International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 8s,2025
https://www.theaspd.com/ijes.php

Climate Change and Its Impact on Water Quality in Major River Basins Worldwide

Dr. Shilpi Shrivastava
Professor & Head, Dept of Chemistry
Kalinga University, Naya Raipur, Chhattisgarh

Dr.Tasneem K.H.Khan
Associate Professor
Department of Chemistry
Anjuman College Of Engineering and Technology, Sadar, Nagpur

Dr. M Sunanda
Assistant Professor
Department of zoology
SR&BGNR Government Arts And Science College (A)
Khammam, Telangana

Dr.T.Deborah paripuranam
Assistant professor
Department of Biochemistry
Nadar Saraswathi College of Arts and science
(affiliated to Mother Teresa University, Kodaikanal), Theni

Dr. Binumol. M
Associate Professor
Department of Botany
Sree Narayana College, Alathur

Mrs. M.Krishnaveni
Head & Assistant Professor,
Department of Biochemistry,
Nadar Saraswathi College of Arts and Science (Autonomous), Vadapudhupatty, Theni

---

Abstract:
Climate change is increasingly recognized as a critical factor influencing the quality of freshwater resources around the world. This paper investigates the multifaceted impacts of climate change on water quality in major river basins, including the Amazon, Nile, Yangtze, Ganges, and Mississippi. With rising global temperatures, changes in precipitation patterns, glacial melt, and the increased frequency of extreme weather events such as floods and droughts, the chemical, biological, and physical characteristics of river water are being significantly altered. These changes can exacerbate the presence of pollutants, reduce oxygen levels, increase sedimentation, and stimulate harmful algal blooms, all of which negatively impact aquatic ecosystems, human health, and agricultural productivity.
Furthermore, the paper explores how climate-driven shifts in land use, population pressure, and industrial development intensify the vulnerability of river basins to pollution and ecosystem degradation. Case studies from different geographic and climatic regions highlight both common patterns and regional specificities in

how climate change interacts with anthropogenic pressures to affect water quality. Special attention is given to the socio-economic and public health consequences of deteriorating water quality, particularly for communities that rely heavily on river systems for drinking water, food, and livelihood.
In response to these growing challenges, the paper reviews current mitigation and adaptation strategies, including integrated water resource management (IWRM), early warning systems, and nature-based solutions such as wetland restoration and reforestation. The study underscores the urgent need for coordinated international policies, continuous monitoring, and transboundary cooperation to safeguard water quality in the face of a changing climate. Ultimately, the paper calls for an interdisciplinary approach that bridges climate science, environmental policy, and community-based water management to ensure the resilience of river basins worldwide.
Keywords: Climate change, water quality, major river basins, freshwater resources, global warming,

INTRODUCTION

Freshwater is fundamental to human survival, economic development, and the functioning of ecosystems. River basins, which collect and distribute the majority of the world's surface freshwater, play a central role in supporting agriculture, industry, urban centers, and biodiversity (1). However, the quality of water within these vital systems is increasingly at risk due to the accelerating impacts of climate change. As global temperatures rise and weather patterns become more erratic, the physical, chemical, and biological characteristics of riverine waters are undergoing profound transformations (2).

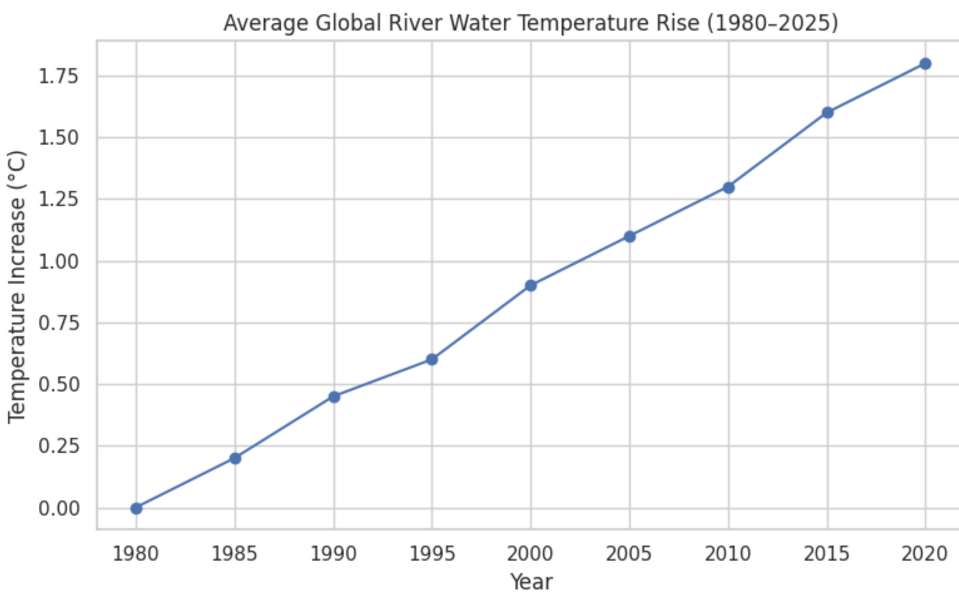

Figure 1 Global River Water Temperature Rise (1980–2025) – Illustrates the increasing trend in freshwater temperatures, affecting dissolved oxygen and aquatic health.

