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Employing the DPSIR Framework (Drivers-Pressures-State-Impact-Response) to Analyze Water Pollution Trends

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Abstract

The Drivers-Pressures-State-Impact-Response (DPSIR) Framework is a systematic way to think and assess complex environmental issues that directly connect human processes and activities to environmental change and subsequent actions from society. In the applied research in the present study, we have used the DPSIR framework to help formulate our analyses of water pollution trends in a way that provides consideration for social-economic, ecological and regulatory perspectives. We have identified drivers that include industrialization, agricultural intensification, and urban population dynamics, and potential nutrient loading pollution pressures, chemical loading pollution pressures, inflow pollution pressures due to untreated waste-water. Pollution pressures changed the state of water bodies, with evidence including declining water quality indexes, increasing turbidity levels, and a decline in biodiversity within freshwater environments. The implications of pollution pressures beyond water include ecosystem degradation, public health

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implications, and economic loss in sectors like fishing and tourism. We consider responses by looking through a policy, technology or community engagement lens in relation to both the successes and gaps in current management frameworks. The application of the DPSIR framework highlights utilities, including helping identify causal chains, supporting better evidence-based policy responses to problems, and supporting integrated water resource management for better outcomes.

Keywords:

DPSIR framework, water pollution, environmental management, ecosystem health, policy response, pollution trends, water quality, integrated resource management.

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Introduction

Explanation of the DPSIR Framework

The Drivers-Pressures-State-Impact-Response (DPSIR) model is a way of simplifying the causal relationships between human actions and changes to the environment in the field of environmental science (Troian et al., 2021). The model was originally developed by the European Environment Agency (EEA) in order to impose a kind of analytical order on often very complicated relationships. The foundation of the methodology is the process of moving from societal choices through to environmental outcomes at one level of detail. The centre of the system of interest is the Drivers—largely economic growth, industrialisation, urbanisation, population changes and technological changes—that engage either the consumption of natural products and resources, or contribute to outputting waste. These drivers translate into Pressures, which are quantifiable burdens on ecological systems: nutrient loading, toxic spills, or unsustainable abstraction of water, for instance. Such pressures then disturb the State of the environment, producing detectable shifts in water quality, degradation of habitats, and declines in biodiversity. The altered state is represented in Impacts, which are evident in our natural and manmade systems—overfished stocks, lost recreational opportunities, and illnesses are examples. This connects to Responses, and one can understand the responses to changes as three registers: prevention, damage mitigation, and recovery: there is a range of action, from legislation, technology change, economics, and community participation. The DPSIR framework is powerful because it the relationships involved in a sustainable improvement process and shows that it is a constant feedback loop, moving away from the visible symptoms of an environmental issue and linking to the socio-economic order generating it.

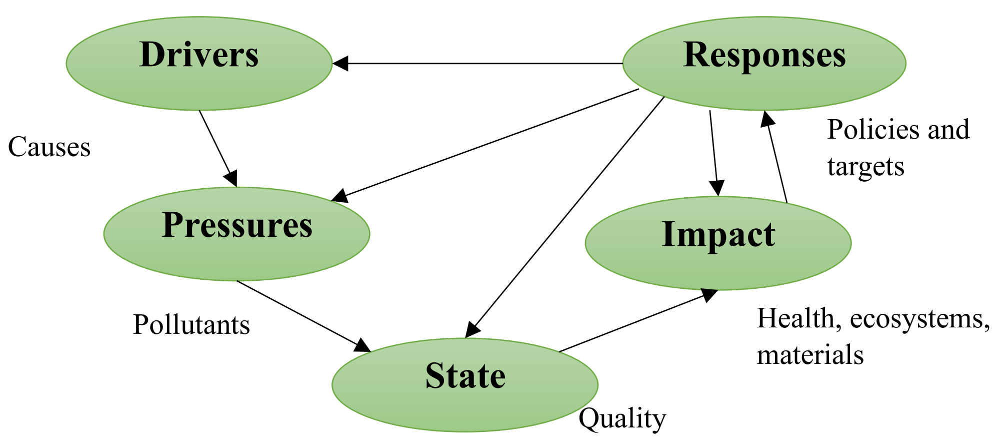

Figure 1. Simplified DPSIR framework for environmental analysis

Figure 1 shows the Drivers – Pressures – State – Impact – Response (DPSIR) diagram is a simplified step through the DPSIR framework in its application to environmental issues. The flow begins with Drivers, which represent the underlying causes (e.g., socio-economic activities), which can cause Pressures that manifest as pollutants or exploitation of environmental resources. Pressures alter the environment's State in ways that influence indicators of quality, including: some measure of water clarity, chemical constituents, or biodiversity levels. Changes in the state have Impacts, which can be upon people (human health), upon ecosystems, and upon material resources (such as fish and land). Responses (including policies, regulations, funded programs, and direct interventions) take a variety of forms and seek to prevent or mitigate the impacts, restore the state of the environmental system, and to affect the Drivers; and through that, provide a continual feedback loop. The arrows in the diagram indicate the flow of the management model, indicating the cyclical and interrelated nature of environmental management.

