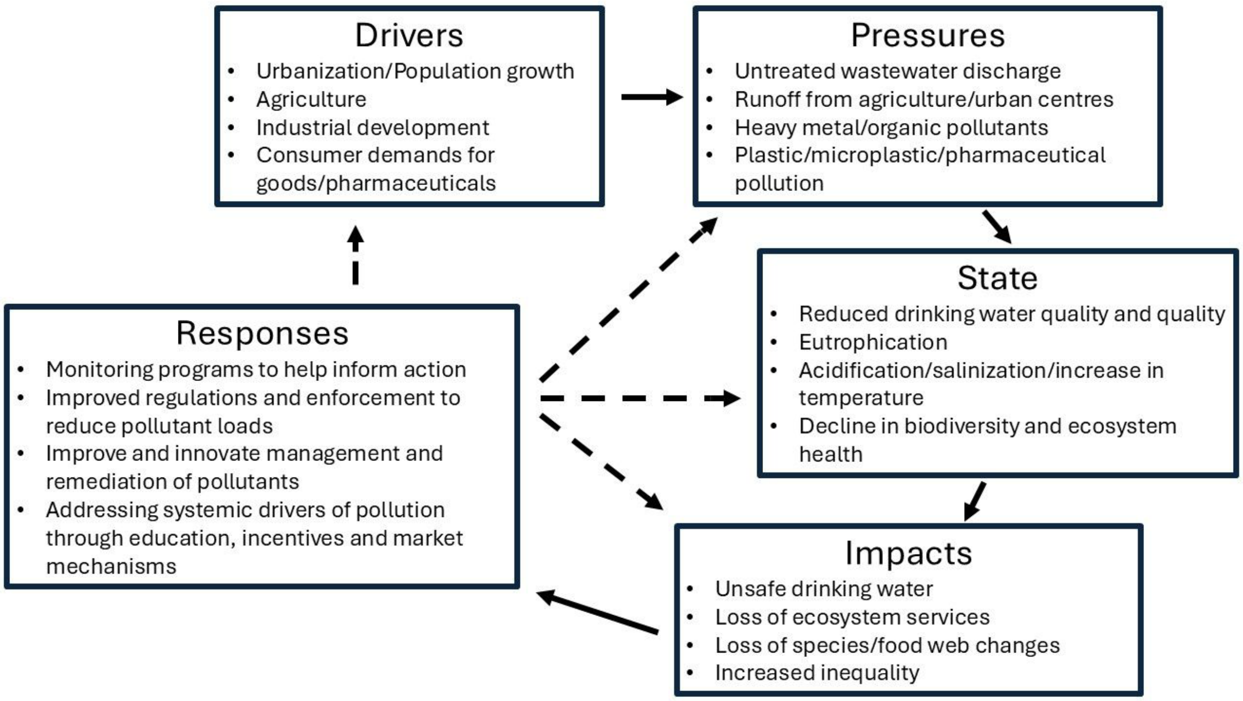

Table 1. Fourteen key measures for improving water quality to bend the curve of global freshwater biodiversity loss, organized across four strategic themes: (i) informing action through monitoring trends, understanding pollutant impacts, and identifying safe limits; (ii) regulating pollutants and enforcing action nationally and internationally; (iii) managing and remediating pollutants at source, in situ, and across catchments; and (iv) addressing systemic drivers of pollution through incentives, awareness, and market mechanisms.

Measure	Monitoring trends and ecological effects of pollutants	Regulating pollutants and enforcing action	Improving management and remediation of pollutants	Addressing systemic drivers of pollution
Establish baseline and target water quality conditions	✓			
Identify biological thresholds for different pollutants	✓	✓		
Developing regulations for interactive pollutants	✓	✓		
Use policy and regulations to limit pollutants		✓		
Develop international agreements to address transboundary water quality drivers		✓		
Identify alternative options to materials and practices that contribute to pollution	✓	✓	✓	✓
Prioritize the global problem of sanitary waste			✓	
Embrace and accelerate science-based technical solutions to control pollution at source			✓	
Embrace and apply science-based technical solutions to control nonpoint source pollution			✓	
Science-based solutions to recover and restore polluted locations			✓	
Leverage nature-based solutions to improve water quality				✓
Incentivize action				✓
Apply market instruments that reflect downstream pollution costs		✓		
Public awareness and behavioural choice				✓

Note: Each measure is mapped to its corresponding theme(s), illustrating their overlapping roles in supporting freshwater ecosystem recovery.

lute pollutants or prevent polluting discharges. We do not consider this option in depth in the current review; however, as e-flows to curb global biodiversity loss have been covered in-depth as a stand-alone review in this special issue to which we direct the reader (Arthington et al. 2024). The related concept of cultural flows, where the rights and decision-making authority of Indigenous Nations or Peoples are recognized in flow management, could also have pivotal importance in protecting water quality, though peer-reviewed examples are still few, and we consider this an area in need of further exploration (Bergbusch et al. 2025).

2. The issue

UN data reveal the global extent of water quality impairment. For example, only around 38% of industrial wastewater and 44% of the world's domestic wastewater is adequately treated prior to release, varying from around 74% to <5% between high- and low-income nations (Jones et al. 2021). Traditional water quality indicators such as dissolved oxygen, nutrients, and pH show that over 40% of water bodies monitored globally are below good quality (https://www.unwater.org/water-facts/water-quality-and-wastewater). Already by the 1990s, nitrogen fluxes through rivers in the world's populated areas were orders of magnitude greater than background (Vitousek et al. 1997). N fluxes are on course to double globally between 1970 and 2050, by which time 80% of loadings to rivers will be from sewage, aquaculture, and agriculture (Beusen et al. 2022). Other example pollution problems with a growing global impact include (i) concentrations of human pharmaceuticals that exceed safe concentrations for aquatic organisms in around 25% of sampling locations globally (Wilkinson et al. 2022); (ii) over 64% of global agricultural land at risk from pesticide pollution, in turn creating risks to surface waters in over 40% of the global land area for insecticides alone (Ippolito et al. 2015; Tang et al. 2021); and (iii) plastics, of which the world's rivers now transport around 20 million tonnes annually into the world's oceans with further substantial growth inevitable despite attempts at regulation (Borrelle et al. 2020).

Considering pollutants by source, firstly, *domestic wastewater*, dominantly human sewage, remains a major impairment to water quality. Around 270–350 billion cubic meters of wastewater are released annually into the world's freshwaters affecting over a million kilometers of river and contributing up to 20% of downstream dissolved carbon loads in the most polluted regions (Cao et al. 2025). Effects include deoxygenation and increased suspended solids loads with the capacity for major biological impacts. Sewage also transports human and animal pathogens such as cholera, dysentery, typhoid, and schistosomiasis that together cause around 1.4 million deaths per year, largely in Africa and Asia, particularly among children (WHO 2023).

Point-source sewage outputs have ameliorated over recent decades in North America and Europe through better regulation of wastewater treatment (US Clean Water Act and the EU Urban Waste Water Treatment Directive), but progress is slower in global regions such as Central and Southern Asia (OECD 2012). Moreover, even following modern biological treatment, organic matter in wastewater can vector persistent chemicals such as PCBs and PFAS (Folorunsho et al. 2025). These and other contaminants, such as microplastics, can also become diffuse pollutants during the post-treatment disposal of sludge to land (Rolsky et al. 2020). Furthermore, typical treatment processes are ineffective at immobilizing contaminants such as human or veterinary pharmaceuticals (Ortúzar et al. 2022). Hundreds of such compounds occur in wastewater as metabolites, excreted products, or through direct disposal to drains. These include medications for diabetes (metformin), epilepsy (e.g., carbamazepine), cancer (cyclophosphamide), heart conditions (e.g., beta-blockers and statins), painkillers (e.g., ibuprofen, paracetamol), antihistamines (e.g., fexofenadine), anti-depressants (e.g., sertraline), hormonal treatments (e.g., birth control), and recreational or lifestyle drugs (e.g., caffeine, nicotine, and cocaine metabolites) (Wilkinson et al. 2022). As well as toxic effects, the widespread occurrence of antibiotics (e.g., sulfamethoxazole), and anti-fungal agents (e.g., fluconazole) pose risks, respectively, to anti-microbial resistance and ecosystem processes such as decomposition. Wastewater routes are also important for the occurrence of veterinary insecticides administered to pets such as dogs, cats, and rabbits (Perkins et al. 2021, 2024; Hadley et al. 2026).

Second, *agriculture* and *inland aquaculture* account for over a third of the global land area and around 70% of water withdrawals. Both livestock (roughly 80% of agricultural land) and crop production (20%) affect water quality through the use of N and P fertilizers, pesticides, and veterinary chemicals, sediment loss, and the disposal of animal slurries—often accompanied by a range of pathogens (Pandey et al. 2014). The catchment-wide and diffuse character of these pollutants poses a particular challenge for regulation (OECD 2017). As noted above, insecticide, herbicide, and fungicidal pollution from agriculture is of particular concern (Holt 2000), while the extensive use of N and P-based fertilizers contributes to eutrophication, harmful algal or cyanobacterial growth, and reduced oxygen concentrations in standing waters—all with negative impacts on freshwater biodiversity and function (OECD 2017; Beusen et al. 2022; Wang et al. 2024).

Agriculture and land-use changes such as deforestation are significant in the mobilization of sediments into freshwater ecosystems, particularly in arid lands, although effects vary with styles of tillage, cropping, and, in particular, vulnerability to climate change. Global systematic review suggests that agricultural expansion under climate change could increase soil erosion in excess of 75% relative to reference conditions (Eekhout and de Vente 2022). Ecological effects include increased turbidity with consequences for primary production and vegetation, but also effects on organisms such as fishes or benthic invertebrates by gill damage, reduced egg survival, and habitat loss (Donohue and Molinos 2009).

Third, *industry* causes both point-source and diffuse freshwater pollution, in the latter case through the emission, long-range transport, and subsequent deposition of air pollutants. These include the acidifying gasses responsible for acid deposition as well as a range of complex and persistent "legacy" compounds, such as polychlorinated biphenyls (PCBs) and poly-brominated diphenyl ethers (PBDEs)—in wide circulation as flame retardants. Industrial processes are diverse and complex so that pollutants include metals, acids, alkalis, hydrocarbons, solvents, dyes, paints, surfactants, phenols, formaldehyde, cyanides, fluorides, and gasses such as chlorine and ammonia (Fang et al. 2024). Industrial processes can also be significant in thermal pollution from diverse sources, such as spirit distilleries (e.g., Scotch Whisky), coal or nuclear power plants and data-handling facilities (Langford 1990; Yuan et al. 2023). Releases of hot water can raise downstream river temperatures by several degrees Celsius with consequences for oxygen concentrations and metabolic stress in ectothermic organisms.