Climate change influences water quality through a range of interlinked mechanisms. Higher temperatures can exacerbate the thermal stratification of water bodies, reduce dissolved oxygen levels, and stimulate the proliferation of harmful algal blooms (3). Shifting precipitation regimes contribute to more intense and frequent flood events, which increase sediment and pollutant runoff, as well as longer and more severe droughts, which concentrate contaminants and reduce river dilution capacity (4). In snow- and glacier-fed basins, altered melt patterns disrupt flow seasonality, affecting both water availability and quality. These processes are further compounded by human activities such as urbanization, deforestation, and agricultural intensification, which amplify the vulnerability of river systems to climate stressors (5). The degradation of water quality has serious implications. It threatens public health, compromises food and water security, disrupts aquatic ecosystems, and imposes higher costs on water treatment and infrastructure (6). In transboundary river basins—shared by two or more nations—these challenges are particularly complex, requiring cooperative management strategies that transcend political boundaries. This paper investigates the impacts of climate change on water quality in major river basins across diverse geographical regions. Through an analysis of recent scientific literature and case studies, it aims to identify emerging trends, regional vulnerabilities, and effective mitigation and adaptation responses (7). The study underscores the importance of integrated, science-based, and globally coordinated efforts to safeguard water quality in the face of a rapidly changing climate.

2. CLIMATE CHANGE DRIVERS AFFECTING WATER QUALITY

The integrity of water quality in major river basins is increasingly compromised by the multifaceted impacts of climate change. Beyond influencing water availability, climate change alters key environmental parameters that govern the physical, chemical, and biological characteristics of freshwater systems (8). This section delineates the principal climate-related drivers contributing to water quality degradation, emphasizing their mechanisms and implications across diverse hydrological contexts.

2.1 Rising Global Temperatures

Rising global temperatures represent one of the most pervasive and direct effects of climate change, with significant implications for aquatic systems. Elevated air temperatures increase surface water temperatures, altering thermal stratification and reducing levels of dissolved oxygen—an essential factor for aquatic life and self-purification processes (9). Warmer conditions also enhance microbial activity, accelerating the breakdown of organic matter and increasing the biochemical oxygen demand (BOD) (10). Furthermore, elevated temperatures create ideal conditions for the proliferation of harmful algal blooms (HABs), which release toxins that threaten drinking water supplies, fisheries, and biodiversity. These changes in thermal and biochemical dynamics fundamentally disrupt the balance of riverine ecosystems and complicate water treatment processes.

2.2 Altered Precipitation Patterns

Climate change is reshaping global precipitation regimes, with many regions experiencing shifts in both frequency and intensity of rainfall. Increased precipitation can lead to excessive surface runoff, transporting sediments, nutrients, pesticides, and pathogens from urban, industrial, and agricultural landscapes into river systems. This inflow of contaminants contributes to eutrophication, turbidity, and microbial contamination. Conversely, in areas with declining or delayed rainfall, reduced river discharge diminishes the dilution capacity of water bodies, leading to higher concentrations of pollutants (11). These altered hydrological patterns strain the natural capacity of ecosystems to maintain water quality and challenge conventional water management strategies.

2.3 Extreme Weather Events (Floods and Droughts)

The growing frequency and severity of extreme weather events—particularly floods and droughts—have profound effects on water quality. Flood events often overwhelm drainage and wastewater infrastructure, resulting in combined sewer overflows and direct discharge of untreated effluents into rivers (12). They also accelerate soil erosion and mobilize contaminants stored in the landscape. In contrast, droughts reduce river flow volumes, concentrating pollutants and lowering oxygen levels, thereby exacerbating water quality stress. Extended periods of drought can also alter water chemistry, increase salinity, and reduce the resilience of aquatic habitats. Both types of extremes expose the vulnerability of water systems to climatic shocks and require adaptive infrastructure and governance responses.

