**National River Conservation Directorate**
Ministry of Jal Shakti,
Department of Water Resources,
River Development & Ganga Rejuvenation
Government of India

# PERIYAR

# Nutrient and Sediment Load Management Report

Centres for Periyar River Basin Management Studies
IIT Palakkad & NIT Calicut

Centre for Ganga River Basin Management and Studies

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## National River Conservation Directorate (NRCD)

The National River Conservation Directorate, functioning under the Department of Water Resources, River Development & Ganga Rejuvenation, and Ministry of Jal Shakti providing financial assistance to the State Government for conservation of rivers under the Centrally Sponsored Schemes of 'National River Conservation Plan (NRCP)'. National River Conservation Plan to the State Governments/ local bodies to set up infrastructure for pollution abatement of rivers in identified polluted river stretches based on proposals received from the State Governments/ local bodies.

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## Centre for Periyar River Basin Management Studies (cPeriyar)

The Centre for Periyar River Basin Management Studies (cPeriyar) is a Brain Trust dedicated to River Science and River Basin Management. Established in 2024 by IIT Palakkad and NIT Calicut, under the supervision of cGanga at IIT Kanpur, the center serves as a knowledge wing of the National River Conservation Directorate (NRCD). cPeriyar is committed to restoring and conserving the Periyar River and its resources through the collation of information and knowledge, research and development, planning, monitoring, education, advocacy, and stakeholder engagement.

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**www.cganga.org**


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# Preface

The Periyar River is one of Kerala's most important river systems, supporting drinking water supply, irrigation, hydropower generation, industries, fisheries, and ecologically significant wetlands. However, increasing anthropogenic pressures, including urbanisation, industrialisation, agricultural activities, and land-use changes, have altered the basin's nutrient and sediment dynamics, affecting water quality and ecosystem health.

This report presents a comprehensive assessment of nutrient and sediment loads in the Periyar River Basin as part of the Condition Assessment and Management Plan (CAMP). Using secondary datasets obtained from the Kerala State Pollution Control Board (KSPCB) and the Central Water Commission (CWC), the study evaluates the spatial and temporal characteristics of water quality, nutrient transport, and sediment dynamics across the basin. The report further examines the major natural and anthropogenic factors influencing these processes and assesses their implications for river health and basin-scale environmental management.

The findings provide a scientific basis for identifying pollution hotspots, understanding nutrient and sediment transport processes, and supporting evidence-based planning for pollution control, river restoration, and sustainable river basin management. This report will serve as a valuable reference for policymakers, researchers, and resource managers working towards the long-term conservation and sustainable management of the Periyar River Basin.

Centres for Periyar River Basin Management Studies (cPeriyar)

IIT Palakkad & NIT Calicut

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## Abbreviations

| | |
|---|---|
| APHA | American Public Health Association |
| BIS | Bureau of Indian Standards |
| BOD | Biochemical Oxygen Demand |
| COD | Chemical Oxygen Demand |
| CPCB | Central Pollution Control Board |
| CWC | Central Water Commission |
| DO | Dissolved Oxygen |
| EC | Electrical Conductivity |
| FAO | Food and Agriculture Organization |
| FC | Faecal Coliform |
| GIS | Geographic Information System |
| GPS | Global Positioning System |
| IS | Indian Standard |
| KSPCB | Kerala State Pollution Control Board |
| LULC | Land Use Land Cover |
| MPN | Most Probable Number |
| $NH_4^+$-N | Ammoniacal Nitrogen |
| $NO_2^-$ | Nitrite |
| $NO_3^-$-N | Nitrate Nitrogen |
| OECD | Organization for Economic Co-operation and Development |
| $PO_4^{3-}$ | Phosphate |
| PRB | Periyar River Basin |
| SSC | Suspended Sediment Concentration |
| TDS | Total Dissolved Solids |
| TKN | Total Kjeldahl Nitrogen |
| TOC | Total Organic Carbon |
| TSS | Total Suspended Solids |
| USEPA | United States Environmental Protection Agency |

| | |
|---|---|
| WHO | World Health Organization |

## 1. Introduction

River basins are fundamental to India's water security, economic development, agricultural productivity, and ecological sustainability. They provide potable water, support irrigation, enable hydropower generation, facilitate industrial operations, sustain inland aquaculture, and offer a wide range of ecosystem services. However, rapid urbanization, industrial expansion, intensified agriculture, infrastructure development, and climate variability have significantly altered natural riverine systems, particularly in terms of nutrient cycling and sediment transport. These changes have led to substantial degradation of water quality, reduced aquatic biodiversity, increased reservoir sedimentation, and heightened risks to public health and ecological resilience. Consequently, effective management of nutrient and sediment loads has become a central focus in national water resource governance and river restoration initiatives (Sinha, 2026).