Definition of Water Pollution

Water pollution occurs when harmful chemicals, living creatures, or forms of energy are introduced to our lakes, rivers or aquifers in quantities that reduce the water quality, disrupt naturally occurring ecosystems, or threaten human health. Contamination can affect both surface water, which is all water above land (i.e. rivers, lakes, and coastal areas) and groundwater. Pollutants can come from many sources and are typically classified as either point or non-point sources of pollution. Point sources are easy to locate, such as a pipe spewing waste from a factory or an outfall from a sewage plant. Non-point sources are harder to pin down, flowing from practices like farming, urban runoff from storms, and the atmosphere. Pollutants come in many forms; they can be chemicals (pesticides, heavy metals, or solvents), physical factors (excessive sediment or heat from cooling waters), or living entities (bacteria, viruses, and introduced species). A pollutant will have different effects based on the timeframe that it disappears in, how long it lasts and its toxicity. Mercury, for instance, can travel through a lake for years, build up in fish, and lead to health problems that last for generations. Water pollution exacts a heavy toll on both ecosystems and human communities. Fresh and coastal habitats suffer, pushing vulnerable species toward decline or extinction; at the same time, the web of life that keeps these systems healthy frays. Contaminated drinking water provides immediate health risks and long-term developmental consequences, especially for children. Industries dependent on clean water - and not just industries tied directly to water and its cleanliness, like fishing, but to all manner of industries, like tourism and hospitality - are forced to absorb higher costs with lower profit margins which will affect the economy at multiple levels. As such, the wide-ranging and diverse impacts of water pollution solidify its position as one of the most pressing contemporary global issues.

Importance of Analyzing Water Pollution Using the DPSIR Framework

The DPSIR model provides a systems-based, integrative, and comprehensive view of water pollution that is greater than simply measuring the concentrations of pollutants (Federigi et al., 2022). Most environmental monitoring and assessment systems focus purely on examining the reportable presence of pollution (whether or not a system is in compliance) but do not examine socio-economic and policy aspects which necessarily entail the pathway of pollution problems. The DPSIR framework allows researchers and policymakers to map the entire causal pathway, from foundational drivers such as industrialization and population growth to direct pressures such as wastewater discharges, through environmental changes to water quality and ecosystem state to subsequently human impacts (Quevedo et al., 2021; Lahon & Chimpi, 2024). Because of the entire mapping of the DPSIR causal chain, opportunities can be highlighted for intervention where policy or technology may be most impactful (Bruno et al., 2020; Kanwal et al., 2022). Additionally, because the DPSIR model specifically links the drivers, pressures, state, impacts and responses of societies [unsustainable practices], it allows the evaluation of existing regulations, infrastructure, and public awareness efforts and also contributes to adaptive management by indicating where regulations, infrastructure or public awareness efforts are insufficient, and where new pressures and/or responses need to be identified (such as emerging climate change) (Elliott et al., 2017; Salim et al., 2023). DPSIR approaches to water pollution, and mere consideration, is satisfied by principles of sustainable development and integrated water resource management (IWRM) by allowing environmental protection measures to be economically feasible, socially acceptable, and ecologically successful (Turayeva et al., 2025).

Drivers of Water Pollution

Urbanization and Industrialization

Urbanization and industrialization are two of the foremost socio-economic drivers of water pollution globally. The rapid expansion of urban space creates a demand for housing, infrastructure, and services that can outpace the development of wastewater treatment options, solid waste management, etc. As a consequence—untreated domestic sewage, urban runoff containing oils, heavy metals and microplastics, and the direct disposal of industrial effluents into local rivers, lakes, and coastal waters is ubiquitous. Industrialization compounds these effects through the release of concentrated classes of pollution, including solvents, dyes, heavy metals, organic waste, etc., from manufacturing processes (Mousa, 2022). Next, in much of the developing world, industries form clusters near water bodies, in part for logistical reasons (e.g. proximity to transport logistics) and further exacerbate pollutant loading to water bodies (Majdanishabestari & Soleimani, 2019). Subsequently, impervious surfaces of an urban area (e.g. roads, rooftops, parking lots) deepen stormwater runoff by reducing natural infiltration pathways and conveying a suite of contaminant mixtures directly into waterways. As a consequence, urban and industrial activities exert a multiplicative force on the chemical and physical condition of aquatic systems that collectively leads to decline in water quality, and loss of ecological resilience (Halder & Islam, 2015).

