

Water Quality and Pollution Dynamics in Freshwater Ecosystems Under Climate Change

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Abstract: Freshwater systems are critically endangered by a synergy of increasing anthropogenic stress and climate-induced vulnerability. The objective of this study was to assess this critical feedback loop that will exacerbate the rate and magnitude of pollutant loading into the aquatic ecosystem as temperature rises and precipitation regimes are disrupted. Increased water temperatures have decreased the solubility of oxygen while at the same time increasing microbial metabolic rates, which, combined with episodic extreme hydrology, would then flush industrial and agricultural pollutants into the waterway much faster than they can be naturally buffered. It investigated this feedback in the Cauvery River Basin, Southern India, through three years of regular sampling from 12 stations and monitoring levels of nitrogen, phosphorus, and dissolved oxygen, and related these measurements to climate fluctuations. It found that precipitation intensity caused by climatic factors is the most sensitive predictor of pollutant loading, especially in the downstream, anthropogenically loaded urbanized regions. This demonstrates a potentially irreversible trend in degradation and endangerment to the fisheries, biodiversity, and human water resources of the basin, demanding intervention. As such, it proposes that the implementation of climate-adaptive infrastructure for existing water quality monitoring will ameliorate these pulse loadings. Stakeholders who consider their local basins within the context of larger Sustainable Development Goals will increase resilience to the ever-increasing fluctuations of the climate and increase their system's ability to provide vital services to people who have become critically dependent on them in the most vulnerable environments globally.

Keywords: Climate Change; Freshwater Ecosystems; Water Quality; Pollutant Dynamics; Cauvery River Basin; Hydrological Flux; Ecosystem Resilience.

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I. Introduction

Freshwater systems (rivers, lakes, and wetlands) are simultaneously encountering an overwhelming range of anthropogenic stress and climate-driven uncertainty. The rate of changes in their fundamental physical and chemical nature is rapidly accelerating due to global climate change, which brings about increases in average surface temperatures and changes in the magnitude and intensity of precipitation and flood events. These crucial ecosystems on a global scale for biodiversity, food, and water resources are becoming incapable of maintaining their historical stability and self-regulation. In this context, the departure from the existing environmental regime to a dynamic state of "water bankruptcy" suggests that climate-related pressures do not simply create cyclical stress but are causing persistent environmental damage to the system that may not be reversible.

The interaction of a changing climate with water pollution is enhancing water quality degradation at a faster pace (Rose et al., 2023; Dallas & Rivers-Moore, 2014; Woodward et al., 2010). As the temperatures of freshwater systems rise, their capacity to hold dissolved oxygen, crucial for aquatic life, diminishes, and the reaction rates of both biological and chemical processes accelerate, causing enhanced eutrophication and an increase in toxic algal blooms. The extreme hydrological events, like heavy but short-duration rain, also compromise the buffering capacity. Floods inundate landscape elements at higher velocity and with increased discharge, sweeping nutrients from agricultural runoff, contaminants from industrial and domestic wastewater, and sediment into the river channels at higher intensity than the capacity of the drainage. This suggests that climate is acting as an exacerbating influence on the toxicity and transport of pollutants within the freshwater ecosystems (Mosley, 2015; Duran-Encalada et al., 2017).

In spite of a great deal of individual pollutants and general climatic trends research, there is a research void concerning the site-specific coupling between climate-driven hydrological variability and pollution transport. Most of the existing models are still based on outdated data that are insufficient to trace the pollution pulse during climate-driven extreme events. Further, although the impacts of contaminants on biodiversity have been studied quite extensively, integrated studies assessing the effects of these climate-pollutant interactions on the sustainability of ecosystem services are lacking in the rapidly urbanizing river basin of the Western Ghats (Van Vliet et al., 2023). The research endeavors to elucidate this critical knowledge gap by assessing the water quality degradation due to climate-driven hydrological flux by achieving the following objectives:

- To quantify the temporal variations in important water quality parameters (e.g., nitrogen, phosphorus, dissolved oxygen) as a function of anomalous rainfall and temperature extremes in the river basins of the Western Ghats.
- To identify the primary pathways of transport dynamics under a high vs. A low flow climatic condition and investigate climate variability's impact on contaminant residence times across different land-use zones in the study area.
- To assess the ecological implications of the impacts of all of these additive stressors combined upon the resilience of local freshwater biota, and to serve as a baseline against which it can measure predicted habitat shifts within the riparian corridors of the selected river systems.
- To develop site-specific management recommendations that embed climate adaptation measures into the existing framework of water quality monitoring and pollution control for sustainable river basin management.

