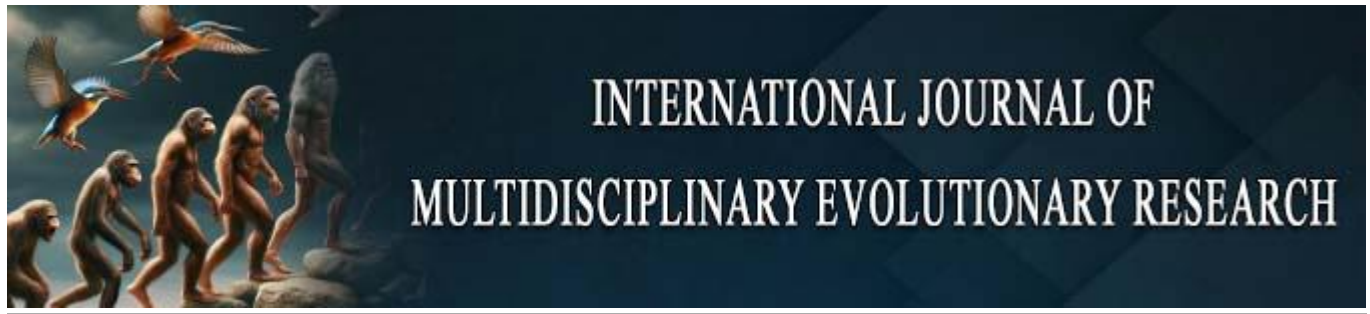




Spatial and Seasonal Variations in Water Quality Parameters in Anthropogenically Impacted River Systems

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Abstract

Rivers are dynamic systems whose water quality varies significantly across space and time, shaped by the interplay of natural processes and anthropogenic pressures. Spatial variation arises from differences in land use, hydrology, geology, and pollutant source distribution along a river continuum, while seasonal variation is driven by climatic patterns, hydrological cycles, and temporally variable human activities. Understanding these variations is essential for safeguarding ecosystem health, ensuring water security, and guiding effective management interventions. This review synthesizes global evidence on spatial and seasonal patterns in anthropogenically impacted rivers, exploring the mechanisms driving variability, the influence of human activities, and the water quality parameters most affected. It also evaluates methodological approaches for assessing these patterns, including statistical analyses, modelling frameworks, and monitoring strategies, while highlighting their implications for adaptive management and policy development. The study emphasizes that addressing spatial and seasonal water quality challenges requires integrated strategies that combine landscape management, environmental flow regulation, real-time monitoring, and stakeholder engagement, underpinned by robust scientific evidence. Future research priorities include the development of high-resolution, multi-parameter datasets, predictive modelling under climate and land use change scenarios, and comparative cross-basin analyses to inform context-specific solutions. By linking science, policy, and practice, river management can be made more adaptive, targeted, and resilient, ensuring the protection of aquatic ecosystems and sustainable use of water resources.

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1. Introduction

1.1. Background and Importance of Water Quality Monitoring

Water quality monitoring is a cornerstone of sustainable water resource management, providing essential data to evaluate the ecological status, detect pollution sources, and assess compliance with regulatory frameworks. In riverine systems, this process is especially critical due to the dynamic interplay between natural hydrological processes and anthropogenic activities. Effective monitoring serves multiple functions: safeguarding public health, maintaining aquatic biodiversity, and enabling informed decision-making for water governance. Early works highlighted that beyond conventional chemical testing, biological monitoring—using organisms such as aquatic invertebrates—can offer integrative insights into the long-term impacts of water quality fluctuations (Resh & Unzicker, 1975).

Modern approaches to river water quality monitoring integrate advanced statistical and computational tools to optimize the placement of monitoring stations and the selection of parameters. Principal Component Analysis (PCA) and other multivariate techniques have proven effective in identifying key monitoring locations that capture the greatest variability in water quality metrics, thereby increasing efficiency without compromising representativeness (Ouyang, 2005). This analytical rigor is essential for large river basins where spatial heterogeneity in water chemistry is substantial.

The importance of robust, continuous monitoring has become more pronounced in the context of climate variability, land use change, and intensifying anthropogenic pressures. For example, river discharge monitoring, often integrated with water quality assessments, provides critical data for understanding hydrological extremes such as floods and droughts, both of which significantly influence pollutant transport and concentration (Depetris, 2021). Without long-term datasets, it becomes challenging to discern anthropogenic impacts from natural variability, undermining the development of adaptive management strategies.

A key consideration in water quality monitoring is network design. Efficient monitoring networks must balance spatial coverage with operational costs. Optimal network design models—often incorporating hydrodynamic modeling and stochastic simulations—ensure that the collected data are spatially and temporally representative of the river system as a whole (Telci *et al.*, 2009). These designs are particularly important for rivers impacted by diverse pollution sources, including agricultural runoff, industrial effluents, and urban wastewater discharges.

Recent advancements emphasize the integration of real-time monitoring systems to provide near-instantaneous detection of pollution events, thus enabling rapid mitigation responses. For instance, real-time sensing platforms equipped with continuous monitoring probes can identify pollution pathways and quantify contaminant loads in small- and medium-scale rivers (Meyer *et al.*, 2019). Such technological innovations not only enhance the temporal resolution of monitoring efforts but also support adaptive management by allowing for prompt interventions.

Ultimately, the significance of water quality monitoring extends beyond scientific research to policy-making and societal well-being. Long-term and spatially extensive monitoring programs underpin the formulation of environmental standards, inform transboundary water agreements, and guide investments in pollution control infrastructure. Without such systems, the risk of undetected degradation is high, potentially leading to irreversible ecological damage and socio-economic losses. As river systems continue to face increasing stress from both human and natural drivers, the value of accurate, continuous, and spatially representative monitoring will only intensify.

1.2. Concept of Spatial and Seasonal Variability in River Water Quality

Spatial and seasonal variability in river water quality reflects the interplay between natural processes and anthropogenic influences that affect chemical, physical, and biological parameters over space and time. Spatial variation occurs due to differences in watershed characteristics, land use patterns, hydrological connectivity, and pollutant source distribution along the river continuum. For example, upstream segments

in relatively undisturbed catchments may exhibit low nutrient and sediment loads, whereas downstream sections—often subject to urban and agricultural runoff—tend to display higher pollutant concentrations (Pejman *et al.*, 2009).