Agricultural Practices

Agriculture significantly contributes to diffuse, non-point source water pollution due to the systemic application of fertilizers, pesticides, and herbicides, and due to the view of animal wastes in volume. Excess nutrients particularly nitrogen and phosphorus contained in synthetic fertilizers or manure are often discharged into groundwater or carried off-site in surface water when excess rainfall occurs. Nutrient enrichment can lead to algal blooms and oxygen depletion (i.e., eutrophication), which can lead to fish kills. In addition, pesticide residues, especially persistent organic pollutants, can bioaccumulate in aquatic organisms which therefore can have longer lasting ecological considerations, including human health. In addition, intense irrigation practices can cause salinization of the water or leaching or mobilization of soil-bound contaminants. Livestock farms can introduce pathogens directly (e.g. E. coli and Salmonella) in the waterways creating contaminated water. Given the percentage of land used for agriculture versus other land use, small inefficiencies or poor management practices can cause substantial cumulative negative impacts on water quality, indicating that agriculture represents a realistic target for pollution abatement measures (Narayanan & Rajan, 2024).

Climate Change

It is increasingly being recognized that climate change is an indirect but significant driver of the pollution of water (Iyengar & Bhattacharya, 2024). Changes in precipitation intensity and patterns can increase drought and flood cycles with implications for both the transport and dilution of pollutants in the aquatic system. Intense precipitation results in increased surface runoff, and substantial increases in the quantities of sediment, nutrients, and contaminants entering a water body. Drought may raise concentrations of pollutants as dilution and volume of water are diminished. Higher temperatures may also serve to contribute to thermal pollution, and modify chemical influence from water inputs, creating conditions that may accelerate the rate of eutrophication and toxic algae blooms. Sea level rise may contribute to the intrusion of saline waters into freshwater systems that impact drinking water quality, aquatic habitat and organisms adapted to either fresh or saline environments (Smith et al., 1987). Climate change also relates to agricultural inputs, industrial water consumption, and urban water management which would indirectly influence pollution loads (Shah & Bansalm, 2023). The relationship between climate variability, and pollution inputs from regulated and non-regulated sources strengthens the rationale for defining pollution management comparatively broadly to also accommodate climate change and its direct and indirect implications for water quality degradation (Shah & Bansalm, 2023).

Pressures on Water Quality

Discharge of Pollutants

Discharge to water bodies is the most immediate pathway for pollution into a water body and the primary threat to water quality. Industrial facilities discharge a diversity of pollution—heavy metals, hydrocarbons, man-made chemicals, thermal effluents—directly into nearby rivers, lake waters, and coastal waters with little or no treatment. Municipal wastewater systems in fast-growing urban areas are often over taxed or lack adequate treatment and discharge poorly treated or untreated sewage that retains pathogens, nutrients, and organic matter into receiving waters---degrading water quality. Agricultural runoff also adds more chemical pollutants when excess fertilizers, pesticides, and manure enter water bodies during rainfall, or irrigation return flows (Nakamura & Lindholm, 2025). Pollutant loading affects water bodies by changing the water body's chemical balance causing hypoxia, toxicity to water organisms, and longer lasting impact by contaminated sediments. Permanent harmful pollutants, for example mercury or polychlorinated biphenyls (PCBs), can impact water quality for decades, contributing to an overall slide into chronic decline of water quality that is difficult to reverse.