Whereas point-source industrial pollution in wealthier nations has been abated partially by deindustrialization (e.g., the UK), regulation, and improved treatment, industrial activities elsewhere remain problematic. This problem is exemplified by pharmaceutical production, where expanded activity in low- and middle-income countries is not matched by sufficient waste-management infrastructure (Wilkinson et al. 2022). Even in richer nations, the traditional array of industrial pollutants is diversifying as emerging chemicals gain public attention, including compounds such as per- and polyfluoroalkyl substances (PFAS) or organic and inorganic nano-products from the electronics, energy, medical, cosmetics, food engineering, and telecommunications sectors.

Fourth are ongoing and legacy impacts from *mining, quarrying and other extractive activities*. Metal, mineral, and aggregate extraction began around 7000 years ago (Radivojević et al. 2010), to which industrialization has since added coal, oil and gas exploitation. These activities occur alongside effects from smelting, refining, coal gasification, and spoil disposal. Metal impacts, specifically, had a pivotal place in the development of aquatic pollution science (Carpenter 1924). Current estimates suggest that around 23 000 active and 160 000 disused metal mines affect around 480 000 km of river channels globally, for example, releasing toxic arsenic, lead, and mercury. Effects also impact 164 000 square kilometers of floodplains on which many freshwater organisms depend, but also where 23 million people are at risk (Macklin et al. 2023). Extensive impacts on freshwater arise from other widespread forms of mining such as open-cast or deep-cast coal extraction in countries including China, Brazil, India, Bangladesh, Australia, the USA, several European countries, Nigeria, and South Africa. Pollutants include acidified mine drainage, sulfate, and iron compounds, other metals, chloride, suspended sediments, and heated discharge (Gombert et al. 2019). Associated processes, for example, in coal gas, coking, or tar production, can be sources of cyanides and phenols (Scullion and Edwards 1980). Tailings ponds, which are used for waste storage in mining operations, can seep or spill hazardous materials that contaminate groundwater and surface waters, impacting both biodiversity and local communities (Jain and Das 2017; Cacciuttolo et al. 2023; Yu et al. 2023). The legacy of extracted metals, such as arsenic and mercury, is still detectable in lake whitefish and burbot around the abandoned Giant Mine on Great Slave Lake in the Northwest Territories, where contamination occurred through the discharge of mine wastewater, atmospheric deposition, and historic direct deposits of tailings into Yellowknife Bay, and remain a concern to local Indigenous communities (Cott et al. 2016).

Fifth, influences from *urbanization and associated infrastructure* on water quality range across their importance as sources of domestic wastewater and plastics, their "heat islands" effect on thermal runoff (Wang et al. 2023), and their role as major sources of artificial light at night (ALAN). With almost half of the human population globally living near freshwaters, ALAN is increasing rapidly worldwide (Kummu et al. 2011) and affects species' behaviour, including flight patterns in insects of aquatic origin, but also physiological processes (e.g., suppressing melatonin production in fish; Kupprat et al. 2020; Hölker et al. 2023). Physical modifications in urban landscapes also typically increase imperviousness, thereby resulting in more rapid discharge through storm drains, often accompanied by untreated wastewater (Perry et al. 2024). Typically, also, road runoff from urban areas and wider road networks carries a cocktail of pollutants that include de-icings salts (Hintz et al. 2022) as well as a range of oils, unburned fuels, polycyclic aromatic hydrocarbons (PAHs), tire pollutants such as 6PPD quinone, and metals from brake or engine wear (Maltby et al. 1995). The toxicological and ecological consequences for aquatic ecosystems are many and varied (Hintz and Relyea 2019; Tian et al. 2021).

Lastly, *nano-, micro-* (<5 mm), and *macro-plastics* (>5 mm) defy straightforward attribution. Sources range across agricultural (e.g., mulching films and silage wrapping), urban runoff and industry (OECD 2017; Strokal et al. 2023) and include single-use plastic or food-packaging litter, poor waste disposal, tire particles, road paint, textile fibers from laundry effluents, sewage sludge disposal to land, and leakage from plastic manufacturing (Wang et al. 2021). Plastic is an increasingly widespread pollutant in surface waters, sediments or organisms and examples include the Laurentian Great Lakes (Hataley et al. 2023), freshwater organisms in remote locations in the Amazon (Souza et al. 2023; Tuvikene et al. 2025) and food-web contamination in British river ecosystems (D'Souza et al. 2020). Risks to organisms arise from ingestion, entanglement, and co-transport of adsorbed compounds, with postulated effects including digestive tract damage (von Moos et al. 2012) or effects on nutrient uptake, growth, and reproduction (Sussarellu et al. 2016; Hurley et al. 2017; de Sá et al. 2018). There is some evidence of drinking water contamination, although assessments of human health effects are still at early stages (Koelmans et al. 2019; Ragusa et al. 2021, 2022).

3. Measures to improve water quality

3.1. Informing action through monitoring trends, understanding pollutant impacts, and identifying safe limits

For many traditional pollutants, such as organic pollution, nutrients, metals, and acidification, there is good understanding of the impacts on freshwater organisms through direct toxicity or associated physiological stress (Hogsden et al. 2009; Dorgham 2014; Amoatey and Baawain 2019). However, direct effects can have more complex ecological consequences for other organisms through competitive, predatory, or resource-limiting effects (Clements 1999; Gessner and Tlili 2016). Moreover, the short- or longer-term effects of emerging pollutants, such as complex organic chemicals, pharmaceuticals, and nano-contaminants are less well understood (Reid et al. 2019), especially where pollutants occur in mixtures or alongside other stressors (Akhtar et al. 2021; Frakes et al. 2022). The consequences of bioaccumulating and biomagnifying substances can also be difficult to quantify where individual effects arise slowly or affect populations through subtle changes in life history or in second generations (Saidon et al. 2024). A further challenge is where climate change or interannual variation complicates pollution effects in two major ways (Larsen et al. 2024). First, atmospheric heating is altering the global hydrological cycle by intensifying floods and droughts in some regions, which can mobilize or dilute pollutants (Singh et al. 2011; Ciszewski and Grygar 2016; Bolan et al. 2024). Secondly, increasing freshwater temperatures have direct effects on the metabolic rates of the many ectothermic organisms while simultaneously reducing oxygen solubility (Zhi et al. 2023). In combination, these effects exacerbate pollutant risks to organisms while also increasing oxygen-mediated stress (Woods et al. 2022). These complexities affect the regulation, management, and control of water quality problems and in many cases require fuller understanding to assess target conditions and drive remedial action (Geissen et al. 2015; Wu et al. 2023; Poyntz-Wright et al. 2025).

In all these cases—establishing baselines or targets, identifying thresholds of pollutant effects, diagnosing the causes or water quality degradation, or assessing the outcomes of management action, monitoring, and assessment are crucial. We note, however, that while biological and chemical assessments of pollution in economically developed countries are widespread and longstanding (e.g., Pharaoh et al. 2023), there is an urgent need for expanded activity elsewhere in world—for example, in the global south (see Section 3.3.1).

3.1.1. Establish baseline and target water quality conditions

The identification of baseline or target conditions is a non-trivial problem partly because of globally shifting baselines (Lofton et al. 2023), but also because most aspects of water quality vary temporally with discharge, seasonality, and even circadian patterns. Although some long-term data sets are available to assess trends, most involve local studies rather than national or continental assessments (e.g., Haase et al. 2023; Pharaoh et al. 2023), and very few empirical data extend backwards more than a few decades for either lakes or rivers (Smol 2019; Whelan et al. 2022). Furthermore, available baselines vary by region or country, making larger-scale assessments difficult (du Plessis 2022). Databases, such as the Global Environment Monitoring System for Freshwater (GEMS/Water) of the United Nations Environment Program (UNEP) aim to understand global trends in freshwater quality, but pre-industrial conditions are barely covered (Gwynne 1982).

In any event, historically pristine conditions are unlikely to offer realistic restoration targets so that water quality restoration is likely to aim for a dynamic range in which pollution is minimized and conditions shifted towards some appropriate and future-proofed reference conditions (Hawkins et al. 2010; Lynch et al. 2024). In Europe, the concept of "reference conditions" for inland waters has been enshrined into legislation through the Water Framework Directive (WFD: Council Directive 2000/60/EC). These target conditions use combinations of models and empirical data to identify water quality and associated communities of organisms that should be expected in the absence of major anthropogenic stressors (Lyche Solheim et al. 2025). Programmes of management measures should then aim to shift conditions towards the reference state, but in practice, restoration progress has been limited, partly because many European freshwater ecosystems face multiple challenges (Birk et al. 2020). In lakes, options for setting restoration targets include paleoenvironmental indicators, which can reveal historical shifts in water quality over decades to centuries through changes in assemblages of organisms preserved in dated sediment cores alongside physical and chemical data on metals, persistent organic pollutants, and soot particles (Smol 2008). Alongside other indicators, changes in diatom (Bacillariophyta) assemblage have been most widely used, as their siliceous frustules are typically well preserved, identifiable to species, and indicative of specific environmental changes (Smol and Stoermer 2010). This paleolimnological approach figures in our selected case study.

Case study: What is natural? Using "forensic paleolimnology" to assess lake contamination with Polycyclic Aromatic Hydrocarbons (PAHs)

One example of using forensic paleolimnological approaches, in this case to understand the occurrence of Polycyclic Aromatic Hydrocarbons (PAHs), was from the controversial industrial developments of the Canadian oilsands (or tar sands), which became commercial in the northern part of Alberta in the late-1960s but accelerated greatly after 1980. Petroleum (as bitumen) in this region is contained in a mixture of sand, clay, and water and requires processing before transport from this remote boreal region. PAHs were of special concern as pollutants linked to the petroleum industry, but the possibility of aerial transport and deposition was largely unknown. Moreover, elevated PAH concentrations can be "natural" and common close to the Earth's surface. Given the lack of systematic monitoring, and the lack of pre-impact PAH data in this case, missing data were reconstructed using paleoenvironmental approaches. Kurek et al. (2013*a*) selected five shallow lakes within a 50 km radius of a major processing facility, AR6 site, as well as a sixth lake ~90 km to the north-west. Each was subject to paleolimnological analyses of PAHs and biological responses to environmental changes using high-resolution sediment cores. ^{210}Pb methods were used for dating the sediments and PAHs were analyzed alongside biological indicators. The cores revealed how PAH contamination increased substantially (ranging from 2.5 to 23 times above pre-development levels) in lockstep with oilsands development beginning in the late-1960s and increas-

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ing in the post-1980s sediments. Rather than being "natural", PAH links to the oil sands industry were further substantiated by "fingerprinting" the types of PAHs to help rule out natural sources, such as forest fires (Kurek et al. 2013*b*).

Outside of Canada, paleolimnological techniques have been used worldwide, for example, in Ireland (O'Dwyer and Taylor 2009), Norway (Eide et al. 2011), Kazakhstan (Guo et al. 2025), Russia (Adams et al. 2018), and the Tibetan plateau (Yang et al. 2016) to show PAH contamination in relation to human activities. In addition to capturing trends in PAH contamination levels, these methods have focused and assessed the effects of regulatory controls, for example, in Europe (Gevao et al. 1998; Muri et al. 2006).