Seasonal variability is largely driven by hydrological cycles, climatic patterns, and seasonal human activities. In monsoon-dominated regions, increased precipitation leads to high river discharge and dilution of certain pollutants, but also heightened transport of sediments, nutrients, and contaminants from surrounding landscapes. Conversely, during dry seasons, reduced flows can lead to the concentration of pollutants, exacerbating water quality issues (Xu *et al.*, 2019). Seasonal cycles may also influence biological processes, such as algal blooms, which in turn alter dissolved oxygen and nutrient dynamics.

Multivariate statistical techniques, including Principal Component Analysis (PCA), Cluster Analysis (CA), and Discriminant Analysis (DA), have proven valuable in disentangling spatial from seasonal patterns. Such methods allow researchers to identify dominant pollution sources and key parameters that vary most significantly with location or season. For instance, in the Dan River Basin, PCA revealed that nutrient pollution dominated in the wet season due to agricultural runoff, whereas point-source pollution from industry was more prevalent during dry periods (Xu *et al.*, 2019).

The nature of spatial and seasonal variability also depends on the interaction between natural drivers and anthropogenic pressures. In Central Asia's Amu Darya River, seasonal snowmelt and glacial contributions altered river chemistry, but these patterns were superimposed on a background of intensive irrigation withdrawals and agrochemical use, resulting in complex spatiotemporal dynamics (Crosa *et al.*, 2006). Similarly, modelling studies on European river networks have demonstrated that seasonal variation is not uniform across space—reaches impacted by urban wastewater often show less seasonal fluctuation compared to agriculturally dominated catchments, where runoff patterns vary considerably with rainfall and cropping cycles (Álvarez-Cabria *et al.*, 2016).

Case studies from tropical and subtropical systems highlight how land use types influence both spatial and seasonal dynamics. In Northeast Brazil, spatial variability was strongly correlated with riparian vegetation cover and proximity to agricultural fields, while seasonal differences aligned with wet and dry cycles affecting sediment and nutrient transport (Cruz *et al.*, 2019). These findings underline the need for monitoring programs that explicitly account for both spatial gradients and seasonal shifts, as neglecting one dimension can lead to incomplete or misleading assessments of river health.

1.3. Anthropogenic Pressures on River Systems

Anthropogenic pressures on river systems encompass a wide range of human activities that alter hydrology, sediment dynamics, water chemistry, and ecological integrity. At the global scale, these pressures have intensified dramatically over the past century, coinciding with rapid industrialization, urban expansion, and agricultural intensification. The concept of “Anthropocene syndromes” in river systems encapsulates the cumulative effects of altered nutrient cycles, pollutant loading, hydromorphological modifications, and biodiversity loss, representing a departure from natural Earth system controls (Meybeck, 2003).

Multiple studies have demonstrated that anthropogenic impacts manifest at both catchment and reach scales. For example, large-scale assessments indicate that over half of the world's river reaches are subjected to significant human pressures, including damming, channelization, urban wastewater discharge, and diffuse agricultural pollution (Ceola *et al.*, 2019). In many of the world's largest rivers, such as the Yangtze, Mekong, and Mississippi, sediment loads have been dramatically altered—either reduced by dam trapping or increased through deforestation and land degradation—affecting floodplain connectivity and delta stability (Best, 2019).

At regional levels, case studies have shown that anthropogenic pressures can rapidly alter hydrological regimes and ecological communities. In South and Southeast Asia, for instance, reach-scale analyses revealed substantial increases in human pressures between 1990 and 2014, driven by urban expansion, irrigation development, and intensified agricultural practices (Liu *et al.*, 2020). These pressures often interact with climatic extremes, exacerbating water quality degradation during low-flow conditions.

The ecological consequences of these pressures are evident in shifts in fish and macroinvertebrate assemblages, which respond to a combination of catchment-scale land use, riparian corridor modification, and in-stream habitat alteration (Marzin *et al.*, 2013). Nutrient enrichment from agriculture can lead to eutrophication, while industrial effluents introduce heavy metals and organic contaminants, disrupting aquatic food webs. Meanwhile, hydrological modifications such as damming can fragment habitats, alter sediment transport, and change thermal regimes, further stressing aquatic species.

Long-term projections for river systems, such as those conducted for the Seine in France, illustrate that anthropogenic changes can often outweigh climatic influences in shaping future hydrology and water quality (Ducharme *et al.*, 2007). This underscores the need to address direct human activities as a priority in river basin management.

Overall, anthropogenic pressures are neither uniformly distributed nor temporally constant—they vary with socio-economic development trajectories, governance capacity, and geographic context. Effective mitigation therefore requires spatially targeted and temporally adaptive strategies that consider the full spectrum of human-induced stressors.

1.4. Water Quality Parameters of Interest

In anthropogenically impacted river systems, water quality is typically assessed through a combination of physico-chemical, biological, and sometimes microbiological parameters, each serving as indicators of ecological health and human influence. Among physico-chemical parameters, nutrients—particularly nitrogen and phosphorus species—are of primary concern due to their role in eutrophication. Elevated concentrations of nitrates and phosphates often stem from agricultural runoff, urban wastewater, and industrial effluents (Álvarez-Cabria *et al.*, 2016). In many watersheds, nutrient pollution is closely tied to land use patterns, with cropland and livestock density acting as major predictors of water chemistry (Wang *et al.*, 2007).

Other key parameters include dissolved oxygen (DO), which reflects the balance between oxygen-producing processes (e.g., photosynthesis) and oxygen-consuming processes (e.g., microbial decomposition of organic matter). Low DO levels

can indicate organic pollution from sewage or agricultural waste, leading to hypoxic conditions detrimental to aquatic life (Ji *et al.*, 2021). Closely related is biochemical oxygen demand (BOD), a measure of the organic load present in the water. High BOD values signal elevated microbial activity, typically from untreated effluents or decaying organic material.

Suspended solids and turbidity are also critical indicators, influencing light penetration, primary productivity, and habitat quality. Increased turbidity often results from soil erosion, construction activities, or unregulated stormwater discharge. Heavy metals (e.g., lead, cadmium, mercury) and other toxic contaminants, frequently originating from industrial discharges, can accumulate in sediments and biota, posing long-term ecological and human health risks (Azrina *et al.*, 2006).

Temperature and conductivity provide further insight into river system health. Temperature influences chemical solubility, biological processes, and species distribution, while conductivity reflects the total concentration of dissolved ions, often elevated due to mining, road salts, or agricultural runoff (Mainali & Chang, 2018). Biological indicators, such as benthic macroinvertebrate diversity, offer integrative measures of water quality, as these organisms respond to long-term and cumulative stressors. Alterations in species richness or dominance patterns often reveal chronic pollution levels that may not be captured in instantaneous chemical measurements (Calderon *et al.*, 2023).