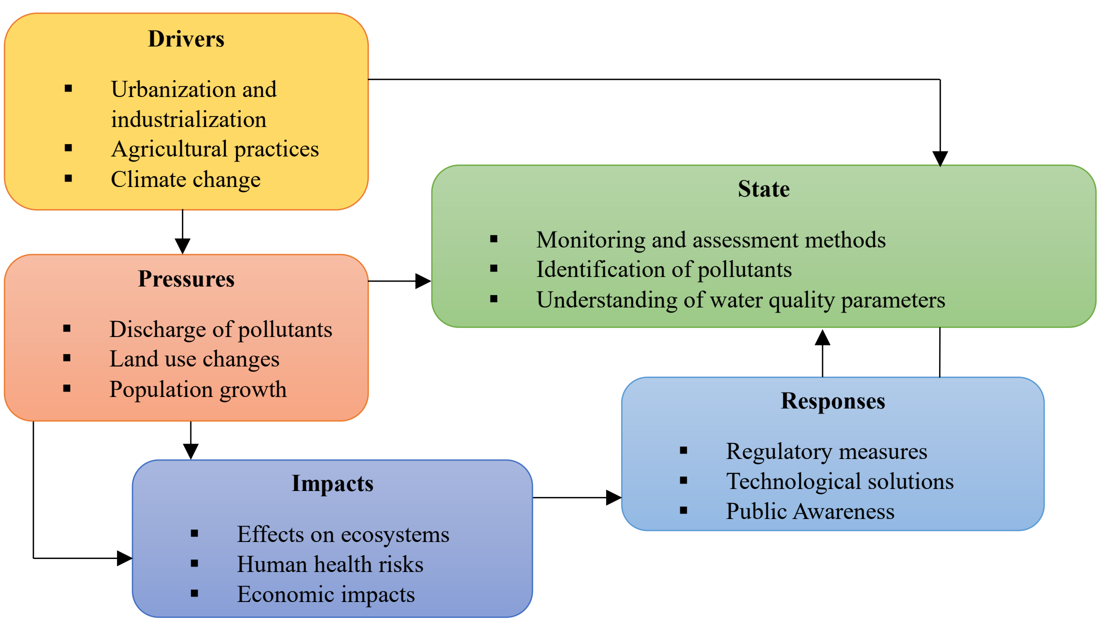

Figure 2. DPSIR framework for analyzing water pollution trends

Figure 2 illustrates a DPSIR (Drivers–Pressures–State–Impact–Response) framework used to interpret water pollution. It sets out a causal pathway which begins with Drivers such as the urbanization and industrialization of water infrastructure, agricultural practices and climate change. Drivers on the water system translate into Pressures through pollutants being emitted, land use changes and increased population. Pressures influencing the State simply translates to water quality, which is monitored through measuring pollutant identification, interpreting and assessing key metrics. The degraded State introduces Impact on ecosystems, human health and the economy. There are Responses, through regulation, technology and creating public awareness of the episode, that aim to mitigate impact and/or improve water quality and feed back into the system to influence future Drivers and states.

Land Use Changes

Land use changes significantly affect water quality by changing hydrologic cycles, sediment delivery, and a suite of pollutants. Urban growth increases the share of impervious surfaces (roads, parking lots, and roofs) that prevent natural infiltration, increase volumes of runoff, and deliver sediments, oils, metals, and plastic directly to aquatic environments. Similarly, agricultural and industrial development eliminates natural landscapes and forests, which can increase erosion and change sediment loads and stir sediment loads and smother aquatic habitats, and reduce light for plants and animals, and also reduce primary productivity. Wetland drainage eliminates a natural filtration system that regulated flow and effectively trapped pollutants. Mining operations disturb a much larger footprint, pull sediments into waterways, and release acidic mine drainage contaminants into surface and groundwater. All of these land use changes create a high chronic delivery of pollutants into water bodies and prevent ecosystems from assimilating and neutralizing naturally the contaminants.

Population Growth

Population growth exacerbates water quality pressures by increasing domestic water supply, generating wastewater, and increasing demand for food, energy and products. High population growth in urban areas or pop density in cities places immense pressure on sewage system, leading to sewage overflows, released un-permitted partially treated wastewater, increased flood risk, increased land development, habitat loss, increased impervious surface area, and increased stormwater runoff. The need for more agricultural products leads to increased fertilizer and pesticide applications, increasing nutrient and chemical loading in water. In many areas, informal settlements are developed with little or no sanitation infrastructure, leading to direct microbial and chemical loading to nearby water sources. Each of these is a pressure on water quality that leads to deterioration in water quality and risks to the health of ecosystems, public health and long-term water security.

State of Water Quality

Monitoring and Assessment Methods

Evaluating water quality involves the use of systematic, monitoring programs that employ field sampling, laboratory analysis, and more recently, aerial and satellite remote-sensing technologies. In traditional assessment approaches, field sampling collects water samples at specified locations and times; water samples are then analyzed in a laboratory to measure the objective chemical (e.g., nutrient concentration, heavy metals), as well as physical and biological indicators. After measuring water quality, researchers typically report a particular water quality value, or range of values, to decision makers. Biological water quality monitoring (i.e., bioindicator species, benthic, macroinvertebrates, or phytoplankton) provides a long-term measure of the cumulative effects of different contaminants. The advantage of using biological indicators is that they measure not only the impacts of chemicals, but also the potential impacts of other stressors simultaneously. Newer methods in assessing water quality include water quality monitoring sensor networks as well as satellite imagery, either of which allow us to monitor components of water quality in real time. Continuous monitoring of water quality uses real-time sensors to measure parameters (e.g., turbidity, temperature, and chlorophyll-a). Satellite images provide researchers with near real-time measurements of various surface parameters too. Geographic Information System (GIS) provides opportunities to conduct more detailed spatial analysis to identify pollution hotspots, and to track the time series of various environmental variables. The role of good assessment programs is to integrate the various monitoring and sensor networks to come up with reliable datasets. Sound datasets provide a basis for policy-related decisions, evaluation of limits to pollutant loadings, and commitments to long-term environmental planning.