3.1.2. Identify biological thresholds for different pollutants

Biological thresholds for pollutants aid pollutant risk assessments, help to set conditions for discharge permits, guide chemical use near waterways, add relevance to otherwise abstract chemical guidelines, and help in interpreting the effects of chronic or episodic pollution. Historically, biological thresholds for pollutants were derived using Median Lethal Dose 50 (LD_{50}) and Lethal Concentration 50 (LC_{50}; Weber 1991; Hendriks et al. 2013; Erhirhie et al. 2018). Both measures identify the concentration that causes the loss of 50% of a group of study organisms over an acute exposure time when compared against controls (CCOHS 2024). Toxicity tests of this type are still used but have three significant limitations. First, their practical use depends on extrapolating laboratory results from a limited range of toxicants and test organisms (e.g., *Daphnia magna* and *Chironomus riparius*) that do not represent field circumstances or genuinely "ecotoxicological" effects on communities of species exposed to multiple stressors—often chronically. Second, lethal effects on individual organisms do not represent sub-lethal effects on processes such as reproduction or ecological interactions between species. Third, in the early 20th century, alternative methods have been sought increasingly for ethical and economic reasons to replace study animals (Bakand et al. 2005; Erhirhie et al. 2018). These include *in vitro* processes where cell culture lines are exposed to pollutants (Eisenbrand et al. 2002; Jia et al. 2015; Erhirhie et al. 2018) or *in silico* methods that create statistical models of acute toxicity (Erhirhie et al. 2018; Zwickl et al. 2022). *In silico* methods are currently restricted to organic pollutants, as inorganics and organometallics are beyond the model's predictive scope while the representation of field exposure is also limited (Nilsen et al. 2019; Zwickl et al. 2022).

Case study: identifying biological thresholds for pharmaceutical pollution—lessons from the field

Building on the challenges of pharmaceutical pollution reviewed above, we highlight two potential approaches to develop solutions. First, Kidd et al. (2007) conducted a landmark study, exposing a whole ecosystem to ethynylestradiol, a synthetic estrogen found in oral contraceptives showing how the population of fathead minnows (*Pimphales promelas*) crashed after exposure due to reproductive failure and failed recruitment. There were also indirect effects on populations of top predators and zooplankton. However, the population of fathead minnows recovered seven years after additions stopped, illustrating population resilience following pollution control (Kidd et al. 2014; Blanchfield et al. 2015). A second approach to assessing thresholds used methods from movement ecology, including acoustic telemetry and radio frequency identification (RFID) passive integrative transponders, coupled with internal implants or lab-based exposures prior to fish release (Hellström et al. 2016; McCallum et al. 2019*a*). Several studies utilizing these methods have shown that exposure to psychiatric pharmaceuticals like antidepressants or anxiolytics can affect the survival, behaviour, migration, and habitat choice of multiple fish species in the wild (e.g., Klaminder et al. 2019; McCallum et al. 2019*b*; Brand et al. 2025). Whole-ecosystem exposures and field-based tracking studies can reveal effects in an ecologically relevant setting and assess if laboratory findings extrapolate to the field. Although there are challenges in nonstandardized endpoints, like behaviour, in chemical risk assessment, one recent advancement was the development of "EthoCred", a reporting guideline to improve the utility of behavioural endpoints (Bertram et al. 2025). Such field-based approaches can reveal if pollutants, like pharmaceuticals, will affect populations, communities, and ecosystem processes.

Studies of effects thresholds like these have contributed to the implementation of advanced wastewater treatment technologies to remove pharmaceuticals, among other emerging contaminants before wastewater effluents are discharged into the environment. Switzerland adopted a strategy for this on a national scale in 2014 (Eggen et al. 2014), and moving forward, modernization of the European Union's Urban Wastewater Treatment Directive will mandate advanced treatment for large wastewater facilities with implementation by 2045 (EU Directive 2024/3019).

3.1.3. Developing regulations for interactive pollutants

Freshwater pollutants often occur in complex mixtures, for example, where metals and acidity co-occur in acidified freshwaters (Ormerod and Durance 2009; Feckler et al. 2025), pharmaceutical compounds are discharged along with organic wastewater (Wilkinson et al. 2022), or fine sediments and pesticides are mobilized alongside excess nutrients from intensive agriculture (Lemm and Feld 2017). Pollutants can therefore interact, creating new mixtures that have the potential to be more toxic in combination than in isolation (Sigurnjak Bureš et al. 2021). For example, nanoparticles can interact with heavy metals and organics, altering their toxicity and allowing the bioaccumulation and food-web transfer of dangerous substances (Canesi et al. 2015).

Recent modelling advances are attempting to characterize interactions as synergistic, additive, or antagonistic (Chatterjee and Roy 2022). Advances in addressing pollutant mixtures will also arise through the categorization of toxic effects from mechanistic first principles that simplify understanding of their interactions (e.g., oxidative stress, electron transport effects, cellular irritation, Acetylcholinesterase (AChE) inhibition etc.; Kramer et al. 2024).

Case study: pollutants in mixtures

In the European Union under the Water Framework Directive, the SOLUTIONS project developed tools such as the Mixture Risk Indicator, enabling water managers to prioritize sites and contaminants in mixtures in a rare case of real-time policy influence (Posthuma et al. 2019). Similarly, in the United States, the U.S. EPA created the Exposure–Activity Ratio (EAR), integrating high-throughput screening data with field concentrations to prioritize mixture risks in Great Lakes tributaries (Blackwell et al. 2019; Corsi et al. 2019). This was operationalized through ToxEval and applied in the Great Lakes Restoration Initiative, where over 700 sites were assessed using omics, caged fish exposures, and adverse outcome pathway (AOP) frameworks (Ankley et al. 2023). In the Maumee River, mixture-linked reproductive impairment in fathead minnows (Cipoletti et al. 2019) helped inform upstream nutrient and contaminant management. Canada has also advanced mixture assessment, particularly through its Aquatic Sites Framework developed by Environment and Climate Change Canada (Environment and Climate Change Canada 2022). This iterative, risk-based process has guided decision-making at contaminated sites such as the South Baymouth port facility on Lake Huron, where sediment and water assessments informed site-specific action plans (Quanz et al. 2020). In the binational Great Lakes Fish Monitoring Program, decades of coordinated work between Canada and the U.S. have revealed declining trends in mercury and PCBs in top predator fish, a clear outcome of sustained contaminant reduction and regulatory enforcement (US EPA 2024). Additional initiatives, such as the Erft River mixture assessments, HELCOM's flounder biomarker programs, and the SETAC Pellston workshop on agricultural runoff, have further strengthened the diagnostic and predictive tools available for aquatic mixture assessment (Lehtonen et al. 2014; Moermond et al. 2016; Markert et al. 2020). Additionally, new toxicity testing frameworks are being developed that link Adverse Outcome Pathways (AOPs) to Dynamic Energy Budgets (DEB) to facilitate mixture toxicity (Murphy et al. 2018, Stevenson et al. in prep.), so that activation of multiple toxicity pathways can be evaluated against energetic tradeoffs within an organism within a predictive framework that could extrapolate to population impacts. These programs help to establish a robust foundation, using multiple lines of evidence and collaboration, predictive modeling, and adaptive monitoring to build the next generation of feedback-informed mixture management.

3.2. Regulating pollutants and enforcing action nationally and internationally

3.2.1. Use policy and regulations to limit pollutants

The development, modernization, and enforcement of regulations are essential to protecting water quality and restoring target conditions. National river pollution laws and regulations have a long history (e.g., UK Rivers Pollution Prevention Act 1876; US Rivers and Harbours Act 1899) and complex evolution. They range from permits, licensing, or standards for specific discharges (Kathuria 2006); operational restrictions or codes of conduct on land-use activities, for example, in agriculture or forestry, that might give rise to diffuse pollution; or outright bans on the production or use of pollutants considered unsafe at any dosage (e.g., dichlorodiphenyl-trichloroethane (DDT), Turusov et al. 2002; Levain et al. 2015). Fines or other penalties might then be imposed for any contraventions of rules. Wang et al. (2011) provide an example in which the implementations of stricter regulations within China's pulp and paper industry caused significant improvements in environmental conditions and overall increased the sustainability of the industry. While policy and legal approaches of this type are often developed at national or regional scales, some are international ranging from global agreement (e.g., Sustainable Development Goals) to continental target-setting through directives that are agreed among allied nation states (e.g., European Union Wastewater Treatment Directive 98/15/EC; Water Framework Directive 2000/60/EC). Evidence shows that, at least initially, this approach drove investment in improving wastewater treatment across Europe with downstream ecological benefit, although this has since slowed (Haase et al. 2023; Pharaoh et al. 2023). Probably these and other rule-based regulations require modernization to accommodate a broader spectrum of contaminants, such as pharmaceuticals, plastics, and nanomaterials, that are not well captured by existing legislation or water treatment. One approach favours shifting the burden of environmental cost onto producers through "polluter pays" principles (Schröder et al. 2016).

Regulations often take the shape of sanctions or penalties intended to keep pollutants within safe limits while providing clear rules for business, industry and land management (King and Lennox 2000). For example, the Commission Regulation (EU) 2023/2055 to restrict microplastics added to products (such as personal care products) after 17 October 2023 to help mitigate the microplastic burden on the environment (European Commission 2023). Some commentators consider, however, that enterprises incur increased costs to enact these regulations, which may increase product pricing or cause hesitation among stakeholders charged with upholding standards (Murty et al. 2006; Wang et al. 2011). Effectiveness of regulations in environmental protection depends largely on a hierarchy of associated actions that include (i) advice, investment or innovation in treatment processes; (ii) compliance monitoring and enforcement through routine inspections, sampling, and mandatory or transparent reporting; and (iii) where these preventative steps fail, warnings, penalties, enforced remediation and criminal prosecution (Gray and Deily 1996; OECD 2014; Ole et al. 2024). Alternative approaches might involve market mechanisms or incentives in water quality regulation which are reviewed in Section 3.4.1.

Case study: reducing pesticide use to protect threatened frogs

The western chorus frog (*Pseudacris triseriata*) breeds in shallow, ephemeral wetlands. It occurs in southern Ontario and south-western Quebec (Canada) in two delineated populations, the Carolinian and the Great Lakes/St. Lawrence—Canadian Shield (GLSLCS) populations. In 2008, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessed the GLSLCS population, located primarily in Quebec, as "Threatened" (COSEWIC 2008), leading to the western chorus frog being added, in 2010, as a Threatened species in Schedule 1 of the Species at Risk Act (SARA; S.C. 2002, c. 29). A recovery strategy for the GLSLCS population identified critical habitat requiring protection (Environment Canada 2015) followed in 2018 by the "Critical Habitat of the Western Chorus Frog (*Pseudacris triseriata*) Great Lakes/St. Lawrence—Canadian Shield Population Order" (Canada 2018, SOR2018-169; henceforth, the Order) intended to protect all federal lands that contain western chorus frog (GLSLCS) critical habitat from further destruction, including abating the application of pesticides. Two distinct emergency orders (under section 80 of SARA) for the La Prairie area (Canada 2016; SOR/2016-211) and the Longueuil area (Canada 2021; SOR/2021-231) in Quebec specifically prohibited the application of pesticides in these areas to aid population recovery. More broadly, Health Canada's Pest Management Regulatory Agency, under the Pest Control Products Act, has proposed to cancel all outdoor applications of the fungicide, chlorothalonil, to protect amphibians and other freshwater aquatic biota (Health Canada Pest Management Regulatory Agency 2022).