In certain contexts, microbiological indicators such as *Escherichia coli* or total coliform counts are essential, particularly in rivers serving as drinking water sources or recreational areas. Elevated bacterial counts often trace back to sewage contamination and poorly managed sanitation infrastructure (Hoang *et al.*, 2018). Collectively, these parameters provide a comprehensive profile of river health, enabling the identification of dominant pollution sources and the assessment of compliance with water quality standards. The selection of specific parameters in a monitoring program should be tailored to the river's catchment characteristics, dominant anthropogenic pressures, and intended management objectives.

1.5. Mechanisms Influencing Spatial Variation

Spatial variation in river water quality arises from a combination of natural environmental gradients and localized anthropogenic influences. At the catchment scale, landscape characteristics—such as topography, geology, soil type, and land cover—play a foundational role in determining baseline water chemistry. For example, geological substrates influence the mineral composition and conductivity of river water, while soil permeability affects nutrient and sediment transport (Hamid *et al.*, 2020). These natural controls often interact with human land use, producing spatially heterogeneous water quality patterns across a river network (Lintern *et al.*, 2018).

Hydrological factors are also central to spatial variation. River segments closer to pollutant sources—such as wastewater outfalls or agricultural drainage points—tend to have elevated nutrient and organic loads, while dilution effects downstream may attenuate concentrations. Flow velocity, discharge volume, and connectivity with floodplains influence the residence time of pollutants and their assimilation or deposition in sediments (Zhao *et al.*, 2020). Moreover, the presence of dams or weirs can create

discontinuities in water quality by altering flow regimes, sediment transport, and thermal conditions.

At multiple spatial scales, environmental factors—including vegetation cover, land management practices, and proximity to urban areas—can strongly shape water quality. In the Huai River Basin, multiscale analysis revealed that forest cover was associated with reduced nutrient concentrations, while intensive agricultural areas exhibited higher nitrogen and phosphorus levels (Xia *et al.*, 2018). Riparian buffers, wetland areas, and meander complexity often serve as natural filters, improving water quality in certain reaches, whereas deforested or channelized sections typically show degraded conditions.

Localized factors can sometimes override broader watershed patterns. Point-source discharges, such as those from industrial plants, can create highly localized pollution hotspots that may persist for kilometers downstream. In coastal and estuarine-adjacent rivers, tidal influences and saline intrusion can further modify spatial water quality patterns, interacting with upstream pollution inputs (Huang *et al.*, 2014). Additionally, environmental flow releases from reservoirs can significantly alter spatial gradients in water quality, particularly in systems where flow regulation has disrupted natural hydrological variability (Zhou *et al.*, 2020). The cumulative effect of these mechanisms results in complex spatial mosaics of water quality, where both gradual gradients and sharp transitions can be observed. Understanding these patterns requires integrative approaches that combine hydrological modelling, geospatial analysis, and field-based water quality monitoring. Such approaches can identify critical source areas, guide targeted mitigation measures, and improve the design of monitoring networks.

1.6. Mechanisms Influencing Seasonal Variation

Seasonal variation in river water quality is driven by a combination of hydrological cycles, climatic patterns, and seasonal anthropogenic activities. In many temperate and tropical river systems, precipitation regimes play a pivotal role. During wet seasons, high rainfall leads to increased surface runoff, which can dilute some pollutants but also mobilize sediments, nutrients, and contaminants from agricultural fields, urban surfaces, and eroded landscapes. In contrast, dry seasons are often characterized by reduced flow volumes, which can concentrate pollutants and exacerbate issues such as eutrophication and oxygen depletion (Xu *et al.*, 2019).

Temperature fluctuations also contribute significantly to seasonal dynamics. Warmer summer conditions can accelerate biochemical processes, enhance algal growth, and reduce dissolved oxygen solubility. In colder months, reduced biological activity and lower runoff may result in decreased nutrient cycling but can also lead to accumulation of pollutants in sediments (Lenart-Boroń *et al.*, 2018). Seasonal differences in sunlight availability and thermal stratification influence photosynthetic activity and organic matter decomposition, further affecting water chemistry.

Human activities exhibit distinct seasonal patterns that influence river water quality. Agricultural practices such as fertilizer application, irrigation, and harvesting often follow seasonal calendars, leading to spikes in nutrient concentrations during specific months. Similarly, industrial effluent discharge and urban stormwater runoff may vary with seasonal demand and rainfall intensity. In tropical systems, these influences can be particularly pronounced,

with wet-season flows carrying substantial pollutant loads from urban and peri-urban catchments (Ibrahim *et al.*, 2021). Natural and anthropogenic drivers often interact in complex ways. For instance, in coastal watersheds, baseflow water quality during dry seasons may be more influenced by groundwater contributions, which can carry legacy pollutants, whereas storm events in the wet season dominate pollutant loading from surface sources (Huang *et al.*, 2014). Landscape characteristics, such as forest cover and riparian vegetation, can modulate these effects by reducing runoff and filtering pollutants, although their efficacy can vary seasonally depending on vegetation growth stages and hydrological connectivity (Álvarez-Cabria *et al.*, 2016).

In some rivers, seasonal variation is also influenced by snowmelt and ice cover dynamics, which affect flow patterns, sediment transport, and nutrient release. For example, in colder climates, spring snowmelt can cause sharp increases in suspended solids and nutrient loads, while summer low flows may concentrate contaminants. The interplay between these mechanisms highlights the importance of considering seasonal hydrological processes in water quality monitoring and management. Robust seasonal datasets are crucial for understanding these patterns and designing interventions that address critical pollution periods throughout the year (Gudas & Povilaitis, 2013).

1.7. Purpose of This Review

This review focuses on synthesizing current knowledge on spatial and seasonal variations in water quality parameters within anthropogenically impacted river systems. The scope encompasses both natural and human-induced drivers of variability, covering a wide geographical spectrum from temperate to tropical regions and from headwaters to estuarine reaches. The intent is to bridge disciplinary perspectives, integrating hydrology, geomorphology, ecology, and environmental management to provide a holistic understanding of how water quality changes over space and time in response to interacting pressures.

The review places particular emphasis on rivers that experience substantial anthropogenic stress, such as agricultural intensification, urbanization, industrial discharge, and hydrological regulation. By exploring both spatial and seasonal variability, it aims to capture the multifaceted nature of river water quality dynamics, recognizing that pollutants and ecological responses are rarely uniform in either time or space. Furthermore, the discussion integrates methodological advances—such as multivariate statistical tools, geospatial modelling, and real-time monitoring—that have improved the capacity to detect, interpret, and predict these patterns.