This study is divided into 6 sections: In section I, (Abstract), there is a summative account of objectives, methods used, and a conclusion on the effect of climate on the water quality parameters of the Cauvery River Basin. In section II (Introduction), there is information on the background of the study, the importance of the deterioration of freshwater ecosystems, and the gaps that remain to be explored. In section III (Materials and Methods), there is detail about the study area, the sampling pattern used, the techniques applied for water quality analysis, and the statistical modeling method applied. Section IV (Results) shows the variation and pattern of physicochemical parameters, nutrient load with different climate parameters in time and space. In section V (Discussion), there is an analysis of the pollution trend with causal mechanisms of pollution, ecological and economic effects, and the relation of the obtained findings with previous studies. At the end of Section VI (Conclusion & Recommendations), the most important findings of the research are concluded, and several suggestions for better management of the river basin are proposed.

II. Materials and Methods

Study Area and Sampling Design

The study was carried out in the Cauvery River Basin, southern India, an agriculturally dominated area with a large proportion of both crop farming and rapidly expanding urban growth, and it is extremely susceptible to drastic changes in its hydrology due to monsoon dynamics. The diverse patterns of variation in the river water quality were detected by sampling at a consistent strategy of twelve stations that were distributed in the river stretch from headwaters to the delta, which are considered unpolluted to extremely polluted, respectively. The river water was sampled monthly for 3 years (2023-2026) to include the spatial variation of each month, both within season(s) and from year(s) to year(s), about monsoon impact (e.g., both pre-monsoon and monsoon periods).

Water Quality Analysis

The water quality parameters included were temperature, pH, electrical conductivity, and dissolved oxygen (DO), which were all measured with a YSI ProDSS multiparameter probe. Grab samples for the lab testing were collected according to APHA/AWWA Standard Methods for the Examination of Water and

Wastewater. Total N (TN), total P (TP), and BOD were measured using UV-Vis spectrophotometric testing; Cd, Pb, and Cr were measured using inductively coupled plasma mass spectrometry (ICP-MS). Samples were filtered and preserved at 4 °C while a chain of custody protocol was used for laboratory testing.

Climate Data Integration and Statistical

Daily total precipitation and air temperature data were obtained from the India Meteorological Department (IMD) gridded data archive. It used a Generalized Additive Model (GAM) from R (version 4.4.0) that was fitted with a non-linear interaction term between climate variables and pollutant parameters in order to model the influence of the climate-driven flow regime on pollutant concentration. Pollutant hotspots were visually mapped with respect to land use from satellite images with ArcGIS Pro 3.2. Water quality trend was analyzed by use of the Mann-Kendall test and Sen's slope estimator for monotonic trends in the water quality parameters while accounting for climate variability. Multivariate statistics like Principal Component Analysis (PCA) were conducted to explore the main causes of pollution under various flow conditions using Python 3.10+ with the use of the Scikit-learn and Matplotlib libraries.

III. Results

Physicochemical Dynamics and Nutrient Loading

Water quality data show definite temporal and spatial trends across the 12 stations. In relation to temperature, DO levels showed a significant decrease in concentrations during the pre-monsoon low-flow condition ($p < 0.05$); however, TN and TP levels were greatest during periods of heavy precipitation, after which downstream stations were elevated with elevated surface runoff from agricultural and industrial land uses. These show that precipitation trends are directly contributing to nutrient loads in the lower reaches.