In summary, Canadian regulations through the Species at Risk Act and the Pest Control Products Act have limited the use of pesticides and reduced exposure to vulnerable freshwater wildlife, such as amphibians, in support of population recovery. The effectiveness of these regulations has not yet been reassessed by the Committee on the Status of Endangered Wildlife in Canada, nor has the progress on their recovery been reported (see Environment and Climate Change Canada 2024); however, bans or use restrictions of pesticides were the predominant factor linked to reductions in pesticide concentrations in most long-term surface water monitoring programs (Chow et al. 2020), suggesting these western chorus frog populations will likely experience pesticide exposure relief through the regulation of pesticide use.

3.2.2. Develop international agreements to address transboundary water quality drivers

Bodies of freshwater, especially rivers and large lakes, often form boundaries between administrative units, including nation states. In addition, many of the world's large rivers, for example, the Danube, Rhine, Jordan, Mekong, Ganges, Nile, Niger, Rio Grande, and St Lawrence, flow through multiple countries. These geographical circumstances mean that responsibilities for water quality are effectively an international issue. Pollution regulations should, therefore, ideally be harmonized and integrated across international boundaries through agreements (Apitz et al. 2006). A shift towards integrated water resource management has occurred over the past decades in some global areas (Wiering and Arts 2006; Wiering et al. 2010). Europe provides a notable example where integrated river basin management and common standards have been sought through the Water Framework Directive (WFD). Among other regulations, this legislation sets targets for broader ecosystem improvement that includes a combined approach to pollution prevention and control (Griffiths 2002). The WFD, adopted in 2000, aims for "good ecological status" in surface waters by 2027 (Hering et al. 2010). While some progress has been made, the latest assessments indicate that only 37% of European surface waters have achieved this status, although there is considerable variability among nations (European Environmental Agency 2024). At the global scale, the 1997 UN Convention on the Non-navigational Uses of Transboundary Watercourses (the UN Water Courses Convention), which entered into force in 2014 after being ratified by 35 countries worldwide, sets out requirements for nations to prevent, reduce, and control pollution of international watercourses that may cause significant harm to other states or the environment.

A further example of international or inter-continental pollution occurs where pollution flux through rivers reaches the oceans, crossing geopolitical boundaries and potentially impacting the coastal ecosystems of other nations. Nutrients, sediments, heavy metals, emerging or persistent pollutants, and plastics flow downstream and can accumulate in transitional or marine zones far from their origin (Souza et al. 2023). These pollutant transfers underscore the fact that pollution is no longer just a local or regional problem but a truly global issue.

While international agreements are integral to reducing pollution spillover to neighboring countries through both freshwater and marine pathways, in practice, this can be difficult due to varying capacity and wider geopolitical tensions among the international actors (Zeitoun et al. 2013). Management is multi-faceted and must incorporate the economical, political, and legal landscapes of the participating countries (Mirumachi and Hulbert 2022). There are, nevertheless, successful examples in the development and extensive implementation of international pollution control—for example, in various agreements to restrict downstream pollution into shared ocean environments (e.g., Müller-Karulis et al. 2024) or in the ongoing recovery of surface waters affected by acid deposition, which we review below. In these cases, collaboration, cooperation, and investment have been key to reducing pollution loads.

Case study: acid deposition neutralized by international cooperation

During the 1980s and 1990s, acid deposition, or acid rain, was a priority concern across North America and Europe because of its impacts on soils and waters (Grennfelt et al. 2020). Industrial development from the mid-1800s onwards had progressively increased gaseous emissions of sulfur and nitrogen oxides from the combustion of fossil fuels leading to the formation of dilute sulphuric and nitric acids in the atmosphere (Menz and Seip 2004). The fallout of these acidifying compounds in dry deposition, rain, mist, and snow (often at rates of 10s of kilograms per hectare annually) acidified soils and surface waters in areas where acid deposition exceeded the capacity of base-cations or mineral weathering to buffer pH decline (Likens et al. 1996). In some regions, plantation forests of non-native trees exacerbated deposition by 50%–80% (Ormerod et al. 1989). Not only did pH decline, but buffering processes in soils were modified so that metals such as aluminum were solubilized and began to enter lakes, streams and rivers at concentrations that were toxic to a wide range of freshwater organisms under increasingly acidic conditions (Krám et al. 1995). In running waters, this was a classical episodic water quality issue—with effects greatest at high flow during snowmelt or rainstorms that diluted buffering and increased acid flux (Lepori et al. 2003; Kowalik et al. 2007). Across large areas of northwest and central Europe, western Britain, and eastern North America, biological diversity declined in acidifying lakes and rivers as sensitive organisms were impacted either by direct toxicity or disrupted food webs: primary producers, decomposers, several invertebrate orders, fishes, and aquatic birds were among those worst affected (Steinberg and Wright 1994). The consequences were perceived not only because of their impact on aquatic biodiversity, but also because of their economic, cultural, and political significance; for example, where resources in some countries reflected the effects of atmospheric pollutants transported across international boundaries.

Peak realization of acid deposition problems in the 1980s led to management and policy responses ranging from local to large-scale, international, and coordinated efforts. At local scales, responses involved addressing the symptoms of acidification by dosing affected catchments or standing waters with calcium carbonate (i.e., liming) with varying success and some concerns about sustainability, negative effects on organisms typical of naturally acid waters, and the resulting non-natural water quality that resulted (Mant et al. 2013). Regionally, policies have included controlling emission sources through industrial planning (Li and Gao 2002) and restricting land uses, such as plantation forests, that exacerbated deposition locally. The most palpable successes of all came from international agreements—for example, the EU Large Combustion Plant Directive (European Environment Agency 2001) that addressed and controlled sulfur emissions from power plants. In the decades since, water quality has progressively returned to pre-acidification conditions, although biological recovery is still partial or slowed, for example, by the continued effects of acid episodes (Ormerod and Durance 2009). New water quality challenges have also arisen in recovering waters, for example, declining calcium concentrations in catchments where soils have been depleted in base cations more rapidly than re-supply in weathering rates from parent minerals (Jeziorski et al. 2008). The difficulties of recovering acidified waters offer a salutary lesson—that avoiding damage to water quality is preferable to the challenge of repairing subsequent damage. However, there is also a positive lesson that even large, geographically extensive and complex water quality problems can be reversed through concerted, evidence-based and internationally collaborative action at all scales from local to global (Stoddard et al. 1999; Gattuso et al. 2009). In this case, scientists, citizens, officials and elected governments have genuinely made a difference in reversing what once appeared to be intractable water quality problems.

3.2.3. Identify alternative options to materials and practices that contribute to pollution

In many cases, understanding of major polluting compounds is sufficient to enable pollution risk reduction by developing and using sustainable alternatives. These changes require societal pressure and buy-in from industries who are sometimes resistant to change (Ekins and Zenghelis 2021). Therefore, proper assessment of new technologies and methods is crucial to providing targeted information on the full environmental footprint, performance, cost-effectiveness, and possible trade-offs, where alternative options are available to combat pollution.

Alternative options to conventional materials and practices are slowly being introduced into different industries. For example, biopesticides (e.g., microbes, plants, and biochemicals) in agriculture are an alternative to synthetic pesticides and control pests through a variety of biological methods of action (e.g., metabolic poison, etc.; Spark and Nauen 2015; Tijjani et al. 2016; Fenibo et al. 2022). In transportation, alternatives to road salt (primarily sodium chloride) such as sugar beet juice de-icing products are being investigated to help reduce the salinization of freshwater (Szklarek et al. 2022). Used in conjunction with salt mixes, they help salt adhere to the road, thereby using less salt product but may still affect ecosystems downstream (Fay and Shi 2012; Schuler et al. 2017). In industry, closed-loop systems can greatly reduce waste water volumes, as well as preventing contaminated discharges into freshwater environments (Azam et al. 2019). Such systems could be incorporated into a number of different industries, from manufacturing to power generation. These examples show that alternatives are both possible and diverse, but still largely in need of research, development, and economic assessment.

Case study: reducing light pollution along freshwater systems through sustainable lighting

Despite the availability of effective mitigation strategies—such as shielding, dimming, and spectral tuning—testing lighting solutions near freshwater habitats is only now receiving attention in environmental research (Hölker et al. 2023). A recent study in Germany tested whether novel shielded LED road lights could reduce insect attraction in rural, peri-urban, and urban contexts (Schroer et al. 2021). Tailored LED road luminaires with shielding were installed to effectively direct the light to the areas to be illuminated, limit visibility to flying insects and prevent the light from spilling over into freshwater and riparian areas. Shielding has been shown to reduce the attraction of insects by at least 50%, resulting in better performance than dimming (Dietenberger et al. 2024). Spectral tuning is often proposed as a solution to minimize light pollution, but has limited effectiveness in freshwater environments because many aquatic species respond to the entire visible spectrum. Therefore, adjusting luminance distribution, minimizing lighting duration, and reducing overall light levels appear to be more effective (Hölker et al. 2023). Implementing such measures will also prevent other environmental impacts, such as disrupting fish migration (Pérez Vega et al. 2024).

3.3. Managing and remediating pollutants at source, in situ, and across catchments

3.3.1. Prioritize the global problem of sanitary waste

Adequate wastewater treatment prior to release varies from over 85% in Europe, North America, Australia, and New Zealand to considerably less than 50% across large areas of Africa, South America, and Asia (Jones et al. 2021). Globally, over 1.5 billion people have no basic sanitation at home. Around 570 million people share toilets or latrines with other households while over 400 million defecate in the open, often near waterways (WHO 2023). The consequences for morbidity and mortality, often among infants, are well recognized: an estimated 1.7 billion people globally depend on drinking water sources contaminated with faeces (WHO 2023). While the focus of this review is on bending the curve of freshwater biodiversity loss, the problem of domestic wastewater is one of the clearest of all opportunities to link freshwater ecosystem protection with human health and well-being. These issues are central to the UN's sixth Sustainable Development Goal which offers clear collateral gains for the freshwater environment, including in relation to target 6.3 on progress on wastewater treatment and ambient water quality (UN-Water n.d.). The challenge is acute, however, for a global population already exceeding eight billion and likely to expand by a further 25% by the mid-2080s concentrated in the globally poorest countries (United Nations 2024). The challenges in nations with contrasting economies are distinct with respect to scale, severity, and urgency—yet the potential solutions are surprisingly consistent. Improved regulation, investment, upgraded infrastructure, systemic catchment management—for example, through sustainable urban drainage, water reuse, and nature-based solutions—and the opportunity to solve health and ecological problems simultaneously must be at the heart of the action.