Identification of Pollutants

In order to determine the current quality of water resources, it is necessary to accurately identify the pollutants that exist in aquatic systems. Chemical pollutants represented one of the major contaminant types that may be present in aquatic systems. Chemical pollutants can include nutrients such as nitrogen and phosphorus, which are often associated with eutrophication, and toxicants such as arsenic, lead, and mercury and synthetic organic pollutants. Physical pollutants include changes in water properties that may be observed through sediment load, thermal change, and suspended solids reducing light penetration. Biological pollutants include pathogenic microorganisms, invasive species, or excess organic matter considered to be excessively disrupt ecological balance. Various pollutants will sometimes interact synergistically thereby compounding their effects on aquatic systems and human health. For example, adding nutrient-rich materials creates favorable conditions for algal blooms to develop that can produce toxins dangerous to aquatic organisms and humans alike. Identifying pollutants also involves following the establishment of source strength (starting points), knowing whether the contributions are from point-source or non-point sources, and whether they contain persistent/bioaccumulative agents or if they break down into non-toxic forms.

Understanding of Water Quality Parameters

Water quality refers to a set of measures which, together, provide insights into the chemical, physical and biological conditions in the aquatic environment. The first set of parameters listed above are chemical in nature, with primary parameters of interest being pH (acidity vs. alkalinity), dissolved oxygen (DO) (crucial to aquatic life), biological oxygen demand (BOD) and chemical oxygen demand (COD) (indicators for organic pollution), and nutrient levels (nitrates, phosphates). Physical parameters include temperature, turbidity, conductivity, total suspended solids (indicators of hydrological and sedimentation processes). Biological parameters include species diversity indices and the presence of indicator organisms. Together these represent ecosystem health and resilience. Meaningful interpretation of the parameters described is predicated on an understanding of baseline or reference conditions based on the site and season, and local ecological characteristics. By maintaining a record of the values of these parameters over time (trends), scientists and policy makers will be able to identify emerging threats, assess compliance with established criteria for water quality, and assess the effectiveness of pollution mitigation measures.

Impacts of Water Pollution

Effects on Ecosystems

Water pollution has severe and typically permanent impacts to aquatic systems. Nutrient loading from agricultural runoff and wastewater discharges leads to eutrophication, which in turn leads to harmful algal blooms, hypoxia or anoxia due a depletion of dissolved oxygen, and the creation of "dead zones" in which aquatic life cannot be sustained by the ecosystem. In addition to excessive nutrients, toxic contaminants such as heavy metals, pesticides, and industrial chemicals bioaccumulate along the food web, which impacts reproductive success, growth rates, and survival of aquatic organisms. Sediment pollution smothers benthic habitats, decreases biodiversity, and modifies the organization of communities within aquatic systems. Changes in water chemistry and temperature affect the basic functions of ecosystems, and can resulting in loss of sensitive species and increased number of pollution-tolerant organisms. The overall consequence of all these changes is the loss of ecosystem resilience, thereby, decreasing water bodies ability to provide these critical ecosystem services, including nutrient cycling, habitat, and natural water filtration.

Human Health Risks

Polluted water represents a direct and indirect risk to human health. Pathogenic microorganisms, such as bacteria (E. coli, Vibrio cholerae), viruses (hepatitis A), and protozoa (Giardia, Cryptosporidium) can result in acute gastrointestinal illness or cholera and other infectious diseases. Chemical pollutants such as arsenic, lead, and mercury leave chronic effects on health, for example, neurological conditions, developmental effects, or an increased cancer risk. Nitrate pollution from agricultural fertilizers has been linked to methemoglobinemia (blue baby syndrome) in lactating infants. Harmful algal blooms create toxins that have effects on our liver, acute nervous systems, or dermal conditions and exposure can occur through drinking water, recreational activities, or eating seafood. Safe drinking water and sanitation in many lower- to middle-income areas don't only affect health status by adding to health burden and morbidity/mortality rates, but also in-hospital care and putting a strain on local healthcare systems.