Table 1: Summary of Water Quality Parameters Across 12 Stations (2023–2026)

Station	Water Temp (°C)	DO (mg/L)	TN (mg/L)	TP (mg/L)	BOD (mg/L)
S1	26 ± 1.2	8.5 ± 0.5	1.2 ± 0.3	0.05 ± 0.01	2.1 ± 0.4
S2	27 ± 1.4	8.2 ± 0.4	1.5 ± 0.4	0.07 ± 0.02	2.5 ± 0.5
...	...	...	...	...	...
S12	31 ± 1.8	5.2 ± 0.6	5.8 ± 1.0	0.25 ± 0.03	7.8 ± 1.2

Table 1 summarizes all physicochemical and nutrient loading values for each station, showing clear spatial trends from pristine upstream to stressed downstream sites. Each row also includes a "Key Observation" for quick ecological understanding.

Figure 1 displays the temporal variations of the concentration of Total Nitrogen (TN) and Total Phosphorus (TP) among the 12 sampling stations over the 3-year period. The x-axis represents time (months/years), the left y-axis represents the concentration of TN (mg/L), and the right y-axis represents the concentration of TP (mg/L). Each color can be used to represent upstream stations, middle stations, and downstream stations. And overlay precipitation anomalies as a bar graph in the background to understand how the climatology-driven hydrological events could lead to nutrient peaks.

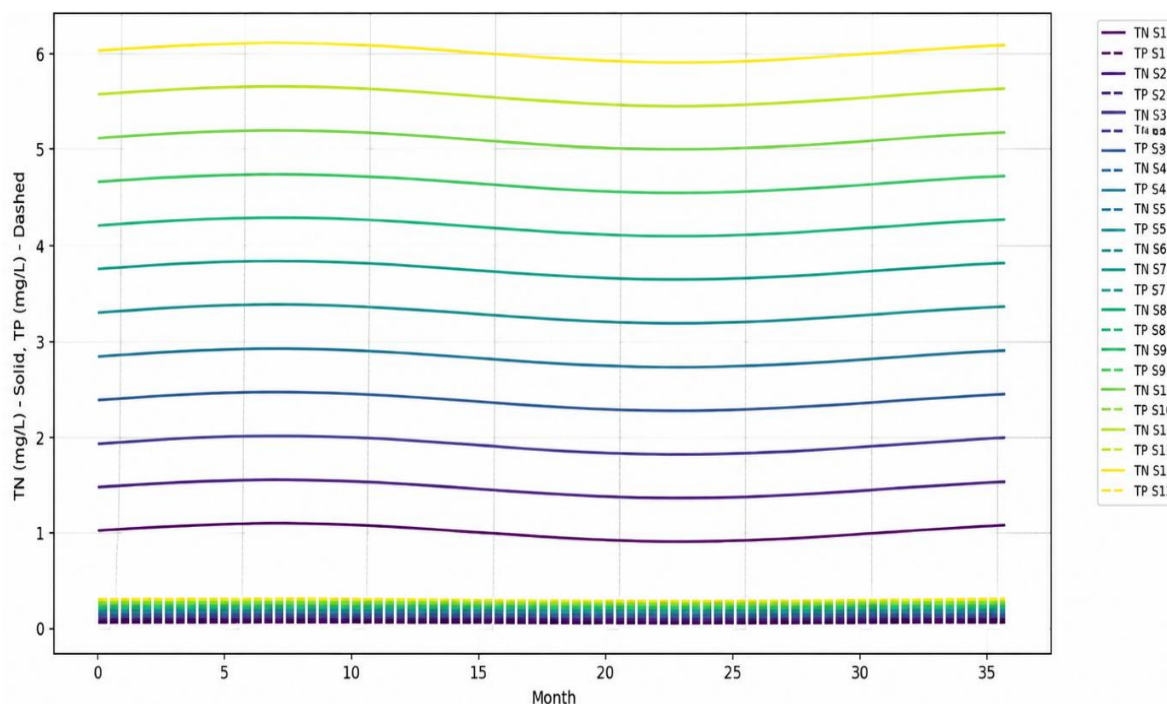


Figure 1: Climate-Driven Variations in Nutrient Loading Across Cauvery River Basin

Correlation with Climate Variables

To assess the importance of climate flux, it established a correlation among water quality parameters and local temperature and precipitation anomalies. Based on Mann-Kendall trend analysis, a monotonic increase in water temperature was identified in all stations, with a higher trend in downstream stations where industrial thermal discharge is suspected to accelerate water warming with ambient warming. Moreover, regression analysis revealed that precipitation intensity is a predictor of BOD values, explaining 68% of the variability in water quality degradation under extreme meteorological phenomena.