Case study: perspectives on sanitary wastewater from different worlds

The challenges of addressing sanitary wastewater are epitomized by a comparison between Europe, specifically the UK, and Nepal. These nations are respectively in the top 15% and bottom 20% of global nations on GDP per capita with a 36X difference in absolute terms.

In the UK and across Europe, sewer infrastructure and biological wastewater treatment expanded from the late 1800s to the early 1900s onwards, although problems with organic waste, de-oxygenation in rivers, and elevated ammoniacal-N concentrations persisted until at least the 1980s in many urban areas. Regulatory intervention in 1991, led from the European Union through the Urban Waste Water Treatment Directive (UWWTD: 91/271/ED), brought increased investment to address poorly performing treatment plants which in turn engendered chemical and biological improvement, particularly across urban areas (Pharaoh et al. 2023). Rivers previously classed as "grossly polluted" regained clean water organisms such as Atlantic Salmon (*Salmo salar*), Otters (*Lutra lutra*), White-throated Dippers (*Cinclus cinclus*), and pollution-sensitive invertebrates (Whelan et al. 2022). These trends provide important evidence for the role of state regulation coupled with funding for compliance in the water sector.

Since around 2010–2015, however, despite additional regulatory developments (e.g., Water Framework Directive 2000/60/EC) progress has stalled. Biological metrics are flatlining or even reversing locally (Haase et al. 2023; Pharaoh et al. 2023). Likely causes include emerging pollutants such as pharmaceuticals, legacy pollutants, and the deoxygenating effect of climate change (Vaughan and Gotelli 2019; Zhi et al. 2023). Infrastructural issues also persist, and for example, around 5%–20% of domestic properties in the UK have foul sewers misconnected directly to surface drains—and ultimately surface waters (Ellis and Butler 2015). Public concern also centers on the continued discharge of untreated sewage into waterways through ageing, combined sewer overflows (CSOs) that blend surface runoff with foul sewage before bypassing water treatment plants. CSOs are licensed and designed to discharge only during elevated precipitation, but in some regions, around 20% discharge near continuously because of mechanical valve failures, increasing populations connected to sewers, blockages caused by inappropriate public disposal of fats and wet-wipes, poorly maintained networks, increasing impervious land cover, increased runoff in urban areas, and changing patterns of rainfall (Perry et al. 2024).

Nepal's wastewater problems are best illustrated with reference to the capital city, Kathmandu, where over 2 million people live at a density of 5169/km^2, with an annual growth rate in 2021 of 1.51% (National Statistics Office 2021). The Bagmati River drains the Kathmandu Valley and surrounding hills. It has significant religious and cultural importance and, just outside the city at Sundarijal, supports clean water organisms (Shrestha et al. 2023). On entering the city, the river receives poorly controlled domestic and industrial sewage, hospital waste, and solid waste. Measurements and models show how dissolved oxygen, BOD, turbidity, suspended solids, and chemical oxygen demand are all deteriorating, consistent with increasing pollutant load, while metal concentrations are elevated (Mishra et al. 2017; Ghimire et al. 2022). Disease-risk indicators such as faecal coliforms, faecal indicators such as Bacteroidales, concentrations of adenoviruses, noroviruses, and enteroviruses, and *Giardia* spp. occur in over three-quarters of samples taken (Tandukar et al. 2018). Biodiversity metrics inevitably show substantial pollution-related changes in indicator taxa (Jüttner et al. 2003; Shah and Shah 2013). Even very low levels of watershed urbanization (as little as 5%) can cause major declines in stream fauna quality, with 10%–20% urbanization driving rivers to near their lowest ecological condition (Thapa et al. 2026).

Current attempts to manage water quality problems in the Bagmati have made little progress, and further deterioration is expected (Ghimire et al. 2022). New wastewater treatment plants have been funded by overseas aid, but operation, maintenance, and technical management have been poor. Further international finance is aiming to expand treatment plants and sewer capacity while nature-based solutions, specifically *Phragmites* reed bed systems, floating *Scirpus* islands, and riparian greening, are being rolled out. Engineering options, such as re-aerating weirs, nets to trap solid waste, and dams to store water to support dilution during Nepal's prolonged dry and post-monsoonal period are also in development. Future cost-positive options include resource recovery from methane as well as P and N for fertilizers. Benefits to well-being and biodiversity are likely to vary, and there will be trade-offs and constraints in funding, maintenance, and land requirements (Ghimire et al. 2022).

3.3.2. Embrace and accelerate science-based technical solutions to control pollution at source

The control of pollution at point sources allows localized, direct, and targeted interventions (OECD 2017). The goal is the removal or reduction of contaminants to allow safe effluent discharge or reuse (Ahmed et al. 2022). The technical solutions available depend on the pollution source but include physical, chemical, and biological processes that are commonly used in tandem through primary, secondary, and tertiary levels of treatment (Shahedi et al. 2020). Many technologies have been proven successful in removing insanitary waste, nutrients, metals, and pathogens, although effectiveness for emerging pollutants depends on the contaminant present and is still a research issue (Bean et al. 2016; Rout et al. 2016, 2021; Tran et al. 2018).

As well as discharge to water, point source treatment has been important in addressing atmospheric pollutants, for example, using scrubbers to remove contaminants from factory smokestacks (Sharif et al. 2021). This includes acidifying contaminants, such as gas mixtures containing hydrogen sulfide, sulfur dioxide, or carbon dioxide (see the case study in Section 3.2.2; Srivastava et al. 2001; National Acid Precipitation Assessment Program 2005).

Case study: ozonation of the City of Montréal's effluent to the Saint Lawrence River

Montreal is situated in the confluence of the Saint Lawrence and Ottawa Rivers and, in the 1970s, decided to convey all its wastewater to its most downstream point. This is the site of the third largest wastewater treatment plant in the world, treating 45%–50% of the wastewater of the province of Québec. Primary treated effluent is discharged into the Saint Lawrence River near the Île-aux-Vaches at a location that minimizes effects on downstream drinking water intakes (Loeb et al. 2012). For many decades, the large dilution potential and assimilation capacity of the Saint Lawrence River reduced the need for more advanced wastewater treatment. However, many studies demonstrated toxicological and ecological impacts on the Saint Lawrence (Marcogliese et al. 2015; Reinling et al. 2017; Dépatie et al. 2020; Pelletier et al. 2022). This included pharmaceutical pollution that required more advanced contaminant removal (Vaudreuil et al. 2024). In 2008, the city selected ozonation to address many of the unregulated dissolved organic contaminants (Loeb et al. 2012). While the formation and discharge of ozonation byproducts of unknown toxicity is expected (e.g., Lajeunesse et al. 2013), ozonation has the potential to remove organic contaminants along with estrogenic and androgenic activity (e.g., Nasuhoglu et al. 2018). As the largest wastewater ozonation system in the world, the upgrade has experienced multiple delays and is now expected to be in service in 2028 (City of Montreal 2025). Moreover, there are concerns about the role of nitrogen and phosphorus in the Saint Lawrence River on eutrophication and the development of hypoxic zones in the Saint Lawrence estuary (Jutras et al. 2020; Environment and Climate Change Canada 2024). Given new standards adopted by the province of Quebec (Règlement sur les ouvrages municipaux d'assainissement des eaux usées (ROMAEU) (Q-2, r.34.1)), the City of Montreal is planning a biofiltration system for the removal of organic carbon and nitrogen to be implemented by 2040, which will also improve the removal of toxic organic compounds through ozonation. Improvements in the quality and ecology of the Saint Lawrence River are expected, but these visionary and innovative developments come at considerable financial cost.

Ozonation for wastewater treatment is not confined to Canada, and the Werdhölzli wastewater treatment plant in Zurich, Switzerland aims, specifically at micropollutant abatement. Here, four ozonation reactors (comprising eight Wedeco SMOevo ozone systems) are used to break down micropollutants in the effluent at the tertiary treatment stage (Walpen et al. 2022). Costs were again high, and part of a 50 million CHF upgrade to the treatment plant (www.xylem.com). In short, this case study highlights the costs (but also the potential for innovation) in modern water treatment, and ozone capacity has expanded in recent decades worldwide to treat drinking water and wastewater (Loeb et al. 2012).

3.3.3. Embrace and apply science-based technical solutions to control nonpoint source pollution

Despite the challenges, technical solutions to address diffuse pollution are available. Controls on agricultural nonpoint pollution typically fall into one of three approaches: source control, process control, or end treatment (Xia et al. 2020). Source control aims to prevent pollution from entering the wider environment in the first place and includes fertilizer management and water-saving irrigation to reduce run-off. Process controls involve techniques that remove pollutants from runoff before they enter freshwater ecosystems, such as microbial treatments (Xia et al. 2020). End treatment technologies typically involve constructed wetlands, wet woodlands, or riparian buffers, which have filtering and remediation abilities that remove pollutants prior to entering waterways, for example, through denitrification (Díaz et al. 2012). Riparian buffers can decrease total nitrogen flux by 70%, total phosphorus by 73%, and total suspended solids by 93% (Clausen et al. 2000), making these, and other wet-

Table 2. Main barriers for the application of alternative deicing agents to sodium chloride.

Barrier type	Barrier description
Market	Chemical costs up to over 10 times higher than those of NaCl.
	Reliance and investments on alternative groundwater protection solutions, mainly geotextiles.
Technical	Limited technical suitability (e.g., for removal of packed snow and ice).
	Need for spreading equipment allowing the use of both NaCl and KFo.
Cultural	Concerns about risks on the environment, pavement, and other materials (e.g., in vehicles), and on footwear and pets.
	Disregard of groundwater deterioration (for instance, Swedish Transport Administration).

lands, an effective solution to prevent downstream eutrophication (Singh et al. 2019). Diffuse management systems also have an important potential role in urban diffuse pollution associated with CSOs (see Section 3.3.1). The increasing intensity and frequency of storm events due to climate change are prompting the management of stormwaters through sustainable drainage systems, porous asphalt pavement, and green infrastructure to intercept, store, or divert rainfall and storm runoff (Beighley et al. 2008; Putman and Kline 2012). Additionally, while the increased reliance on electric vehicles or other alternative fuel sources will reduce some vehicular emissions, an overall reduction in personal vehicular journeys on roadways will be one of the most impactful options available (Ercan et al. 2022). There is widespread recognition of the need to evidence and accelerate the roll-out of these methods as part of the general move towards nature-based solutions (see Section 3.3.4).