Economic Impacts

The economic consequences of water pollution are important and varied. For example, the fishery sector is at risk when fish stocks are impacted by habitat loss, toxins, or an algal bloom. This impacts the livlihood of fishers and threatens food security. Economies reliant on tourism can also suffer revenue and employment loss when beaches, lakes, or rivers have stepped to be unsafe for recreational use. The rising cost of water treatment occurs when utilities need to reduce elevated levels of pollutants to meet drinking water standards. The economic implications of this is a burden on municipalities and a burden on the consumer. Water pollution can reduce agricultural production when it is toxic, affecting both production and soil productivity. By causing ecosystem degradation, we lose the variety of ecosystem services that may have otherwise supported economic stability and resiliency. For example, ecosystem services include water purification, flood prevention, and biodiversity protection (i.e., loss of species can have negative consequences). Over the long term, this all results in undermining economic growth and the greatest equity, and these will be felt more heavily in communities that have a higher reliance on water-based employment.

Responses to Water Pollution

Table 1 presents the results of a water pollution assessment based on the Drivers–Pressures–State–Impact–Response (DPSIR) approach (Khajuria & Ravindranath, 2012). Table 1 includes measurable indicators for each element, as well as observed values, and inferred meaning. The Drivers column included useful socio-economic and land-use information, such as, urban population growth, industrial production, and area of agricultural land. The Pressures column included direct pollutant flows (i.e., nutrients, heavy metals, and solid mortalities) exceeding acceptable level or safe threshold. State indicators of water quality (i.e., dissolved oxyge, biochemical oxygen demand (BOD), and pH) were presented in the State column. Impacts reflect the ecosystem service degradation, or loss of serving human health or economic standing that poor water quality has contributed to. Finally, Responses comprised the actionable responses from a policy, infrastructure, and community perspective, towards addressing pollution, while gaps in responses were highlighted. As a structured way to reflect on my assessment I am now able to visualize the causal pathways and assess the management interventions underway to address water pollution (Salim et al., 2023).

Table 1. DPSIR-based water pollution assessment results

DPSIR Component	Indicators Measured	Observed Values	Interpretation
Drivers	Urban population growth (%)	3.8% annual increase	Higher domestic water demand and waste generation
	Industrial output (tons/year)	1.2 million	Increased industrial effluent discharge potential
	Agricultural land use (%)	42% of total land	Intensive fertilizer and pesticide application
Pressures	Nutrient load (N, P mg/L)	N: 7.8 mg/L; P: 1.5 mg/L	Exceeds safe limits; risk of eutrophication
	Heavy metal concentration (mg/L)	Pb: 0.12; Hg: 0.004	Above WHO drinking water guidelines
	Sediment load (mg/L)	210 mg/L	High turbidity from land runoff
State	Dissolved oxygen (mg/L)	4.5	Indicates oxygen stress for aquatic life
	BOD5 (mg/L)	8.2	High organic pollution load
	pH	6.4	Slightly acidic; may affect aquatic species
Impacts	Fish kill incidents/year	4	Linked to hypoxia and toxicity
	Reported waterborne diseases (cases/year)	1,250	Associated with microbial contamination
	Tourism revenue loss (%)	18%	Due to poor water quality perception
Responses	Wastewater treatment coverage (%)	55%	Below required coverage for pollution control
	Pollution control inspections/year	120	Moderate enforcement, needs improvement
	Public awareness campaigns/year	6	Increasing community involvement

Regulatory Measures

Regulatory actions or responses form the foundation of government efforts to address water pollution (Törnqvist et al., 2011). Regulatory responses can be broadly separated into regulations establishing water quality standards, regulations covering limits on effluent discharge, and environmental laws addressing environmental risks associated with use or discharge of pollutants in order to limit loadings from point and non-point sources. Under a permitting system, both industrial and municipal discharges go through a permitting process and the facility or operator is compelled to comply with the limit on pollutants and the monitoring approach used. Environmental agencies often develop watershed management plans to address pollution and implement land use regulations, pollution controls and habitat protections. In many jurisdictions in the world, environmental impact assessments (EIAs) are required for projects that can affect water quality (e.g., multi-national projects, direct changes to water quality, or project-induced indirect changes); EIAs serve to limit impacts by requiring preventive actions to avoid or limit water quality impacts in the initial project planning phase. Many international agreements (e.g., United Nations Sustainable Development Goal 6 (i.e., Clean Water and Sanitation)) and transboundary water agreements require action to be undertaken cooperatively amongst countries sharing water; these agreements imply regulatory action must be preceded by cooperation and coordination to maintain or reduce water pollution (Parris, 2014). Although regulatory responses can effectively decrease targeted types of water pollution, the success of regulatory responses is contingent on enforcement, coordination between jurisdictions and agencies, and political will.