2.4 Glacier and Snowpack Melting

Glacier and snowpack meltwater plays a critical role in sustaining river flows, particularly in mountainous and high-latitude regions. Climate-induced reductions in snow accumulation and accelerated glacial retreat are altering the seasonal and annual flow regimes of major rivers such as the Ganges, Indus, Yangtze, and Colorado. Initially, increased melt rates may cause glacial lake outburst floods (GLOFs), releasing sudden surges of water laden with sediments and debris. Over time, however, diminished glacial mass leads to reduced baseflow during dry seasons, impacting water availability and quality (13). Moreover, newly exposed rock surfaces may leach heavy metals and other geogenic contaminants into rivers, further complicating water safety. These shifts not only disrupt hydrological stability but also threaten long-term water security in downstream regions.

3. MECHANISMS OF WATER QUALITY DEGRADATION

Climate change exerts a profound influence on the physical, chemical, and biological processes that determine water quality in river basins. The mechanisms of degradation are multifactorial and often synergistic, arising from complex interactions between climate-driven stressors and anthropogenic activities. These mechanisms reduce the ecosystem services provided by freshwater bodies, compromise biodiversity, and pose significant challenges to water security and public health. The following subsections detail the primary scientific processes through which climate change degrades water quality in fluvial systems.

3.1 Thermal Stratification and Oxygen Depletion

Thermal stratification, the vertical temperature layering of water bodies, has become more pronounced with increasing global temperatures. In thermally stratified systems, the surface layer (epilimnion) becomes warmer and less dense, while deeper layers (hypolimnion) remain cooler (14). This stratification impedes vertical mixing and gas exchange, particularly the reoxygenation of bottom waters. The hypolimnion, isolated from atmospheric oxygen, experiences oxygen depletion due to microbial respiration and decomposition of organic matter. Hypoxic (<2 mg/L O_2) and anoxic (0 mg/L O_2) conditions accelerate internal loading of nutrients and trace metals from sediments through reductive dissolution. For example, phosphorus bound to iron oxides in sediments is released under anoxic conditions, fueling eutrophication in the overlying water column (15). Similarly, anoxia enhances the release of toxic substances such as ammonia, sulfide, and methylmercury. These changes disrupt redox-sensitive biogeochemical cycles and degrade habitat suitability for aquatic organisms, particularly stenothermal and oxyphilic species.

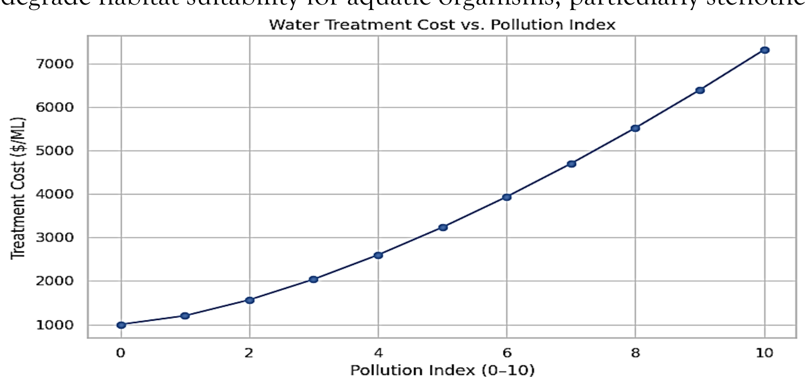

Figure 2 Water Treatment Cost vs. Pollution Index – Indicates that higher pollution levels drastically raise treatment expenses.

3.2 Nutrient Loading and Algal Blooms

Nutrient loading, particularly of nitrogen (N) and phosphorus (P), is intensified by climate-induced increases in runoff, extreme precipitation, and land-use changes. During storm events, agricultural fields, urban landscapes, and wastewater discharge points release large quantities of nutrients into rivers. These nutrients stimulate primary production, often leading to eutrophication and the proliferation of harmful algal blooms (HABs), especially in warm, stagnant waters.Cyanobacterial blooms, in particular, thrive under elevated temperature regimes and stratified conditions. Species such as *Microcystis aeruginosa* produce potent toxins (e.g., microcystins) that pose severe risks to human health, aquatic fauna, and livestock. Beyond toxicity, dense algal blooms reduce light penetration and disrupt photosynthesis, leading to diurnal oxygen fluctuations and subsequent hypoxia following bloom decay (16). The associated increase in biochemical oxygen demand (BOD) further exacerbates oxygen stress and organic pollution.Additionally, excess nitrogen can lead to nitrate contamination of groundwater and surface waters, causing methemoglobinemia ("blue baby syndrome") and promoting denitrification processes that release nitrous oxide (N_2O), a potent greenhouse gas—linking nutrient pollution back to climate change.