Case study: alternative deicing agents in Finland—a status update 20 years after the first pilot study

At high latitudes, the deicing of roads and aircraft runways is practiced to increase traffic safety. Sodium chloride (NaCl) has been the most frequently applied deicer due to its suitability and low price. This leads to gradual salinization of groundwaters and ecological effects in freshwater ecosystems, which have prompted solutions to address adverse impacts (Hellstén et al. 2005*a*; Salminen et al. 2011). In Finland, studies of organic deicing agents have aimed to replace primarily sodium chloride and urea used on roads and runways, respectively (Hellstén et al. 2005*a*, 2005*b*). The use of formates and acetates developed after the completion of successful field trials in Finland 20 years ago, which demonstrated how the replacement of NaCl reversed groundwater salinization trend and gradually improved groundwater quality (Salminen et al. 2010). Impacts on roadside vegetation and microbial activity were also studied in the context of the trials. The number of road sites operated by the Finnish governmental transport agencies where potassium formate (KFo) is applied has steadily increased and is currently around 50. Additionally, the city of Lahti, located on the Salpausselkä terminal moraine formation, which is a highly valuable region for water supply, has opted for KFo. However, a range of barriers for the application of groundwater-friendly deicing chemicals exist (Table 2). At least in Finland, this case study shows how research conducted at multiple scales provided stakeholders with answers to several key concerns (Table 2) and paved the way to the acceptance of alternative deicers (Hellstén et al. 2005*a*, 2005*b*; Salminen and Kalevi 2011). Higher chemical costs remain the main limitation to the wider application of KFo and sodium formate (NaFo).

3.3.4. Science-based solutions to recover and restore polluted locations

Legacy pollution from historic human activities (e.g., industry, military, and agriculture) and contemporary pollution incidents mean that management in many instances must focus on restoration or recovery. The challenges are often large because some of the pollutants involved (e.g., PCBs, PFAS, and PBDEs) are persistent, dispersed or circulating through food webs, and distributed in groundwaters, soils, and catchments upstream of sites targeted for restoration. Efforts are invariably focused on sites (i) where cost-effective progress can be made with existing technology and (ii) that can be identified using decision-support frameworks available for contaminated sites (e.g., Sorvari and Seppälä 2010; Wu et al. 2022) or pollution at catchment scales (e.g., Peacock et al. 2012). In many cases, the proposed restoration and recovery actions pose risks that need to be considered (Bonano et al. 2000; Huysegoms and Cappuynss 2017).

The potential approaches to restoration and recovery invariably depend on interdisciplinary skills from hydrogeologists, chemists, engineers, ecologists, and other environmental professionals. Specific options depend on the extent of contamination, whether issues are episodic or chronic, the type of contaminants, and the ease of removal, treatment, or other management. Where the pollutant is inert or in contaminated sediment, physical removal using silt traps, vacuum apparatuses, or physical cleaning of river substrata are options. For heavy metals, physical excavation for off-site treatment or disposal is sometimes possible, which in some deeper waters (e.g., lakes) may require dredging (Palermo and Hays 2014). However, efforts to remove materials can disturb and mobilize pollutants, such that in some cases it may be better to either do nothing or to apply a sub-aqueous cap (Paleromo 1998) of activated carbon (Azcue et al. 1998) or sand (Biberhofer et al. 2019). In some cases, plant growth is encouraged on the caps using traditional ecological restoration planting methods (see Piczak et al. 2024). If capping cannot occur, phyto- or bioremediation using plants, bacteria, or other organism groups can sequester materials such as metals via uptake (Weis and Weis 2004). Redox conditions in some wetlands may also contribute to the degradation of contaminants (Williams 2002). In some cases, wetland plants that uptake contaminants are harvested for disposal off-site (Badejo et al. 2015). Where metals arise from current or abandoned mines, remediation at source should be a go-to option, for example, using selective metal precipitation, adsorption, electrochemical processes, or membrane processes, although some techniques require development (Rodríguez-Galán et al. 2019).

For groundwater contaminants, restoration and recovery options are more limited, and it may be necessary to pump out groundwater, treat it, and then re-introduce it to the aquifer or release it into surface waters. So-called "pump and treat" methods are common but costly with effectiveness dependent upon scale, type of contamination, and hydrogeology. Such efforts are rarely sufficient to address human health concerns and often aim to prevent further contaminant spread into downstream ecosystems (Mackay and Cherry 1989).

For episodic events, such as oil spills, initial efforts typically focus on trying to reduce dispersion and downstream transport of the pollutant followed by rapid efforts at clean-up. Although concentrations are usually locally elevated, such spills can be addressed more easily than where contaminants have accumulated for decades or more. Ensuring that government agencies have means to enable spill reporting and rapid incident response is important, but equally, efforts should be aimed at addressing the sources and causes to reduce incident frequency.

Case study: recovery and restoration of the contaminated Randle Reef in Lake Ontario

Hamilton Harbour is a 2150 ha embayment at the west end of Lake Ontario where poor water quality reflects the surrounding land use, including historical heavy metal production (e.g., iron and steel; Ramin et al. 2012; Santiago et al. 2012). The Hamilton Harbour remedial action plan (RAP) describes strategies to clean and restore the area (Great Lakes Water Quality Agreement 2012), one of which is to address sediment contamination by heavy metals (Santiago et al. 2012). The harbour's Randle Reef area (60 ha) was prioritized by the RAP in 1992 due to the high sediment concentrations of industrial contaminants, especially PAHs (Murphy et al. 1990; Remedial Action Plan Team & Rodgers 1992). The remediation project is intended to reduce the exposure of organisms in the harbour to persistent toxic substances by diminishing the extent to which concentrated sediment PAHs can mobilize into the water column (Santiago et al. 2012). In 2015, construction began on an engineered containment facility (ECF) constituting the largest sediment remediation project in Canadian AOC history (Krantzberg 2020). The ECF is an approximately 7.5 ha peninsula attached to Pier 15 of Hamilton Harbour (Santiago et al. 2012) and will contain a total of 695 000 m^3 of contaminated sediment once capped (Jawed and Krantzberg 2018). The completed area is proposed to constitute 2/3 marine port and 1/3 open space with potential for naturalization or light industrial activity (Santiago et al. 2012). The project design avoids disturbance of the most contaminated sediments, while concurrently providing a functional port space in a major shipping center. As of early 2025, the final stages of construction are ongoing. Monitoring studies are ongoing but the overall success in restoring the polluted site is currently unknown.

3.3.5. Leverage nature-based solutions to improve water quality

Nature-based solutions (NbS) are gaining recognition in the otherwise engineering and technology-oriented domain of water management. By definition, NbS are "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al. 2016). As such, they are potentially attractive for policy makers and investors in that they can, in principle, deliver multiple benefits including, in some circumstances, recovery of freshwater biodiversity.

NbS focused on water-related challenges often target the management or restoration of wetlands or riparian zones. Vegetated riparian zones are transitional regions between terrestrial and aquatic environments, while wetlands can either be transitional or in-line features along waterways. Both can effectively intercept, sequester, and sometimes transform pollutants into less harmful substances, for example, through denitrification or oxidation (Moreno et al. 2007; Dosskey et al. 2010; Vidon et al. 2010). Although both wetlands and riparian zones occur naturally in catchment ecosystems, green engineering or ecological restoration can encourage these zones in strategic locations (Osborne and Kovacic 1993; Ardon et al. 2010; Dosskey et al. 2010).

In addition to water quality benefits, NbS offers potential value to reducing flood risk, while also providing biodiversity benefits (Acreman et al. 2021), though some needs remain with respect to incentivizing roll-out and evidencing benefits at whole-catchment scales. Critical design questions that remain at the landscape scale include how many wetlands are needed, where should riparian zones be restored for the greatest benefit, what size and type are most efficient, and where should they be placed to meet pollutant reduction targets most cost-effectively?

Case study: evidencing the value of nature-based solutions in Ontario and the Gulf of Mexico

Restoring large wetlands (>40 ha) is often prohibitively expensive in agricultural landscapes (Kadlec 2016). In contrast, small wetlands (0.03–0.32 ha) can have greater nutrient removal efficiency per unit area due to their higher perimeter-to-area ratios (Cheng and Basu 2017; Ghermandi et al. 2010; Shen et al. 2025). A recent study of eight small agricultural wetlands in Southern Ontario confirmed 30%–60% P removal and 25%–50% N removal, especially during spring and summer when runoff and biological activity are highest (Page et al. 2023). Smaller wetlands are also often seasonally disconnected from downstream waters, thereby increasing nutrient retention by extending residence time, increasing denitrification (Hefting et al. 2004), and reducing downstream transport during dry periods (Cheng et al. 2023; Lee et al. 2023). Benefits can also reach downstream transitional and marine systems

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and Cheng et al. (2020) showed that increased wetland area by 10% in nutrient-rich zones could reduce nitrogen loads to the Gulf of Mexico by 54%. Similarly, Shen et al. (2025) estimated that restoring 2.3 million hectares of small wetlands could increase nitrogen removal by 21%, compared to only 5% for an equivalent area of larger wetlands. Together, these findings highlight the critical role of multiple, small, strategically placed wetlands as a scalable, cost-effective, and impactful nature-based solution for improving global water quality. In this example, the capacity for nature-based solutions extends to become nature-based catchment management.

3.4. Addressing systemic drivers of pollution through incentives, awareness, and market mechanisms

3.4.1. Incentivize action

While penalties and rules are intended to prevent inappropriate action (see Section 3.2.1), incentives act by encouraging, promoting, or rewarding actions that are beneficial for water quality through financial or nonfinancial methods (Smith 1998; FAO 1999; Enters 2001). Financial approaches are typically targeted at sectors such as farming or forestry, or at individuals ranging from civic leaders to individual landowners who have the capacity to act positively. Financial incentive programs are increasingly common in agricultural landscapes to achieve improvements in water quality (see Segerson (1990) and the case study below). Approaches include (i) access to funds or premium markets where land users deliver positive environmental outcomes, for example, through earned recognition or premium product labelling where certain standards are met; (ii) cross-compliance where grant funding depends on positive action; or payments for ecosystem services (PES), for example, water quality improvement delivered through nature-based methods (see Section 3.3.4); (iii) the use of environmental bonds and point/nonpoint source trading (Malik et al. 1994). Group incentives (including rewards and penalties) have also been applied in some situations where watershed-level targets are set for multiple farmers to engage in collective action (reviewed in Segerson 2022).

Nonfinancial incentives might include advice, training, technical assistance provided without cost, or involvement in demonstration projects that bring kudos. In China, research has revealed meaningful reductions in pollution when civic leaders are provided performance incentives for achieving water quality targets linked to promotion criteria (Kahn et al. 2015; Wang et al. 2020).

Incentives have been embraced in nature conservation (see Hutton and Leader-Williams 2003), with several notable examples specific to water quality improvement and pollution mitigation. For example, residential septic system owners are typically responsible for maintaining their systems to prevent nutrient and other inputs into ground and surface waters yet there are few if any mechanisms to enforce such maintenance (Withers et al. 2012). As such, incentives are often used to induce individual landowners to invest in septic upgrades (Mullen et al. 2017). These benefit the individual landowners by increasing property value and improving local water quality with community gain.