The objectives of this review are threefold. First, to compile and critically assess global evidence on the mechanisms driving spatial and seasonal variations in river water quality, identifying commonalities and context-specific differences. Second, to evaluate how anthropogenic activities modulate these patterns, including their interactions with natural hydrological and climatic processes. Third, to translate scientific findings into actionable recommendations for monitoring design, management interventions, and policy integration, with a view to sustaining ecological integrity and water security under future environmental change.

By establishing a coherent framework that links environmental processes, human pressures, and management strategies, this review seeks to support more targeted and

adaptive approaches to river basin management, ensuring that spatially and seasonally sensitive water quality issues are effectively addressed.

2. Discussion

2.1. Global Evidence on Spatial Variation in Anthropogenically Impacted Rivers

Spatial variation in river water quality is a globally observed phenomenon, arising from the interplay between natural watershed characteristics and anthropogenic activities. In many regions, human influences have intensified spatial heterogeneity by introducing new pollutant sources, altering hydrological regimes, and transforming land cover. This variation is rarely uniform along a river's length; instead, different reaches often exhibit distinct water quality profiles shaped by the distribution of population centers, industrial facilities, agricultural zones, and natural buffers. Understanding these spatial patterns is essential for designing effective monitoring strategies and targeted management interventions.

One recurring finding across global studies is that urbanization creates strong downstream water quality gradients. Urbanized reaches typically show elevated concentrations of nutrients, heavy metals, organic pollutants, and microbial contaminants compared to upstream segments with lower population density. For example, in a coastal watershed of Southeast China, Huang *et al.* (2014) observed that headwater streams in forested areas maintained relatively low nutrient levels, whereas downstream segments draining industrial and urban zones had significantly higher pollutant loads. This demonstrates the spatial imprint of point-source discharges, stormwater runoff, and reduced riparian cover on river chemistry (Huang *et al.*, 2014).

Agricultural land use is another major driver of spatial variability, with nutrient runoff and sediment transport often dominating pollution profiles in rural and peri-urban catchments. Studies across large river networks, such as those analyzed by Álvarez-Cabria *et al.* (2016), have shown that spatial distribution of nitrate and phosphate concentrations reflects both diffuse agricultural inputs and site-specific hydrological conditions. Their modelling indicated that natural factors like geology and precipitation interact with land management practices to shape nutrient hotspots. These findings underscore that spatial variation cannot be attributed solely to human land use; rather, it emerges from the coupling of human pressures with environmental context (Álvarez-Cabria *et al.*, 2016).

In some basins, the influence of natural factors can rival or even exceed anthropogenic impacts, especially in sparsely populated areas. Mainali and Chang (2018) found in a South Korean River basin that 20–70% of the spatial variability in water quality trends could be explained by landscape features such as slope, elevation, and hydrological connectivity. These characteristics influenced both the movement of water and the transport of pollutants, revealing that physical geography shapes baseline water quality conditions against which human impacts are superimposed (Mainali & Chang, 2018).

However, the effects of land cover are not universally beneficial. In urbanized Beijing watersheds, Liu *et al.* (2018) reported that forest cover could improve water quality for some indicators, such as turbidity, but have negligible or even adverse effects on others, depending on its spatial location relative to pollutant sources. This complexity arises because

riparian vegetation can intercept runoff and filter pollutants, but when positioned downstream of major pollution sources, its mitigating effect may be limited (Liu *et al.*, 2018).

Hydroclimatic conditions also exert a significant influence on spatial water quality patterns. Across the Australian continent, Liu *et al.* (2022) demonstrated that catchment topography and hydrological connectivity play major roles in controlling solute export patterns. In some cases, these natural factors had equal or greater influence than anthropogenic activities, particularly in areas with low population density. The findings highlight that spatial variation is context-dependent and that natural and human drivers often operate in combination rather than isolation (Liu *et al.*, 2022).

In large transboundary river basins, such as those studied by Diamantini *et al.* (2018) in Europe, spatial variation often arises from differences in land use intensity, pollution control measures, and socio-economic development between sub-catchments. For example, areas with advanced wastewater treatment facilities displayed markedly lower nutrient and organic pollutant levels compared to regions with inadequate sanitation infrastructure. These differences result in distinct water quality regimes within the same basin, illustrating that governance and management capacity are critical spatial determinants (Diamantini *et al.*, 2018).

Globally, the spatial variability in anthropogenically impacted rivers manifests not only in pollutant concentrations but also in pollutant types and dominant sources. In industrialized regions, localized clusters of manufacturing facilities often contribute heavy metals and persistent organic pollutants to specific reaches. In agricultural landscapes, nutrient pollution and sedimentation dominate. In urban contexts, complex mixtures of contaminants, including hydrocarbons, microplastics, and pathogens, are common. These distinct source profiles mean that spatially targeted interventions are essential; a nutrient reduction strategy suitable for an agricultural catchment may not address the heavy metal contamination in an industrial corridor.

Overall, the global evidence shows that spatial variation in water quality is shaped by a mosaic of natural and anthropogenic factors whose influence varies across scales. Recognizing these patterns is crucial for designing monitoring networks that capture representative conditions and for implementing management measures that are spatially tailored to address dominant stressors in different parts of a river system. Failure to account for these spatial nuances can lead to ineffective or inefficient water quality interventions, ultimately compromising both ecological health and water resource sustainability.

2.2. Seasonal Variation in Water Quality Parameters

Seasonal variation in river water quality parameters is a well-documented phenomenon observed across a wide range of climatic regions and hydrological settings. These changes are driven by seasonal fluctuations in precipitation, temperature, flow regimes, and biological activity, as well as the timing and intensity of human activities. In many river systems, wet and dry seasons create distinct water quality profiles, with parameters such as nutrient concentrations, suspended solids, dissolved oxygen, and microbial indicators showing significant temporal shifts. Understanding these patterns is crucial for accurately assessing ecological health, identifying pollution sources, and developing seasonally adaptive management strategies.

Hydrological changes are among the most influential drivers of seasonal variability. In monsoon and tropical regions, wet-season flows can dilute some pollutants while simultaneously mobilizing large quantities of sediments, nutrients, and organic matter from surrounding landscapes. For example, in the Dan River Basin, Xu *et al.* (2019) found that wet-season conditions were associated with higher concentrations of suspended solids and nutrients due to increased runoff from agricultural lands, while dry-season flows often concentrated pollutants because of reduced dilution capacity (Xu *et al.*, 2019). Similar patterns have been documented in the Yamuna River, India, where seasonal monsoons bring elevated loads of organic and inorganic pollutants, particularly from urban and industrial areas, contrasting with the pollutant concentration effects of low-flow dry seasons (Hassan *et al.*, 2017).