3.3 Sediment Transport and Erosion

Climate-driven increases in rainfall intensity, coupled with land degradation and deforestation, accelerate soil erosion and sediment delivery to river systems. Suspended sediments reduce water transparency (turbidity), impairing photosynthesis and disrupting aquatic food webs. Fine sediments (<63 µm) also act as vectors for adsorbed pollutants, including heavy metals (e.g., lead, cadmium, arsenic), persistent organic pollutants (POPs), and pathogens.High sediment loads during flood events can cause physical abrasion of benthic habitats, smothering of spawning grounds, and burial of macroinvertebrate communities. Moreover, sedimentation in reservoirs and wetlands reduces water storage capacity and alters hydraulic residence times, affecting the retention and degradation of pollutants. The geomorphological restructuring of river channels from increased sediment deposition also modifies flow regimes and exacerbates flood risks.From a water treatment perspective, elevated sediment loads increase the demand for filtration, coagulants, and disinfectants, raising operational costs and complexity, especially in low-resource settings.

3.4 Salinity Intrusion and Pollutant Concentration

Sea-level rise, reduced freshwater discharge, and prolonged droughts contribute to salinity intrusion in estuaries, deltas, and lowland river reaches. Saline water encroaches upstream through both surface and groundwater pathways, leading to brackish conditions that alter ionic composition and water chemistry. Elevated salinity reduces the palatability and usability of water for drinking, irrigation, and industrial applications, and imposes osmotic stress on freshwater biota.Salinity changes also affect chemical speciation and mobility of pollutants. For instance, increased chloride concentrations can enhance the solubility of heavy metals and influence the partitioning of organic contaminants (17). Concurrently, reduced river flows during droughts concentrate existing pollutants, including nutrients, pharmaceuticals, and endocrine-disrupting compounds, raising their ecological toxicity and health risks.This mechanism also compromises the functioning of wetlands and riparian buffers, which play a critical role in natural water purification. As the buffering capacity of ecosystems is exceeded, the resilience of freshwater systems to climate change diminishes.

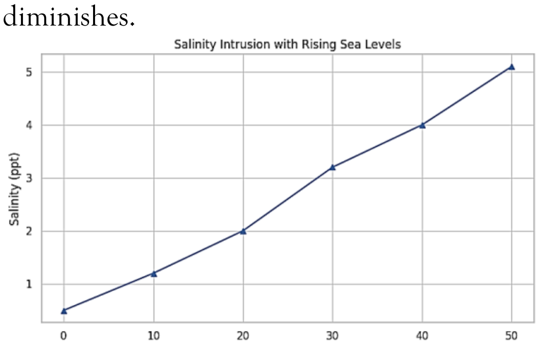

Figure 3 Salinity Intrusion with Rising Sea Levels – Highlights the increase in salinity in coastal rivers, affecting agriculture and drinking water.

4. CASE STUDIES FROM MAJOR RIVER BASINS

Understanding the influence of climate change on water quality requires context-specific analysis. The following case studies examine five of the world's most critical river basins, each representing diverse climatic zones, land-use pressures, and hydrological regimes. These basins illustrate how climate-induced alterations in temperature, precipitation, and hydrological extremes interact with anthropogenic stressors to degrade water quality.

4.1 Amazon Basin (South America)

The Amazon Basin, encompassing over 6 million square kilometers, is globally significant for its hydrological output and biogeochemical cycling. Recent studies indicate that the basin is experiencing increasingly erratic precipitation patterns, longer dry seasons, and elevated evapotranspiration rates, consistent with warming trends in the tropical South American region.Water quality degradation in the Amazon is primarily driven by deforestation-induced erosion, unregulated gold mining, and climate-exacerbated hydrological changes. Intense rainfall events mobilize vast quantities of sediments and associated nutrients—particularly phosphorus—into aquatic systems, leading to increased turbidity and eutrophication in oxbow lakes and floodplain channels (18). Elevated water temperatures and nutrient enrichment create optimal conditions for cyanobacterial blooms. In addition, mercury used in artisanal gold mining becomes more bioavailable under warmer, anoxic conditions, leading to methylmercury formation and bioaccumulation in aquatic food webs, posing neurotoxic risks to both humans and wildlife.

4.2 Ganges–Brahmaputra Basin (South Asia)

The Ganges–Brahmaputra Basin, a transboundary river system spanning five countries, sustains one of the densest human populations on Earth. The basin's hydrology is increasingly influenced by Himalayan glacial retreat, erratic monsoonal rainfall, and rising temperatures. These changes are altering both seasonal discharge patterns and water quality regimes.High pollutant loading, driven by untreated municipal wastewater, agrochemical runoff, and industrial effluents, is compounded by climate-driven stressors. Intense precipitation events increase surface runoff and mobilize pathogens and nutrients, while reduced dry-season flows impair dilution capacity (19). The lower basin, particularly the Bengal Delta, is subject to salinity intrusion due to sea-level rise and upstream abstraction. Salinity stress is altering the ionic balance of both surface and shallow groundwater systems, reducing potable water availability and affecting rice cultivation. Furthermore, rising water temperatures are correlated with increased pathogen survival and enhanced microbial resistance, raising public health concerns related to enteric diseases and antimicrobial resistance (AMR).