There are challenges and developmental needs with some forms of incentive, however. Although global examples of PES and other green finance schemes are growing, uncertainties include rates of uptake by land managers who are more focused on production, administrative complexity, the quantification of environmental benefits, and regulatory governance of both the economic and environmental dimensions (Wunder et al. 2025). Financial incentives involving public funding for private individuals and organizations also raise concerns around ethics, fairness, and selection criteria. Hence, cost-sharing incentives are common given that they require both private and public investment (Dupont 2010).

Overall, incentive programs can be effective in some cases while in other contexts command-and-control policies and regulatory approaches may be more effective (Malik et al. 1994). Importantly, also, ceasing inappropriate incentives—for example, those that increase environmental impacts and costs—is a further important opportunity for water quality restoration (Reyes-García et al. 2025).

Case study: incentivizing action through stewardship: the Cows and Fish Approach

An effective way to incentivize positive environmental action is by promoting stewardship, where local actors protect, care for, or use the environment responsibly in different socio-ecological settings (Bennett et al. 2018). Three important elements of effective stewardship are (i) building awareness or knowledge of local ecosystems function; (ii) fostering a sense of ethics—an encoded set of conscientious responsibilities and obligations to care for land, water, air, and biodiversity; and (iii) ecological literacy leading to appropriate choices that embody restraint in resource exploitation and a sense of legacy (Barnes 2013), which may extend to hands-on work such as restoration (Barritt 2019) and monitoring (i.e., community or citizen science; Shao and Bishop 2025).

A stewardship approach of this type has been implemented in agricultural landscapes in Alberta through the "Cows and Fish" initiative (also known as the Alberta Riparian Habitat Management Project). This initiative was established in 1992 as a collaborative initiative between multiple organizations, including the Alberta Cattle Commission, Trout Unlimited Canada, and Fisheries and Oceans Canada (Fitch and Adams 1998). "Cows and Fish" works at the grassroots level to foster riparian stewardship that benefits both people and ecosystems, particularly managing grazing management to enhance landscape health (including water quality) and restore riparian areas (Fitch and Adams 1998;https://cowsandfish.org/). The delivery model is complex and has required building relationships to engender trust and offer voluntary actions. Funded management tools are used to demonstrate possible actions rather than paying people for specific activities which could then be voluntary. The organization also provides educational resources and conducts workshops with local stakeholders. Finally, monitoring is used to reveal what is or is not working. Actions toward stewardship goals have brought communities together, enabling them to reconnect, focus on environmental issues, and expand their efforts from individual land holdings to a watershed scale. Landscape-scale metrics suggest that stewardship has brought positive trends in ecosystem resilience, economic benefits, and biodiversity gains, for example, the kilometers of shorelines protected or hectarage of riparian habitat enhanced through livestock grazing management (Cows and Fish Winter Newsletter 2025). Although the Cows and Fish Program does not measure water quality directly as an indicator of success, riparian habitats are considered crucial to ensuring ecosystem functions, such as filtering nutrients and sediment to improve water quality (Miller et al. 2010).

3.4.2. Apply market instruments that reflect downstream pollution costs

Market mechanisms and incentives in pollution control, as opposed to command-and-control regulation, use environmental economics to account for the negative cost externalities that arise from pollution (Luo et al. 2024). These work by changing the pricing system to include environmental considerations in ways that affect supply or demand (Liu and Brouwer 2023). These bottom-up approaches can be effective as they equalize a polluter's marginal cost to reduce pollution, rather than having standard regulations across the board.

Market instruments include pollution charges, government subsidy reductions, market friction reductions, and tradable permits as categorized and reviewed by Stavins (2002). Pollution charges effectively impose a tax on the pollution a source creates, which should incentivize mitigation plans as a way of lowering their tax rate (Pigou 1920). Reducing government subsidies can also help alleviate the overuse of subsidized inputs (e.g., fossil fuels) to promote the adoption of more sustainable and less polluting practices (Panaiotov 1994; Stavins 2002). Reducing market frictions is a way of removing barriers that prevent a given market from addressing environmental issues, such as liability rules (e.g., "polluter pays" principle) or product labelling campaigns that aim to better inform consumers about the environmental implications of product choice (Stavins 2002). Finally, tradable permits can include credit programs as well as cap-and-trade systems. Credit programs, such as water quality permit trading, allocate a limited amount of pollution permits into a marketplace, which can be traded among market operators. The intention is to encourage pollution reduction and to offer flexibility through buying/selling permits according to their pollution loads. For example, improving wastewater treatment plans by water companies can lead to surplus credits that might then be sold to other firms that need to meet their pollution control target (Liu and Brouwer 2023). Together, uptake of these market instruments can help internalize external environmental costs by directly charging the polluter.

Case study: Lake Taupō nitrogen market

Lake Taupō is New Zealand's largest lake, with a catchment size of 3947 square km that hosts activities spanning agriculture, forestry, urban land, and conservation uses (Duhon et al. 2015). An increase in catchment development, specifically agriculture, has impacted water quality, specifically elevated nitrogen from diffuse nonpoint pollution sources (NPS; Kerr et al. 2015). To address this, the Waikato Regional Council introduced a groundbreaking package (Variation 5 of the Waikato Regional Plan) in 2011 that combined regulation, public funding, and a cap-and-trade market mechanism with an overall goal of restoring water quality to 2001 levels by 2080 with a nutrient cap to reduce nitrogen inputs to 20% below the baseline (Kerr et al. 2015). The Taupō trading scheme is the world's first NPS-NPS cap and trade scheme, whose main aim was to control diffuse NPS nutrient sources (Shortle 2012). Farmers were required to obtain resource consents for nitrogen-leaching farming activities and were then allocated Nitrogen Discharge Allowances (NDAs) based on their historical leaching levels from 2001 to 2005, with compliance ensured through management plans (Kerr et al. 2015). To reduce pressure on the farming community through this change, the Lake Taupō Protection Trust was established with $81.5 million NZD from the Taupō District Council (22%), Waikato Regional Council (33%), and central government (45%; Lake Taupō Protection Trust 2014), enabling the purchase of NDAs or high-leaching land for conversion into low-impact uses (Kerr et al. 2015). Alongside this, a trading system was created to allow NDAs to be bought and sold, ensuring flexibility and efficiency while keeping total nitrogen within the cap (Kerr et al. 2015). This programme met its target 3 years ahead of schedule, reducing nitrogen inputs by 20% and reducing manageable nitrogen emissions by 170 tonnes per year (OECD 2015). The initiative demonstrated that regulating and trading diffuse agricultural pollution is technically feasible and encouraged innovation in land management. While the full environmental benefits will take decades to measure due to the residence time of water in Lake Taupō (approximately 11 years; Stewart et al. 2025) and residence time of nutrients in groundwater (up to 100 years; Kerr et al. 2015), the system has already provided critical lessons for water-quality governance, and has shown that the alignment of economic incentives with rightsholder support is possible.

3.4.3. Public awareness and behavioural choice

Raising public awareness on our collective ability to influence water quality is integral to enacting lasting change, as was observed with the mobilization of the public, government, and media to tackle the issue of acid rain (Grennfelt et al. 2020). Depending on the political regime, public opinion, and societal pressures, particularly from environmental nongovernment organizations (eNGOs), can be effective in pressuring political leaders on their environmental responsibilities (Bernauer and Caduff 2004; Anderson et al. 2017). In the UK, for example, some large eNGOs have more members than all political parties combined, and they lobby effectively on environmental matters including water quality. Given this potential, there are public benefits to greater awareness of political influences when electing government representatives. This includes raising awareness on how each politician's platforms and parties may contribute to improving water quality and ensuring these platforms have actionable steps to improve water quality, coupled with accountability.

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People can also affect water quality through consumer choices (Zaharia and Zaharia 2015). This includes supporting companies that have eco-friendly initiatives, boycotting companies that are known water polluters, buying second-hand, and considering the "repurpose, re-use, repair, recycle" mantra. In recent years, there has been a large increase in the purchase of second-hand goods, particularly clothing (Mobarak et al. 2025). Indeed, industry is now capitalizing on these trends with buy-back programs and vintage collections (e.g., Gap, SAIL, Patagonia, Urban Outfitters; McKie et al. 2023). Nevertheless, supply chains in fashion textiles are one of the major causes of water pollution, accounting for ~20% of industrial water pollution globally (Niinimäki et al. 2020; Bailey et al. 2022). Encouraging mindful consumption could be a useful indirect strategy. This strategy has not always proven to be successful, as consumers have been shown to overlook sustainable products if they do not also provide functional, financial, and aesthetic benefits (Rahman and Koszewska 2020).

Approaches to enhance environmental literacy, conservation outreach, and public engagement include community-lead initiatives, such as waterway clean-ups, adoption of local freshwaters, public lectures, and engagement in citizen science (Toomey and Domroese 2013; McKinley et al. 2017; MacPhail and Colla 2020). The latter engages people in environmental monitoring and biodiversity recording. It also increases public outreach and education, while fostering greater public engagement and support for conservation efforts. Several notable examples of citizen science exist around the globe. For example, in the UK, the "Riverfly Partnership" encourages amateur surveys of river quality using invertebrates and, in Australia, FrogID is a citizen science project led by the Australian Museum that allows users to track frog distributions using a mobile phone app (Rowley et al. 2019). Another important approach to enhance public buy-in is through making waterways more accessible, such as free fishing days and guided educational tours.

Finally, as the case study below illustrates, there is an opportunity to raise public awareness of how individual actions can contribute to, or avoid, freshwater pollution. Actions range across avoiding littering, appropriate use of sewers and drains, responsible use of pesticides, and regular servicing of vehicles to avoid emissions. Some evidence suggests that appropriate behaviours stem from understanding combined risks to personal and environmental well-being (Little et al. 2023). People will continue to have a large influence on environmental policy; therefore, awareness that gains public support will be important in waterway restoration (Brodie et al. 2025).

Case study: public awareness of microplastic pollution

Cigarette ends (=butts or filters) are often the most common litter item found on shorelines of aquatic ecosystems globally, implying that they are readily and casually littered after use (Vanapalli et al. 2023). The University of Toronto "Trash Team" hypothesized that this was because most people are not aware that cigarette butts contain plastic, and that tossing a filter on the ground was no different than littering other single-use plastic items. To test this hypothesis, and determine whether increased awareness would change behavior, leading to less littered cigarette butts in aquatic ecosystems, the Trash Team implemented a project entitled "Kicking Plastic's Butt!". The project was an arts-based awareness campaign with quantitative transects sampled before and after to determine whether the campaign aligned with a decrease in littered butts. The campaign (https://uofttrashteam.ca/cigarettebutts/) included multiple types of art, for example, posters depicting people smoking single-use plastic straws, cutlery, and bottles before throwing them on the ground with the tagline—"if you knew this was plastic, would you throw this on the ground? Cigarette butts are plastic too." These posters were then posted with streetcar ads on the main street of the Toronto waterfront for two months (Fig. 2). In addition, the team commissioned a short film (https://www.youtube.com/watch?v=Yuftex4oLQc) questioning pedestrians informally about their understanding of what cigarette butts were made out of. Out of 21 people, only one knew cigarette butts were substantially made from plastic. Finally, an artist-in-residence—Emily Chudnovsky—created sculptures out of cigarette butts that were on display in the window at the local Patagonia and Ripley's Aquarium near the lakefront. Indicating the effectiveness of the campaign, test transects revealed a reduction in littered cigarette butt numbers during the campaign (reducing the amount that would reach Lake Ontario). Moreover, repeating the project in another area of Toronto led to the same result. In this instance, an engaging awareness campaign led to a change in behaviour that can reduce pollution in aquatic ecosystems.