Temperature variation across seasons influences chemical solubility, biological processes, and microbial activity in rivers. Warmer conditions during summer months can accelerate algal blooms and microbial decomposition, leading to reduced dissolved oxygen levels and potentially hypoxic conditions. In contrast, colder winter temperatures often slow biochemical processes, sometimes improving oxygen availability but also reducing the breakdown of organic pollutants. In a study of the Turag River in Bangladesh, Rahman *et al.* (2012) reported that dissolved oxygen levels peaked in cooler months and dropped significantly during warmer seasons, coinciding with algal bloom occurrences and higher biological oxygen demand (Rahman *et al.*, 2012).

Microbiological parameters also display marked seasonal fluctuations, often linked to hydrological and temperature changes. High rainfall events can increase bacterial loads through stormwater and sewage overflow, particularly in regions with limited wastewater treatment infrastructure. In Nigeria's River Mkomon, Ioryue *et al.* (2018) observed that coliform counts were significantly higher during the wet season due to increased surface runoff from settlements and agricultural fields (Ioryue *et al.*, 2018).

The seasonal timing of human activities also plays a substantial role in influencing water quality patterns. Agricultural fertilization, pesticide application, and irrigation schedules often follow seasonal cycles, resulting in nutrient spikes during planting and harvesting periods. Industrial production cycles and hydropower operations may also vary seasonally, affecting pollutant discharge timing and volumes. In Northeast Brazil, Cruz *et al.* (2019) found that the wet season coincided with increased nutrient loads from agricultural runoff, whereas the dry season reflected higher concentrations of pollutants from point sources, such as untreated municipal wastewater (Cruz *et al.*, 2019).

Statistical approaches have been instrumental in disentangling the drivers of seasonal variability in river water quality. Techniques such as principal component analysis (PCA) and cluster analysis have been used to identify parameters most sensitive to seasonal shifts and to classify river segments according to their seasonal pollution profiles. For instance, Pejman *et al.* (2009) applied multivariate statistical methods to the Haraz River Basin and demonstrated that seasonal variability was largely controlled by hydrological conditions and the seasonal intensity of agricultural and urban activities (Pejman *et al.*, 2009).

Overall, global evidence underscores that seasonal variation is a product of both natural cycles and human-driven changes,

with their relative influence depending on climate zone, watershed characteristics, and land use patterns. Recognizing these temporal dynamics is vital for effective river management, as interventions that do not account for seasonal peaks in pollutant loads may fail to achieve intended water quality improvements.

2.3. Interactions Between Spatial and Seasonal Variability

The interaction between spatial and seasonal variability in river water quality is a complex phenomenon that emerges from the combined influence of hydrological, climatic, geomorphological, and anthropogenic factors. While spatial variation reflects differences between locations along a river network, seasonal variation captures changes over time. These two dimensions are not independent; rather, they interact in ways that can amplify or attenuate water quality fluctuations depending on local conditions and the timing of pollutant inputs. Understanding this interplay is crucial for developing management strategies that are both location-specific and seasonally adaptive.

In many systems, spatial gradients in water quality are seasonally dynamic, meaning that the magnitude and even direction of differences between upstream and downstream segments can vary throughout the year. For example, in the Dan River Basin, Xu *et al.* (2019) observed that during wet seasons, downstream reaches experienced larger nutrient spikes than upstream sections due to intensified agricultural runoff, whereas in dry seasons, upstream segments closer to point-source discharges showed relatively higher pollutant concentrations because of diminished dilution capacity (Xu *et al.*, 2019). This demonstrates that the spatial footprint of pollution sources is mediated by seasonal hydrology.

Research on entire river networks has also shown that certain reaches are more sensitive to seasonal forcing than others. Álvarez-Cabria *et al.* (2016) used spatial modelling to assess nitrate, phosphate, and temperature variability across river systems and found that reaches dominated by diffuse agricultural inputs displayed stronger seasonal swings, while reaches receiving continuous point-source inputs showed relatively stable but chronically elevated pollution levels (Álvarez-Cabria *et al.*, 2016). This suggests that the type and location of pollution sources determine how seasonal processes manifest spatially.

Anthropogenic activities often exacerbate the interaction between spatial and seasonal variation. In Northeast Brazil, Cruz *et al.* (2019) documented that electrical conductivity and total dissolved solids increased progressively downstream in the dry season as evaporation concentrated dissolved ions, whereas during the wet season, the same downstream gradient was dominated by sediment and nutrient inputs mobilized from upstream agricultural lands (Cruz *et al.*, 2019). Such findings highlight that the spatial sequencing of pollution processes can change with the seasons, altering water quality hotspots.

Interactions are also shaped by land use patterns, which can modulate seasonal responses differently across spatial zones. In a coastal watershed of Southeast China, Huang *et al.* (2014) found that forested upstream areas buffered seasonal nutrient fluctuations, while midstream agricultural areas exhibited high seasonal variability in both nitrate and turbidity. Downstream urbanized zones, by contrast, showed less pronounced seasonal variability because of the dominance of continuous wastewater inputs, even during periods of high rainfall (Huang *et al.*, 2014). This illustrates

that spatial variation in land cover determines the degree to which seasonal hydrological cycles affect water quality.

Temporal shifts in pollutant transport pathways also interact with spatial variation. In tropical rivers, Ibrahim *et al.* (2021) reported that the wet season's high flows redistributed pollutants from localized urban discharges to more distant downstream reaches, effectively altering the spatial distribution of degraded water quality compared to the dry season (Ibrahim *et al.*, 2021). Such seasonal redistribution can complicate source attribution if monitoring programs do not capture these temporal dynamics across multiple locations.

Regulated river systems introduce another layer of complexity, as dam and reservoir operations can shift the seasonal expression of spatial patterns. In the Huai River Basin, Wang *et al.* (2023) showed that land use–water quality relationships varied not only between wet and dry seasons but also according to reservoir release schedules, which altered downstream flow regimes and pollutant dispersion patterns (Wang *et al.*, 2023). This underscores the need to account for both anthropogenic hydrological regulation and natural seasonal cycles when analyzing spatial-temporal interactions. These interactions are not purely additive; they can produce emergent effects where the combination of spatial and seasonal processes leads to patterns not predictable from either dimension alone. For instance, the Amu Darya River study by Crosa *et al.* (2006) revealed that the seasonal melting of snow and glaciers modified longitudinal salinity gradients, such that midstream sections experienced temporary improvements in water quality during the melt period, despite chronic upstream pollution (Crosa *et al.*, 2006).