4.3 Nile River Basin (Africa)

The Nile River Basin spans a wide latitudinal gradient, encompassing both humid and arid climatic zones, with hydrology strongly influenced by interannual variability in the Intertropical Convergence Zone (ITCZ). Climate projections indicate rising temperatures, declining rainfall in the Ethiopian Highlands, and increased evapotranspiration in downstream arid zones—compounding water scarcity and quality issues. Water quality challenges in the Nile are linked to high nutrient inputs, untreated wastewater, and agricultural runoff. Climate-induced low-flow conditions enhance the concentration of pollutants, particularly in the lower Nile. Additionally, the construction of upstream reservoirs, including the Grand Ethiopian Renaissance Dam (GERD), alters sediment fluxes, nutrient cycling, and salinity gradients. In the Nile Delta, seawater intrusion—exacerbated by sea-level rise and subsidence—is salinizing groundwater and surface waters, degrading water quality for irrigation and drinking. Combined with intensifying hypoxic conditions in drainage canals, these changes are eroding ecosystem services and agricultural productivity.

4.4 Yangtze River Basin (China)

The Yangtze River Basin, home to nearly one-third of China's population, is undergoing rapid hydrological and ecological transformation due to industrialization, urbanization, and climate change. Intensifying precipitation events, coupled with anthropogenic land use changes, have accelerated pollutant loading into the river system, particularly in its middle and lower reaches.Thermal stratification in large reservoirs, such as the Three Gorges Reservoir, is enhancing hypolimnetic oxygen depletion, promoting internal nutrient loading and the release of legacy phosphorus and heavy metals from sediments. Eutrophication is widespread in tributary lakes such as Lake Taihu, where elevated nutrient levels and warmer temperatures fuel recurrent cyanobacterial blooms dominated by *Microcystis* spp. Additionally, the Yangtze estuary is experiencing progressive salinization due to reduced freshwater outflows and sea-level rise, threatening the ecological integrity of estuarine wetlands and increasing the cost of water treatment in urban centers.

4.5 Mississippi River Basin (North America)

The Mississippi River Basin, the fourth-largest in the world, is highly developed and agriculturally intensive. It has become a paradigmatic case of nutrient-driven water quality degradation under climate variability. Increasing precipitation intensity, driven by a warming climate, leads to enhanced surface runoff and river discharge, particularly in spring months.This hydrologic shift results in episodic nutrient pulses—primarily nitrates and phosphates—from row crop agriculture and livestock operations into the river system. These nutrients are transported downstream into the northern Gulf of Mexico, where they drive hypoxia through enhanced primary production and subsequent microbial oxygen consumption. The annual formation of the hypoxic “dead zone,” which often exceeds 15,000 km^2, has severe ecological and economic consequences. Simultaneously, rising air temperatures reduce oxygen solubility and promote algal growth in upstream freshwater systems. During periods of low flow, pollutant concentrations increase, including sediment-bound pesticides and pharmaceuticals, further complicating water treatment and ecosystem health management.

5. SOCIO-ECONOMIC AND ECOLOGICAL IMPACTS

The degradation of water quality under the influence of climate change has far-reaching consequences that extend beyond environmental systems into the core of socio-economic stability and public welfare. Impacts are often multidimensional and interlinked, creating feedback loops that undermine development goals, public health, food security, and ecosystem resilience. This section examines the primary socio-economic and ecological consequences of declining water quality in climate-stressed river basins.

5.1 Public Health Risks

Deteriorating water quality poses direct and indirect risks to human health, particularly in densely populated and low-resource regions. Increased surface runoff during extreme rainfall events transports pathogens, including *Escherichia coli*, *Vibrio cholerae*, *Giardia lamblia*, and viruses such as norovirus and rotavirus, into drinking water sources. Warmer temperatures also enhance the survival and proliferation of these microorganisms, heightening the incidence of waterborne diseases such as diarrhea, cholera, typhoid fever, and dysentery.The emergence of harmful algal blooms (HABs), driven by nutrient enrichment and warming waters, further compounds health risks. Cyanotoxins such as microcystins and cylindrospermopsin can cause hepatotoxic and neurotoxic effects upon ingestion or exposure. In parallel, the proliferation of antimicrobial-resistant (AMR) bacteria in contaminated river systems—linked to improper wastewater disposal and climate-enhanced microbial selection—poses a growing public health challenge with implications for global health security.Marginalized communities are disproportionately affected due to limited access to safe drinking water, inadequate sanitation infrastructure, and poor health services. As water quality declines, reliance on unsafe sources increases, exacerbating public health inequities and increasing mortality and morbidity rates.