4. Overcoming the challenges

Water quality impairment through pollution is among the greatest of all challenges to the protection and restoration of freshwater biodiversity (Vörösmarty et al. 2010). In combination, this reflects

i) the geographical scale of the problem from local to global;
ii) the large quantities and extensive diversity of traditional, legacy, and emerging pollutants involved;
iii) the multiple pollutant sources and processes from site-specific to catchment-wide and long-range;
iv) the timescales from episodic pollution incidents to long-term loading over decades to centuries;
v) the range of toxicological and ecological effects on organisms and ecosystem processes;
vi) the interactions between the effects of pollution and other stressors, notably climate change;
vii) the political, social, economic and technological constraints on the actions needed
viii) the priority currently given to human uses of catchments without full recognition of the consequences downstream.

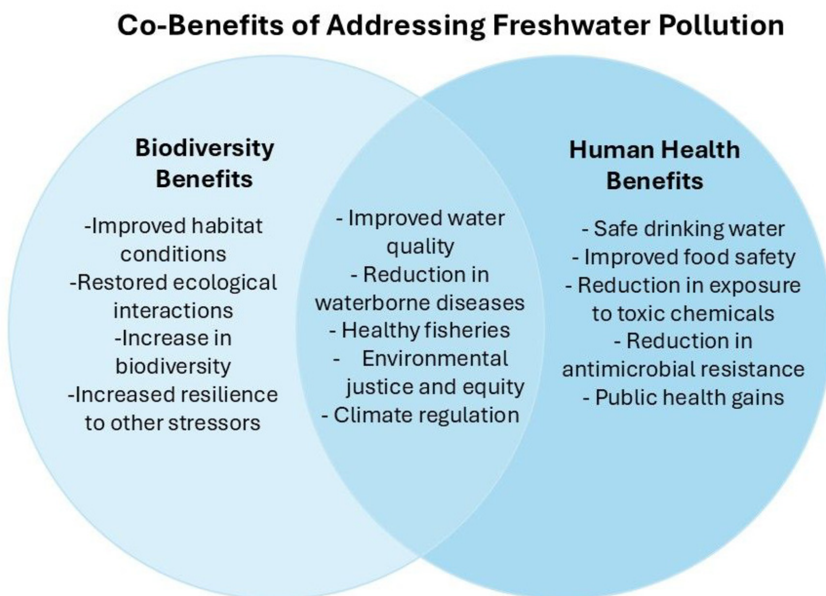
Simultaneously, the risks and impacts on amenity, health, and human well-being are large both now and for future

Fig. 2. A behaviour change experiment: using posters in the City of Toronto to raise awareness of a widely overlooked source of plastic pollution.

generations. And yet, our review reveals solutions that can discourage and replace damaging activities, or alternatively, encourage or incentivize positive actions. They include bespoke, local innovations (e.g., Sections 3.3.2, 3.3.4), catchment management using nature-based designs (e.g., Sections 3.3.3, 3.3.5), market-based mechanisms, or "stewardship" initiatives (e.g., Sections 3.4.1, 3.4.2) and national, international or even global policies. The evidence shows clearly that regulations or agreements can have positive impacts when enforced, funded, discharged with political conviction (e.g., Sections 3.2.1, 3.2.2), and supported by effective evidence (e.g., Section 3.1.3). Among the successes are some of the most impactful environmental actions ever undertaken, such as the transatlantic and European efforts to reverse the impacts of acid rain or the initial improvements in urban water quality achieved through the EU Urban Wastewater Treatment Directive (Council Directive 91/271/EEC, 1991) and the US Clean Water Act (1972). The most pertinent question, therefore, is not about *what* we need to do—but about *how* to make it happen.

One important opportunity is in combining actions that simultaneously benefit people, climate resilience, and wider biodiversity conservation with those that improve freshwater ecosystem quality, particularly given the ongoing global initiatives that offer the required momentum. From a human well-being perspective, improving water quality is not only

Fig. 3. Examples of co-benefits of addressing freshwater pollution for biodiversity and human health.



intrinsically important in biodiversity conservation, but also in protecting the goods and services provided by freshwater ecosystems (Fig. 3). Safeguarding biological resources in functional, unpolluted freshwater ecosystems ensures that they can provide the food, fibre, genetic resources, cultural inspiration, environmental regulation, and other benefits that are critical to human well-being (Lynch et al. 2023). At a global level, the Inter-governmental Panel on Biodiversity and Ecosystem Services is already informing and advocating the transformative actions needed (e.g., IPBES 2024). A forthcoming IPBES report in 2026 will illustrate the business benefits of protecting and restoring freshwaters, while existing data already hint at the substantial economic impacts of freshwater pollution (Russ et al. 2022).

Tackling freshwater pollution has a pivotal role also in reducing the burden of water-borne diseases through infectious agents (Forstinus et al. 2016) or toxicants (Singh et al. 2024) that accompany water quality degradation over large parts of the world. The potential benefits in reduced human morbidity and infant mortality demonstrate the synergies that could arise both for people and ecosystem quality if pollution were controlled more effectively (Sandifer et al. 2015). These needs resonate with the international initiatives, specifically through the Sustainable Development Goals, particularly SDG 3 (Good health and well-being), SDG 6 (Clean water and sanitation), and SDG 10 (Life below water), which illustrate the nexus that links water, biodiversity, and human health benefits. The disparity of health, pollution and insanitary impacts between the world's richest and poorest communities or nations means that addressing freshwater pollution also has clear resonance with poverty alleviation, social justice, and gender equality (SDG 1, 10, and 5).

Synergies also arise with broader biodiversity initiatives, specifically the UN Global Biodiversity Framework (GBF), in which a range of targets link the protection or restoration of terrestrial, marine, and inland water ecosystems (https://www.cbd.int/gbf/targets). They include, for example, extensive restoration of damaged ecosystems (Target 2), protecting 30% of land, sea, and inland waters (Target 3), reducing pollution below harmful levels (Target 7), and mobilizing major funding (Target 19). If attained, the actions towards these targets not only integrate scalable action in the terrestrial environment with downstream benefits to freshwater ecosystems but also will reduce harmful pollutant flux to the marine environments. Given that both the Sustainable Development Goals and GBF have extensive sign-up by over 190 UN countries, these are national as well as international opportunities. In a positive development, more than 50 nations and the EU have now signed up to the Freshwater Challenge, a voluntary, country-led partnership with the goal to restore 300 000 kilometers of degraded rivers and 350 million hectares of degraded wetlands by 2030, while securing the protection of freshwater ecosystems important for biodiversity and ecosystem services, in support of existing international environmental agreements such as the GBF (www.freshwaterchallenge.org).

Lastly, at a global level, the imperative to mitigate and adapt to climate change, as articulated by the Intergovernmental Panel on Climate Change (IPCC), adds momentum to the need to address pollution. Water quality and quantity are seen by the IPCC both as being at significant risk from climate change, but also as crucial to resource provision, ecosystem services, and human well-being as agriculture, domestic supply, and other water resource needs become impacted (IPCC 2022). Adapting to future climates will be made more difficult where water quality is impaired, but conversely, available evidence shows how addressing pollution increases climate resilience (Vaughan and Gotelli 2019).

Beneath these global drivers is the need for national and regional action, for example, through long-term planning, improved effectiveness of approaches, mobilizing political support and financial resources, and awareness raising by governmental and civic organizations. These apply not only in the freshwater environment directly but also in the urban, agricultural, and industrial landscapes that form freshwater catchments and ultimately influence conditions downstream (Giri and Qiu 2016). Because many freshwater pollutants reach rivers, lakes, or wetlands from or via the land or through groundwater, freshwater pollution cannot be addressed only by freshwater practitioners. Collaboration across disciplines, sectors, and domains, for example, in agriculture, planning, and the regulatory sector, is a key need (Plantinga 1996; Sophocleous 2002; Oki and Kanae 2006). National catchment management initiatives to allow this integration are many, varied, and sometimes long-standing—for example, catchment authorities, nutrient management boards, cross-sectoral partnerships, and landscape-scale designations such as national parks. They require the resources and administrative or legal powers to make a difference.

Landscape-scale initiatives also need to address modern forms of pollution such as light (Hölker et al. 2023) or noise (Te Velde et al. 2024), for example, by including highway authorities or local government in decisions. For these and other emerging pollutants, notably pesticides, pharmaceuticals, or per- and polyfluoroalkyl substances (PFAS), rapid technological change or product development sometimes advances more rapidly than regulatory controls (Tang et al. 2019). In the UK, for example, Whelan et al. (2022) illustrated how recovery from insanitary pollution, industrial discharges, and acid deposition was juxtaposed with growing problems, such as intensifying agriculture, endocrine-disrupting substances, plastics, and human or veterinary pharmaceuticals (see also Hannah et al. 2022). This means that research, monitoring, and evaluation must be sufficiently funded to keep sufficient pace to inform management action. In the case of pollutant mixtures and stressor interactions, this also implies understanding effects on ecosystems sufficiently well to address impacts in an order of priority that optimizes recovery (Kaushal et al. 2018; Paul et al. 2022).

Overcoming the challenge, then, is as much about the instruments at our disposal to implement what we know is needed.

5. Conclusion

The degradation of water quality is a complex and pervasive problem that has had negative impacts on freshwater life, human health, and economic opportunity. Over geographically extensive areas affecting most river systems and many standing waters, pollutants have been released either legally, illegally, or incidentally over inter-decadal to centennial timescales. Effects on freshwater organisms occur through direct toxicity, biomagnification, or bioaccumulation, often with additional ecological consequences that transcend organisms and taxa, resulting in ecosystem-level changes. Many of the existing approaches currently aimed at reducing water pollution are insufficient, and require a previously unmatched step-change in approach that is sufficiently multifaceted to address the major impacts. Fortunately, evidence suggests that solutions are available, workable, and effective given sufficient political, financial, and civic support. Measures to improve water quality include setting well-informed targets; regulating and enforcing actions nationally and internationally to reduce pollutant loads; ensuring that polluters pay; managing pollutants at source, across catchments, and internationally; funding nature-based solutions at scale using government finance or market mechanisms, and raising awareness of the problems and solutions. We identified a number of "success stories" from around the globe, but admittedly these are poorly documented in the literature with most studies focused on documenting "problems". Although some of the "success stories" were complete, many were partial, emphasizing the challenges with work in this space. Protecting and restoring water quality in freshwater ecosystems through regional, national, and global actions will bring manifold benefits for freshwater biodiversity and human well-being.

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