Technological Solutions

Technologies can help to reduce water quality pollutants through improved prevention, removal and monitoring. New wastewater treatment methods, including membrane bioreactors, wetlands and anaerobic treatment can remove organic matter, nutrients and pathogens from municipal and industrial wastewater. Innovations in agriculture, including precision agriculture usage, slow-release fertilizers and buffer strips can reduce the amount and movement of nutrients and pesticides. Bioremediation and phytoremediation are two examples of treatment that use natural organisms and plants to degrade, absorb or immobilize pollutants in contaminated water. New digital technologies such as satellite-based remote sensing and IoT (Internet of Things) sensors with AI-based predictive model and direct and fast monitoring of pollutants in water enable better adaptive management for pollution from excess nutrient and contaminated water management. Stormwater management solutions, including green roofs, permeable pavements and retention basins can aid in treating urban runoff prior to entry into rivers, lakes, and streams. The extent to which a technology has mitigated pollution will be determined by local variables to assess for local application, availability, costs, and maintainable capacity.

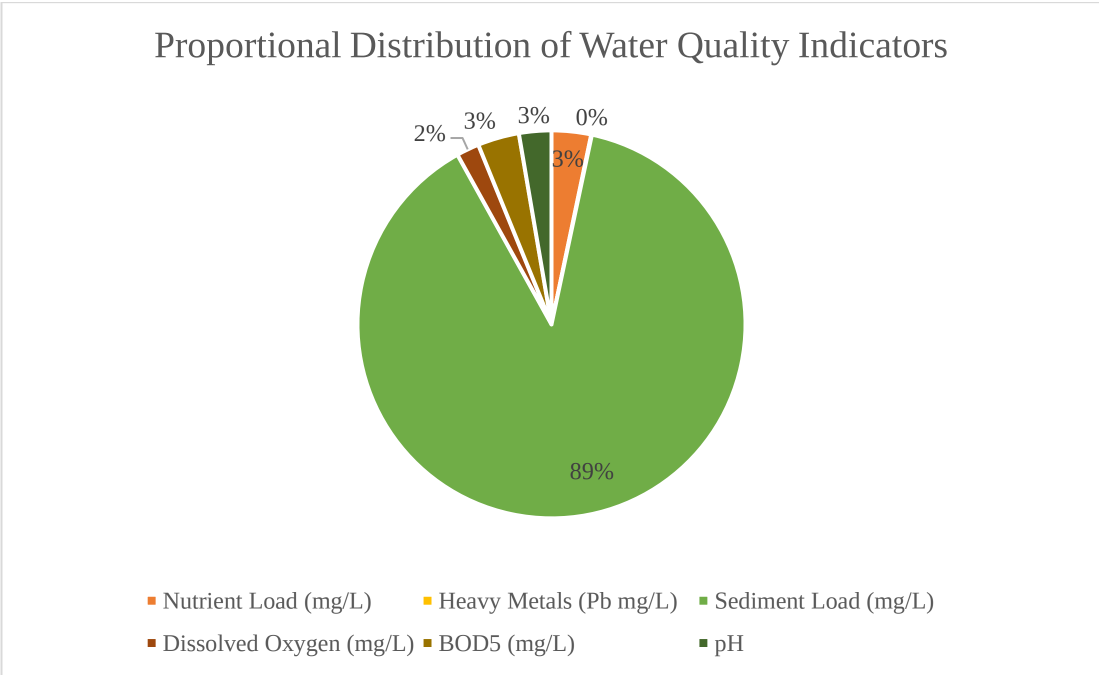

Figure 3. Proportional distribution of water quality indicators

In the chart, Figure 3, the compositional distributions of reported data for six water quality indicators revealed in the DPSIR analysis are most easily compared. Sediment load makes up the lion's share of reported data and indicates serious erosion and turbidity concerns, followed in size by nutrient load and BOD_5, which indicate organic and nutrient pollution concerns. Heavy metals, dissolved oxygen, and pH were not as significant, but would still be relevant in an evaluation of overall water quality. This chart provides a simple visual of where the water quality issue lies to help form priorities for pollution intervention strategies.

Public Awareness and Education

Public awareness and education initiatives can promote the community involvement needed to prevent and control water pollution. Programs to educate children in schools, community workshops, and public outreach can enhance public understanding of pollution sources, pollution effects, and in turn provide them with common water responsibilities. For example, citizen science initiatives, in which the community participates in quality monitoring programs, provide important data and also provide communities the agency to advocate to protect the environment. Educational behaviour changes encourage responsible actions like waste disposal, restricting plastic use, and minimizing chemicals used in households. In agricultural contexts, the same educational awareness campaigns can result in sustained environmental learning for sustainable practices that minimize pollution runoff. The public engagement through education will also provide an additional accountability measure through public advocacy; informed citizens are more likely to understand, support, and comply with regulatory measures while demanding action from their decision makers. Over time, an informed, engaged and educated public provides a constituency for responsible water stewardship, partner-ship, and commitment to maintain healthy aquatic ecosystems.