5.2 Impact on Agriculture and Fisheries

Agriculture, the largest consumer of freshwater globally, is highly sensitive to both the quantity and quality of water. Poor water quality resulting from increased salinity, nutrient loads, and agrochemical residues compromises irrigation efficiency, soil health, and crop productivity. Salinity intrusion—particularly in coastal deltas like the Nile and Ganges—reduces soil permeability, alters osmotic balances in plant cells, and reduces yields of staple crops such as rice, wheat, and maize.Fisheries, both inland and estuarine, are severely affected by eutrophication and oxygen depletion. Hypoxic or anoxic conditions disrupt trophic structures, reduce reproductive success, and increase mortality among economically valuable fish species (20). HABs can result in massive fish kills due to toxin production and oxygen consumption. Moreover, bioaccumulation of heavy metals, mercury, and persistent organic pollutants (POPs) in aquatic organisms poses long-term risks to food safety and human nutrition.These impacts translate into economic losses, food insecurity, and loss of livelihoods, especially for communities that rely heavily on subsistence farming and artisanal fishing.

5.3 Biodiversity Loss and Ecosystem Disruption

Aquatic ecosystems are highly sensitive to water quality parameters such as temperature, oxygen levels, pH, and pollutant concentration. Climate-induced degradation alters these parameters beyond the tolerance thresholds of many aquatic and riparian species, leading to shifts in species composition, reduced genetic diversity, and local extinctions.In particular, freshwater biodiversity is threatened by a combination of stressors including hypoxia, toxic contamination, sedimentation, and invasive species proliferation. Amphibians, benthic macroinvertebrates, and native fish populations are among the most vulnerable groups. Fragmentation of habitats due to dam construction, altered flow regimes, and sediment load reduction disrupts migration routes and breeding cycles.Loss of keystone and foundation species diminishes ecosystem functionality, reducing services such as nutrient cycling, water purification, and carbon sequestration. Once degraded, freshwater ecosystems often exhibit low resilience and slow recovery, making biodiversity loss one of the most irreversible consequences of water quality decline.

5.4 Economic Costs of Water Treatment and Resource Degradation

Declining water quality significantly increases the operational and capital costs associated with water treatment. Elevated sediment loads, chemical contaminants, and microbial pollution require advanced filtration, coagulation, disinfection, and sometimes desalination processes to meet potable standards. These costs escalate during flood events or periods of contamination, placing a financial burden on municipalities and water utilities, particularly in developing regions.In addition to direct treatment costs, economic losses stem from reduced agricultural productivity, diminished fishery yields, degraded recreational value of water bodies, and the loss of hydropower potential due to sedimentation. Health-related expenditures, including treatment of waterborne diseases and productivity losses due to illness, further strain national economies.Moreover, water-related conflicts—exacerbated by transboundary pollution and scarcity—can destabilize regions, increasing governance and security costs. The cumulative economic impact of water degradation under climate change is projected to be substantial, with global estimates suggesting GDP losses in water-stressed regions could reach several percentage points by mid-century if current trends continue.

6. ADAPTATION AND MITIGATION STRATEGIES

Mitigating the impact of climate change on water quality requires coordinated, multi-level approaches that integrate science, policy, and community engagement. Strategies must be adaptive, inclusive, and context-specific, capable of addressing both immediate water quality threats and long-term systemic vulnerabilities. This section outlines key adaptation and mitigation strategies currently in practice or proposed for enhancing water quality resilience in major river basins worldwide.

6.1 Integrated Water Resources Management (IWRM)

Integrated Water Resources Management (IWRM) is a holistic framework that promotes the coordinated development and management of water, land, and related resources to maximize social and economic welfare without compromising ecosystem sustainability. IWRM is essential for aligning water quality objectives with climate adaptation goals.Under IWRM, water quality management is embedded within the broader hydrological cycle, considering upstream-downstream linkages, pollution sources, and land-use dynamics. It emphasizes stakeholder engagement, cross-sectoral coordination, and adaptive governance. In river basins vulnerable to climate-induced extremes (e.g., floods and droughts), IWRM facilitates the implementation of dynamic flow regulation, pollution control zoning, and conjunctive use of surface and groundwater to buffer water quality fluctuations. Additionally, the integration of water quality monitoring networks into IWRM frameworks enables early detection of pollutant trends and climate-related anomalies.