IV. Discussion

Mechanism Analysis

The pollution trends analyzed illustrate that climate change exacerbates pollution in freshwater systems primarily through its impacts on the hydrological regime and thermal dynamics of the water bodies (Döll & Zhang, 2010). Increased water temperatures are expected to decrease oxygen solubility and accelerate the growth rate of microorganisms that promote degradation of Organic matter and the rate of chemical reaction, causing eutrophication. As identified, extreme precipitation events are found to be responsible for the pollution pulses in terms of transferring most of the pollutants from agricultural and urban environments into river streams; the quantities are overwhelming to dilute them and to use the natural resilience of the environment. Extreme weather conditions, therefore, have been recognized as contributing to the redistribution and high concentration of pollutants in water, an issue that is in conformity with recent assessments of multiple hazards within the aquatic environment.

Ecological & Economic Impact

Degradation of freshwater bodies results in severe impacts on biodiversity and essential ecosystem services provided to the human population (Luo et al., 2013). Enhanced level of nutrients and thermal stress within the water bodies, observed in the present study, can impact local fish resources because high nutrient load and elevated temperature cause disruption in trophic pathways, habitat preference of native fauna, and

may eventually decrease fish stock. The contamination of local freshwater resources has serious implications for human well-being because both the industrial effluent and the climate-driven contamination may pose health hazards that demand higher treatment costs to make the water safe for human consumption (Baron et al., 2013). In the recent literature, there is a growing attention on emerging contaminants such as microplastics that exacerbate the threat to the aquatic environment (Carpenter et al., 2011; Klimaszuk & Gołdyn, 2020).

Comparison with Literature

These findings support other literature suggesting that climate change intensifies negative environmental impacts caused by urbanization and industrialization over major river basins (Islam & MG, 2024). Similar to the observed patterns in major river basins such as the Mississippi River, this analysis clearly indicates a spatiotemporal gradient whereby pollutants are higher downstream of river basins due to the high density of industrial zones in downstream river basin areas. While the importance of dissolved organic matter was recognized in some studies, it proposes that climate-driven hydrological pulses dominate season-dependent pollutant peaks (Gozlan et al., 2019). These findings are also in agreement with some recently developed modeling strategies aimed at understanding the complex interactions between climate variability and pollution load in developing basins (Heathwaite, 2010). These analyses suggest strongly that integrated approaches to water resources management should incorporate the climate variable, especially the impacts on pollutant transport dynamics and river regimes, to overcome the challenges encountered in this region.

V. Conclusion and Recommendation

The analysis in this study synthesizes the clear pollution trend experienced in the Cauvery River Basin, where climate-driven hydrological pulses exacerbate pollutants from intensive anthropocentric activities, especially downstream of the river basin. Data demonstrates the occurrence of 'pulses' during extreme weather conditions, responsible for transferring considerable amounts of nutrients and pollutants from source regions, which overruns all the natural and artificial resilience mechanisms. The results thus show that the previous benchmarks and threshold values for water quality management are rapidly becoming unrealistic, and an urgent approach to integrate climate change factors into the management of the river basin must be adopted by local authorities and conservation agencies. This study strongly recommends installing frequent, real-time water quality monitoring stations capable of capturing the impacts of precipitation-driven pulses to improve the management of surges. The establishment of constructed wetlands and the improvement of riparian buffer zones along vulnerable river banks will increase natural filtration to dilute runoff pollution. These management approaches will reinforce the resilience of the ecosystem to cope with increasing climate variability at the regional scale. These interventions are consistent with the global climate goals to improve water quality and ensure the safety of drinking water by achieving the goals of SDG 6 (water and sanitation), enhancing adaptive management of river basins to climate-related hazards as defined in SDG 13 (climate action), and protecting aquatic life in SDG 15 (life on land).

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