Spatial and seasonal variability in river water quality are deeply interconnected, with their interaction mediated by pollution source types, land use configuration, hydrological regimes, and human interventions. Effective monitoring and management require integrated frameworks that capture these spatio-temporal linkages, ensuring that control measures are targeted to the right places at the right times. Without such integration, interventions risk being spatially misplaced or temporally mistimed, reducing their effectiveness and potentially allowing degradation to persist unnoticed.

2.4. Methodological Approaches to Studying Spatial and Seasonal Variation

The study of spatial and seasonal variation in river water quality requires robust, systematic, and often multidisciplinary methodologies capable of capturing both the complexity and variability of hydrological and ecological processes. These approaches must be carefully designed to ensure that monitoring programs detect not only localized pollution hotspots but also the temporal dynamics that influence pollutant transport and transformation. Methodological strategies have evolved significantly over the past two decades, integrating advances in statistical analysis, modelling, remote sensing, and high-frequency monitoring technologies.

A foundational step in such studies is the design of a representative monitoring network. This involves determining the number and location of sampling stations, as well as selecting the parameters and frequency of measurements. Nguyen *et al.* (2019) emphasized that network design should account for spatial heterogeneity,

pollutant source distribution, and hydrological regimes, recommending that sampling frequencies range from monthly for baseline surveillance to event-based for capturing episodic pollution spikes (Nguyen *et al.*, 2019). The strategic placement of stations along longitudinal gradients—from headwaters to estuaries—ensures that both spatial patterns and temporal dynamics are adequately represented.

Statistical analysis plays a central role in interpreting spatial and seasonal variation. Multivariate statistical techniques such as Principal Component Analysis (PCA), Cluster Analysis (CA), and Discriminant Analysis (DA) are commonly employed to identify key pollution parameters, group sampling sites with similar characteristics, and detect temporal shifts in water quality patterns. For example, Pejman *et al.* (2009) used PCA and CA to analyze Haraz River Basin data, revealing clear seasonal clustering of water quality variables that aligned with wet and dry hydrological periods (Pejman *et al.*, 2009). Similarly, Singh *et al.* (2004) applied multivariate methods to the Gomti River in India, enabling the separation of spatial influences from temporal variation and identification of parameters most responsive to seasonal changes (Singh *et al.*, 2004).

Beyond traditional statistical tools, methodological frameworks such as Dynamic Factor Analysis (DFA) provide advanced capabilities for detecting and characterizing spatiotemporal variability. Aguilera *et al.* (2018) proposed DFA for integrating large datasets with complex temporal and spatial dependencies, allowing researchers to extract underlying trends and link them to environmental drivers (Aguilera *et al.*, 2018). This approach is particularly useful when aiming to disentangle natural variability from anthropogenic signals.

An important methodological consideration is the temporal resolution of data collection. Traditional grab sampling, while widely used, may miss critical short-term events such as storm-driven pollutant pulses. Cassidy and Jordan (2011) demonstrated that near-continuous time-series data for phosphorus provided a far more accurate representation of pollutant dynamics than instantaneous sampling, especially in surface-water dominated catchments (Cassidy & Jordan, 2011). Advances in in-situ sensors and telemetry now enable high-frequency monitoring, offering real-time detection of seasonal and spatial shifts in key parameters such as turbidity, dissolved oxygen, and conductivity.

Geospatial and remote sensing techniques also contribute significantly to spatial-seasonal studies. Satellite-derived data on land use, vegetation cover, and surface temperature can be integrated with water quality measurements to assess how catchment characteristics influence seasonal water quality patterns. Land use change detection, combined with hydrological modelling, allows for scenario-based predictions of how spatial patterns might evolve under different climate or management regimes. Shi *et al.* (2017) illustrated the utility of multi-scale land use analysis in understanding seasonal water quality variation, showing that agricultural intensity had a seasonally dependent influence on nutrient concentrations (Shi *et al.*, 2017).

When monitoring resources are limited, rationalizing sampling locations without compromising data quality becomes a key methodological challenge. Varekar *et al.* (2016) compared the modified Sanders approach with multivariate statistical optimisation for seasonal sampling location selection, concluding that data-driven optimisation

improved both cost efficiency and representativeness (Varekar *et al.*, 2016). Such optimisation approaches are vital for large-scale monitoring where budget and logistical constraints limit station density.

In conclusion, methodological approaches to studying spatial and seasonal variation in river water quality are increasingly integrative, combining statistical analysis, high-frequency monitoring, geospatial tools, and network design optimisation. A well-structured methodology must be sensitive to the interplay between spatial heterogeneity and temporal dynamics, capable of capturing both long-term trends and short-term events. This ensures that findings are robust, management recommendations are evidence-based, and monitoring programs remain adaptive to emerging challenges.

3. Management and Policy Implications

Effective management of spatial and seasonal water quality challenges in rivers requires an integrated approach that recognizes the interconnected nature of hydrology, ecology, land use, and socio-economic activities. The dynamic variability of water quality across both space and time means that interventions must be adaptive, data-driven, and spatially targeted to address the dominant pollution sources and hydrological conditions of specific reaches. Traditional “one-size-fits-all” solutions are often inadequate in systems where upstream and downstream segments respond differently to seasonal cycles, or where pollutant sources vary in intensity across the year.

One of the key management implications is the need for catchment-wide coordination that integrates spatial and temporal variability into planning. Seasonal changes in flow regimes, such as wet-season flooding or dry-season low flows, can alter pollutant transport and transformation processes. In the Dan River Basin, Xu *et al.* (2019) found that seasonal peaks in nutrient and sediment concentrations often occurred in different parts of the basin, meaning that mitigation strategies needed to be location-specific and seasonally timed to be effective (Xu *et al.*, 2019). This requires not only hydrological monitoring but also flexible regulatory mechanisms that can respond to real-time water quality conditions.

The relationship between flow regime and water quality underscores the importance of managing water quantity alongside quality. Nilsson and Renöfält (2008) highlighted that maintaining ecological flow requirements can reduce pollutant concentrations by enhancing dilution, sediment flushing, and habitat health (Nilsson & Renöfält, 2008). Adaptive catchment management should therefore consider environmental flow allocations, especially in regulated river basins where dam releases can be scheduled to coincide with periods of high pollutant loads, thereby improving downstream water quality.