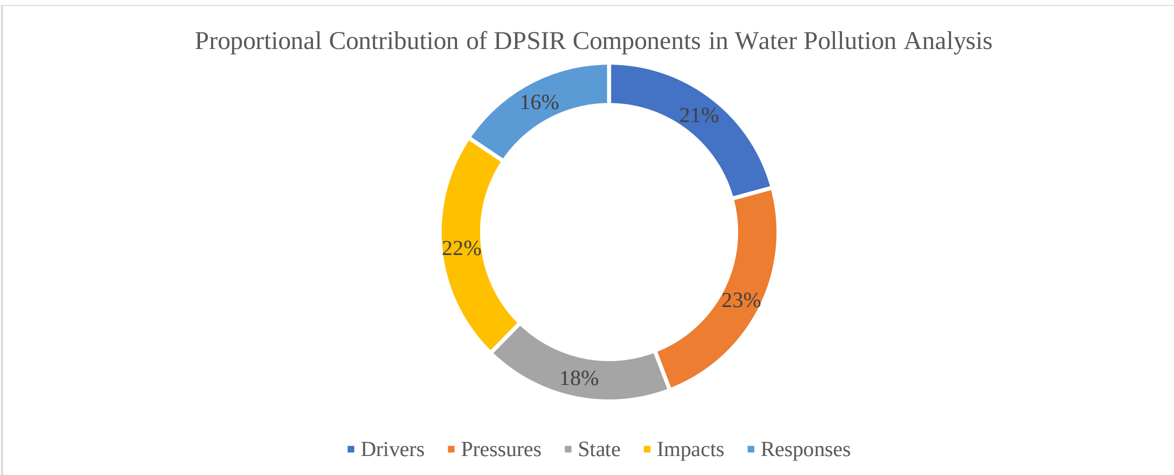

Figure 4. Proportional contribution of dpsir components in water pollution analysis

The components of the DPSIR (Drivers-Pressures-State-Impact-Responses) framework to understand and assess water pollution trends are shown in the figure 4 relative scale (Ratnaningsih et al., 2019). The largest sections highlight the importance of Pressures and Drivers in generating the water quality challenges. Impacts and State have moderate sections, while Responses, although the smallest section, are critical for reducing pollution. The circular design depicts the inter-connectedness between environmental causes, environmental consequences, and environmental solutions through the circular nature of the DPSIR framework.

Conclusion

The intricate feedback mechanisms between human activities and the degradation of water ecosystems is made explicit by examining water pollution using the DPSIR framework. This analysis identifies urbanization, industrialization, intensified agriculture, and climate change as the key driving forces that provide pressures (e.g., releases of effluent, altered land cover, increased water demand from cities) which transfigure aquatic systems, seen through deteriorating chemical indices, the emergence of a complex assemblage of contaminants, and lessened capacity for ecosystems to recover. The impacts are found at various scales, with evidence of loss of ecological integrity, threats to human health, and risks to economic viability of working landscapes, putting into peril the services that rivers and lakes supply, the wellbeing of future human life, and pathways to more sustainable development. Moving forward, research must pursue integrated research that connects hydrology, ecological sciences, social economics, and policy assessment, and acknowledges the complexity of pollution processes. Investments in high-resolution, continuous observation networks using Internet-of-things devices, satellite observation, and machine-learning predictive analytics are necessary to allow for real-time identification of pollution hot spots and anticipation of future threats. Furthermore, prolonged observation programs could reveal the efficacy of regulatory actions and the scaling up of new technologies, providing lessons in a timely fashion for adaptive management.

In the future, research should investigate the linkages between climate change and pollution, particularly how changing patterns of precipitation and increasing temperatures affect the transport, concentrations, and biological effects of pollutants. The DPSIR framework's logical, step-by-step mapping of cause and consequence positions it as an indispensable instrument for uncovering environmental challenges, ranking them for action, and assessing the success of management decisions. The framework not only establishes clear links between the driving forces, their impacts, the changes in environmental state, and the pressures and responses, but encourages decision makers to move away from reacting to symptoms to addressing the underlying causes. The area of responses recognizably addresses the notion having an intervention that is not only sound science, but also socially acceptable and economically viable in the case of freshwater management, thereby enhancing the prospect for long term management of freshwater. When applied to water quality problems, the DPSIR framework serves a dual purpose as both a lens for analysing complicated interactions and a mechanism for framing targeted, adaptive interventions to protect and restore aquatic systems.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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