6.2 Nature-Based Solutions (e.g., Wetlands, Reforestation)

Nature-based solutions (NbS) offer cost-effective, multifunctional strategies for enhancing water quality while providing co-benefits such as biodiversity conservation and carbon sequestration. Wetlands, riparian buffers, and restored floodplains act as natural filters, removing nutrients, sediments, and pathogens through physical, chemical, and biological processes. Reforestation of degraded catchments reduces surface runoff, soil erosion, and non-point source pollution.Constructed wetlands have been successfully implemented for secondary and tertiary wastewater treatment in both rural and peri-urban areas. Meanwhile, agroforestry and regenerative agricultural practices reduce nutrient leaching and pesticide runoff. NbS also help regulate hydrological extremes by attenuating flood peaks and maintaining baseflows during droughts, thereby stabilizing water quality across seasons. The strategic integration of green infrastructure into watershed planning is increasingly recognized as a climate-resilient complement to conventional engineering approaches.

6.3 Technological Interventions and Early Warning Systems

Advanced technologies are critical for both mitigation and adaptive management of water quality under climate stress. These include real-time water quality monitoring systems, remote sensing for land-use and pollutant source mapping, and predictive models that integrate climatic, hydrological, and biochemical data.Early warning systems (EWS) use hydroclimatic forecasts, sensor networks, and machine learning algorithms to detect potential contamination events, such as algal blooms, sediment surges, or chemical spills. These systems enable proactive responses, including targeted treatment interventions, public health advisories, or temporary source switching in water supply systems.On the treatment front, innovations such as membrane filtration, UV disinfection, electrocoagulation, and bioremediation techniques enhance the removal of emerging contaminants, including pharmaceuticals and microplastics. In developing regions, decentralized, solar-powered purification systems offer sustainable alternatives for rural water quality management.

6.4 Policy Reforms and Transboundary Cooperation

Effective policy frameworks are fundamental for addressing climate-related water quality challenges, particularly in river basins that span multiple administrative or national boundaries. Climate-resilient water governance requires legal and institutional mechanisms that enforce water quality standards, incentivize pollution control, and facilitate basin-wide coordination.Policy reforms should focus on integrating climate risk into water quality regulation, strengthening compliance monitoring, and mainstreaming environmental flow requirements. Economic instruments—such as pollution taxes, water pricing, and payment for ecosystem services (PES)—can encourage behavioral change and investment in pollution abatement. Transboundary river basins (e.g., the Nile, Ganges, and Mekong) necessitate cooperative frameworks based on data sharing, joint monitoring, and equitable water allocation. International conventions such as the UNECE Water Convention and the UN Watercourses Convention provide legal bases for such collaboration. Climate change adds urgency to these efforts, as shared risks demand shared responsibilities and joint adaptive planning.

7. CONCLUSION AND RECOMMENDATIONS

The intensifying effects of climate change are exerting profound pressure on the water quality of major river basins around the globe. Through mechanisms such as rising temperatures, altered precipitation regimes, extreme weather events, and cryospheric changes, climate change interacts with anthropogenic activities to degrade the chemical, physical, and biological integrity of freshwater systems. The impacts are far-reaching—

affecting human health, food production, ecosystem services, and economic stability—particularly in regions already facing socio-environmental vulnerabilities.Case studies from the Amazon, Ganges–Brahmaputra, Nile, Yangtze, and Mississippi river basins illustrate the complex interplay between climate dynamics and local land use, governance structures, and pollution sources. These examples underscore the reality that while global patterns of climate influence are discernible, responses must be tailored to the hydrological, socio-economic, and ecological characteristics of each basin.Despite these challenges, there is significant opportunity for proactive adaptation and mitigation. Strategies such as Integrated Water Resources Management (IWRM), nature-based solutions (NbS), advanced monitoring technologies, and transboundary cooperation offer scalable and cost-effective pathways for safeguarding water quality. However, successful implementation requires robust institutional capacity, policy coherence, equitable stakeholder participation, and the mainstreaming of climate resilience into water management frameworks.

RECOMMENDATIONS:

1. **Enhance Monitoring and Data Integration:**

Establish basin-wide, climate-informed water quality monitoring networks that integrate remote sensing, in-situ sensors, and predictive models for real-time analysis and early warning.

2. **Invest in Nature-Based Solutions:**

Prioritize watershed restoration, wetland conservation, and reforestation to mitigate non-point source pollution, stabilize hydrological regimes, and improve ecosystem resilience.

3. **Strengthen Climate-Water Governance:**

Reform institutional frameworks to integrate water quality goals with climate adaptation plans at national and transboundary levels, ensuring adaptive, inclusive, and accountable decision-making.

4. **Promote Technological Innovation:**

Deploy low-cost, decentralized water treatment technologies and support research into emerging contaminants, especially in underserved rural and peri-urban areas.

5. **Foster International and Cross-Sectoral Collaboration:**

Encourage knowledge-sharing platforms and basin-level agreements to facilitate integrated water quality management across political boundaries, informed by climate science and supported by financial mechanisms.