Landscape pattern management also plays a critical role in addressing spatial-seasonal variability. Studies such as Wang *et al.* (2023) in the Huai River Basin show that land use directly influences both the spatial distribution and seasonal fluctuations of water quality, with agricultural areas contributing more diffuse nutrient loads during wet seasons and urban areas generating continuous point-source pollution (Wang *et al.*, 2023). Policy measures that promote riparian buffer zones, wetland restoration, and sustainable agricultural practices can significantly reduce pollutant inputs, while land use zoning and development controls can help mitigate the

impacts of urban expansion.

From a governance perspective, integrating water quality objectives into broader land and water resource management plans is essential. This includes cross-sectoral coordination between environmental agencies, agricultural departments, urban planners, and hydropower operators. For example, Horn *et al.* (2004) stressed that water quality models used for policy-making should incorporate mesoscale watershed processes, allowing for the simulation of both spatial and seasonal pollutant dynamics (Horn *et al.*, 2004). Such modelling can inform regulatory frameworks, enabling seasonally adjusted discharge permits, targeted agricultural runoff controls during planting seasons, and adaptive reservoir management.

Policy implementation should also be supported by continuous and high-resolution monitoring systems. Emerging real-time water quality monitoring technologies can detect seasonal spikes in pollutants and identify spatial hotspots with unprecedented accuracy. This information can be used to trigger rapid response measures, such as temporary restrictions on fertilizer application or emergency wastewater treatment interventions. However, deploying such systems requires investment in monitoring infrastructure, data management capacity, and training for local authorities.

Community involvement is another critical element. Seasonal water quality challenges often coincide with periods of heightened local water use—such as agricultural irrigation in dry seasons or fishing in wet seasons—making stakeholder engagement essential. Participatory water management, where local communities contribute to monitoring, decision-making, and enforcement, can improve compliance and enhance the cultural and social relevance of policies.

In the context of climate change, the need to address spatial and seasonal variability will become more urgent. Altered precipitation patterns, changing snowmelt dynamics, and increased frequency of extreme events are expected to intensify seasonal shifts in river water quality. Adaptive management strategies that are informed by predictive modelling and scenario analysis will be vital in maintaining ecological health and water security.

Addressing spatial and seasonal variability in river water quality requires:

1. **Adaptive, seasonally aware regulation** that aligns interventions with hydrological and pollutant cycles.
2. **Integrated flow and quality management** to optimize ecological and dilution benefits.
3. **Landscape-based interventions** to mitigate diffuse and point-source pollution.
4. **Advanced modelling and monitoring systems** for real-time detection and targeted action.
5. **Stakeholder engagement** to ensure compliance and socio-economic sustainability.

These approaches, when embedded in coherent policy frameworks, can significantly enhance the effectiveness of water quality management in diverse and dynamic river systems.

3.1. Strategies for Managing Spatial and Seasonal Water Quality Challenges

Effective strategies for managing spatial and seasonal water quality challenges in rivers must be grounded in an understanding of how hydrological variability, land use, and anthropogenic activities interact across different spatial and

temporal scales. Because pollutant sources and transport mechanisms change over time and space, management approaches must be adaptive, location-specific, and seasonally responsive, rather than relying on static, uniform interventions.

One fundamental strategy is landscape pattern optimization. Land use configuration has a direct impact on both spatial and seasonal water quality dynamics, and strategic management of these patterns can enhance pollutant mitigation. Gu *et al.* (2025) demonstrated that adjusting the spatial distribution of croplands, forest buffers, and urban green infrastructure can significantly improve seasonal water quality by reducing runoff nutrient loads during wet seasons and stabilizing sediment retention year-round (Gu *et al.*, 2025). This highlights the importance of implementing riparian buffers, wetland restoration, and conservation agriculture practices tailored to the hydrological calendar.

Another critical strategy involves linking flow regime management with water quality objectives. Flow regulation through dams, weirs, or water diversion structures can be used strategically to control pollutant concentrations. Nilsson and Renöfält (2008) argue for adaptive catchment management approaches that synchronize environmental flow releases with periods of high pollutant loading, thereby maximizing dilution and flushing potential (Nilsson & Renöfält, 2008). This is particularly important in regulated basins, where flow variability can be artificially constrained, intensifying pollutant concentrations during dry seasons.

Model-based decision-making forms another pillar of effective strategy development. Simulation and optimization models can help predict how pollutants will behave under different hydrological and management scenarios. Mujumdar and Sasikumar (2002) proposed a fuzzy risk-based approach for seasonal water quality management, integrating uncertainty into model predictions and enabling more robust decision-making in the face of incomplete data (Mujumdar & Sasikumar, 2002). Such modelling can support the design of seasonal discharge limits, guide reservoir operation schedules, and inform targeted agricultural restrictions during sensitive periods.

Integrated basin-scale management frameworks are essential for ensuring that interventions address the cumulative impacts of diverse pollution sources. Chen *et al.* (2006) presented a sustainable water quality management framework that incorporates Geographic Information Systems (GIS) to map pollution hotspots, model pollutant transport, and plan intervention strategies at the basin level (Chen *et al.*, 2006). This approach facilitates coordination among different stakeholders—agricultural producers, industrial operators, municipalities, and conservation agencies—ensuring that mitigation measures are spatially optimized and seasonally aligned.

Strategies should also prioritize source-specific seasonal interventions. In agricultural zones, nutrient management plans can limit fertilizer application before forecasted heavy rains to reduce runoff losses. In urban areas, upgrading stormwater systems and incorporating green infrastructure can mitigate the wet-season surge of pollutants. For industrial facilities, seasonal self-monitoring programs can ensure compliance during periods when low flows heighten pollution impacts. This targeted approach ensures that resources are invested where and when they yield the highest returns in water quality improvement.

The role of real-time monitoring cannot be overstated. High-

frequency sensors combined with remote data transmission enable near-instantaneous detection of pollutant spikes, allowing for rapid management responses such as adjusting dam releases, deploying aeration systems to counter oxygen depletion, or issuing temporary water use restrictions. Real-time data also improve the calibration of predictive models, enhancing their capacity to forecast seasonal pollution events and guide preemptive action.

Finally, stakeholder engagement and policy alignment are vital. Seasonal and spatial management strategies require cooperation across administrative and sectoral boundaries. This means aligning agricultural policies with water quality targets, integrating urban planning with stormwater management, and embedding water quality considerations into hydropower licensing. Local communities must be part of the process, both as beneficiaries and active participants, to ensure social acceptance and compliance. Education and awareness campaigns that link seasonal pollution risks to human health, ecosystem services, and economic productivity can further support behavioral changes that complement technical interventions.

An effective strategy for managing spatial and seasonal water quality challenges should integrate:

1. **Landscape pattern management** to reduce pollutant generation and enhance seasonal resilience.
2. **Flow regime coordination** to synchronize hydrological management with pollutant load dynamics.
3. **Model-based planning** to optimize decisions under uncertainty.
4. **Basin-scale coordination** to address cumulative impacts and align interventions spatially and temporally.
5. **Source-specific seasonal controls** tailored to key land uses and pollution types.
6. **Real-time monitoring and rapid response systems** for dynamic management.
7. **Policy integration and stakeholder engagement** to ensure coherence and effectiveness.

When applied collectively, these strategies create an adaptive and spatially nuanced management system capable of responding to the complex realities of river basin water quality dynamics.

3.2. Integrating Scientific Evidence into Policy and Regulation

Integrating scientific evidence into policy and regulation for spatial and seasonal water quality management in rivers requires a deliberate effort to connect research findings, monitoring data, and decision-making processes. River systems are inherently dynamic, with water quality varying significantly across locations and throughout the year due to hydrological changes, land use practices, climatic conditions, and human activities. Policies that overlook these complexities risk implementing measures that are ineffective, misaligned with actual pollution dynamics, or even counterproductive. The central challenge lies in translating robust, context-specific scientific knowledge into regulations that are not only enforceable but also flexible enough to adapt to environmental change and socio-economic realities.

A critical foundation for effective policy integration is the incorporation of river science into governance frameworks at both local and basin scales. As Horn *et al.* (2004) point out, water quality modelling should be explicitly designed to meet policy requirements by incorporating mesoscale watershed

processes that reflect both spatial heterogeneity and seasonal variability. Such models can simulate how pollutants behave under different land use scenarios, hydrological conditions, and management interventions, providing regulators with predictive insights to guide decision-making. For instance, nutrient reduction targets can be linked to hydrological forecasts, enabling pre-emptive management actions before high-risk wet season runoff events.

Central to this integration is the development of comprehensive monitoring systems and the efficient use of the data they produce. Traditional monitoring networks often fail to capture rapid seasonal changes or fine-scale spatial patterns, leading to regulatory blind spots. Bunn *et al.* (2010) argue for integrated monitoring systems that combine chemical parameters with ecological indicators to provide a holistic understanding of river health. Such systems can underpin adaptive regulations by setting site-specific and seasonal water quality benchmarks, replacing static annual averages that may not accurately reflect actual conditions. This approach also enables near-real-time compliance assessment and timely adjustments to management strategies. Expanding the data base through non-traditional sources is increasingly recognized as valuable. Citizen science programs, as highlighted by König *et al.* (2021), can complement official monitoring efforts, especially in areas with sparse coverage, by providing localized, high-frequency observations. When validated and integrated with formal datasets, these observations can inform rapid policy responses to seasonal challenges such as algal blooms, sediment surges, or pollution spills. Moreover, engaging local communities in monitoring builds trust, increases public awareness, and enhances compliance with regulations. Embedding ecological flow requirements into legal and regulatory frameworks is another crucial step. Nilsson and Renöfält (2008) stress that water quantity and quality are deeply interlinked, particularly in regulated river systems where altered flow regimes can amplify seasonal water quality problems. Regulatory provisions that mandate seasonal environmental flow releases can help maintain ecological processes and dilute pollutants at critical times of the year. For example, controlled wet-season releases can flush accumulated sediments and nutrients, while maintaining dry-season baseflows can prevent excessive concentration of pollutants.

Effective regulation must also account for the multi-scalar nature of water quality drivers. Gu *et al.* (2025) demonstrate that landscape patterns influence water quality differently across spatial and seasonal scales, making it essential to integrate land use planning with water quality objectives. Policies can require the preservation of riparian buffers in upstream agricultural zones to mitigate nutrient surges during wet seasons, while imposing stricter effluent limits in downstream industrial areas during low-flow periods. This kind of spatially and seasonally differentiated regulation ensures that interventions target the most pressing risks in each context.

Regulatory frameworks must also be adaptable in the face of climate change, which is expected to intensify seasonal extremes and disrupt established water quality patterns. Hou *et al.* (2021) propose hybrid policy instruments that combine regulatory measures with economic incentives, allowing for flexible responses to complex pollution scenarios. This might involve dynamically adjusting discharge limits based on seasonal flow forecasts or providing subsidies for

implementing pollution control technologies during high-risk periods. Such flexibility is vital for maintaining effectiveness as climate and land use patterns evolve.

Finally, institutional coordination is essential for ensuring policy coherence. Spatial and seasonal water quality challenges often stem from fragmented governance across sectors such as agriculture, urban development, industry, and environmental protection. Integrated river basin organizations can facilitate cross-sectoral and cross-jurisdictional coordination, ensuring that policies in one domain do not undermine objectives in another. In transboundary basins, harmonized seasonal water quality standards, shared monitoring protocols, and cooperative enforcement mechanisms are necessary to address upstream-downstream interdependencies.

Integrating scientific evidence into policy and regulation for spatial and seasonal water quality management requires a multi-pronged approach. This includes policy-oriented modelling that reflects spatial and seasonal dynamics, integrated and participatory monitoring systems, embedding ecological flow requirements into regulations, landscape-informed land use controls, flexible policy instruments, and strong institutional coordination. By embedding these elements into governance structures, water quality policies can become both scientifically sound and operationally effective, ensuring that interventions align with the complex and changing realities of river systems.

4. Conclusions and Future Research Directions

This review highlights that spatial and seasonal variations in river water quality stem from the combined influences of natural processes and anthropogenic pressures, each interacting differently across locations and timeframes. Effective management demands an integrated approach that considers both dimensions simultaneously, supported by robust monitoring, predictive modelling, and adaptive governance. Scientific evidence must be embedded into policy frameworks that are flexible, location-specific, and responsive to hydrological cycles, land use patterns, and emerging environmental pressures.

Future research should focus on generating high-resolution, long-term datasets that combine physical, chemical, and biological indicators; developing predictive models that incorporate climate and land use change; and exploring governance mechanisms that operationalize scientific recommendations effectively. Cross-basin comparative studies can also help identify universally applicable principles while respecting local contexts.

By linking strong science, inclusive stakeholder engagement, and adaptive policy, river systems can be managed to sustain ecological health and human needs in the face of ongoing and future challenges.

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