6. **Incorporate Water Quality in Climate Finance and Policy:**

Ensure water quality protection is embedded in national climate strategies (e.g., NDCs) and that international funding mechanisms allocate resources to water-climate nexus projects.

REFRENCES

1. Bates, B. C., Kundzewicz, Z. W., Wu, S., & Palutikof, J. P. (Eds.). (2008). *Climate change and water* (Technical Paper of the Intergovernmental Panel on Climate Change). IPCC Secretariat. https://www.ipcc.ch/site/assets/uploads/2018/03/climate-change-water-en.pdf
2. Whitehead, P. G., Wilby, R. L., Battarbee, R. W., Kernan, M., & Wade, A. J. (2009). A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal*, 54(1), 101–123. https://doi.org/10.1623/hysj.54.1.101
3. Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Kabat, P., Jimenez, B., ... & Shiklomanov, I. A. (2007). Freshwater resources and their management. In *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Cambridge University Press.
4. Vörösmarty, C. J., Green, P., Salisbury, J., & Lammers, R. B. (2000). Global water resources: Vulnerability from climate change and population growth. *Science*, 289(5477), 284–288. https://doi.org/10.1126/science.289.5477.284
5. Milliman, J. D., & Farnsworth, K. L. (2011). *River discharge to the coastal ocean: A global synthesis*. Cambridge University Press.
6. Jiménez-Cisneros, B. E., Oki, T., Arnell, N. W., Benito, G., Cogley, J. G., Döll, P., ... & Mwakalila, S. S. (2014). Freshwater resources. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. IPCC Working Group II.

7. Rabalais, N. N., Turner, R. E., & Wiseman Jr., W. J. (2002). Gulf of Mexico hypoxia, aka "The dead zone". *Annual Review of Ecology and Systematics*, 33(1), 235–263. https://doi.org/10.1146/annurev.ecolsys.33.010802.150513
8. Arnell, N. W. (2004). Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environmental Change*, 14(1), 31–52. https://doi.org/10.1016/j.gloenvcha.2003.10.006
9. Rockström, J., Falkenmark, M., Lannerstad, M., & Karlberg, L. (2012). The planetary water drama: Dual task of feeding humanity and curbing climate change. *Geophysical Research Letters*, 39(15). https://doi.org/10.1029/2012GL051688
10. Li, Y., Tang, C., Cai, Y., Zhang, Z., & Sun, J. (2019). Effects of land use and climate change on water quality in the upper Yangtze River Basin. *Environmental Science and Pollution Research*, 26(7), 6832–6842. https://doi.org/10.1007/s11356-019-04106-1
11. Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z. I., Knowler, D. J., Lévêque, C., ... & Sullivan, C. A. (2006). Freshwater biodiversity: Importance, threats, status and conservation challenges. *Biological Reviews*, 81(2), 163–182. https://doi.org/10.1017/S1464793105006950
12. Mishra, A., & Lilhare, R. (2016). Assessment of climate change impact on water quality using coupled hydrological–water quality model. *Environmental Monitoring and Assessment*, 188(2), 1–17. https://doi.org/10.1007/s10661-016-5100-0
13. UNESCO. (2019). *The United Nations World Water Development Report 2019: Leaving no one behind*. UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000367306
14. Giri, S., & Qiu, Z. (2016). Understanding the relationship of land uses and water quality in Twenty First Century: A review. *Journal of Environmental Management*, 173, 41–48. https://doi.org/10.1016/j.jenvman.2016.02.029
15. Kannel, P. R., Lee, S., Lee, Y. S., Kanel, S. R., & Khan, S. P. (2007). Application of water quality indices and dissolved oxygen as indicators for river water classification and urban impact assessment. *Environmental Monitoring and Assessment*, 132(1), 93–110. https://doi.org/10.1007/s10661-006-9505-1
16. Schnoor, J. L. (2014). Water quality in a changing world. *Environmental Science & Technology*, 48(2), 884–890. https://doi.org/10.1021/es405056e
17. United Nations Environment Programme (UNEP). (2016). *A snapshot of the world's water quality: Towards a global assessment*. UNEP. https://www.unep.org/resources/report/snapshot-worlds-water-quality
18. Pahl-Wostl, C. (2007). The implications of complexity for integrated resources management. *Environmental Modelling & Software*, 22(5), 561–569. https://doi.org/10.1016/j.envsoft.2005.12.024
19. Hoekstra, A. Y., & Mekonnen, M. M. (2012). The water footprint of humanity. *Proceedings of the National Academy of Sciences*, 109(9), 3232–3237. https://doi.org/10.1073/pnas.1109936109
20. Vorosmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., ... & Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature*, 467(7315), 555–561. https://doi.org/10.1038/nature09440