Excessive nutrient inputs, particularly nitrogen (N) and phosphorus (P), are recognized as primary drivers of eutrophication in freshwater and coastal ecosystems. Elevated nitrogen concentrations stimulate the overgrowth of algae and macrophytes, reduce water quality, lower dissolved oxygen levels, and can create hypoxic or anoxic conditions that may result in fish mortality and ecosystem collapse. Nutrient enrichment also promotes the occurrence of toxic algal blooms, some of which produce toxins that pose direct risks to drinking water safety, fisheries, and recreational activities. Nutrient pollution originates from multiple anthropogenic sources, including municipal sewage discharge, agricultural fertilizer runoff, livestock waste, industrial effluents, and urban stormwater runoff. In regions characterized by tropical monsoon climates, nitrogen transport is intensified by increased rainfall, surface runoff, soil erosion and seasonal flooding, which contribute to pronounced temporal variability in nutrient loads (Wurtsbaugh et al., 2019; Tiwari & Pal, 2022).

Sediment movement constitutes a fundamental geomorphic and biogeochemical process in river systems, facilitating the connection between upland catchments, floodplains, reservoirs, estuaries, and coastal ecosystems. Both suspended and bedload sediments influence channel morphology, floodplain fertility, aquatic habitat structure, and the downstream transport of organic matter and nutrients. Elevated sediment loads degrade water quality by increasing turbidity, reducing light penetration, limiting primary productivity, suffocating benthic ecosystems, and accelerating siltation in reservoirs and water delivery systems. Additionally, sediments act as carriers for particle-bound contaminants, including heavy metals, persistent organic pollutants, and phosphorus, thereby playing a critical role in the transport and long-term retention of pollutants within river basins (Vercruysse et al., 2017; Li et al., 2020).

A growing body of research highlights the strong interconnection between sediment transport and nutrient dynamics. Fine-grained sediments absorb and retain nutrients and pollutants during periods of low flow, then release them during high-flow events, dredging operations, or reservoir drawdowns. Internal nutrient loading can sustain eutrophic conditions even when external pollution sources are reduced, thereby complicating water quality management and restoration efforts. Therefore, comprehensive assessments of sediment and nutrient loads are essential for understanding river health, identifying pollution sources, and developing effective catchment management strategies (Lloyd et al., 2016; Wijesiri et al., 2019).

At the national level, the Ministry of Environment, Forest, and Climate Change (MoEFCC), the Central Pollution Control Board (CPCB), and the Ministry of Jal Shakti have emphasised the significance of basin-scale water quality assessment, pollutant load quantification, and scientifically advised river restoration strategies. The CPCB's framework for river water quality monitoring recommends load-based assessments to evaluate pollutant movement, identify pollution hotspots, verify regulatory compliance, and prioritise management activities. Similarly, the National Framework for Sediment Management emphasises the need to maintain sediment continuity and incorporate sediment budgets into river basin planning and restoration efforts. These policy frameworks all emphasise the need to assess nutrient and sediment loads as a scientific foundation for evidence-based water resource management, pollution control, and sustainable river basin restoration (CPCB, 2019; MoEFCC, 2023).

The Periyar River Basin holds significant hydrological, ecological, and socio-economic value within Kerala. Originating in the Western Ghats, a recognized global biodiversity hotspot, the river flows through forested upstream regions, agricultural lands, urban centers, and industrial zones before discharging into the Vembanad Lake system and the Arabian Sea. The basin supplies drinking water to major metropolitan areas, including Kochi, supports extensive irrigation networks, enables hydropower production, and maintains fisheries, wetlands, and estuarine ecosystems. Given its critical role in Kerala's economy and environmental sustainability, the preservation of water quality and ecological integrity in the Periyar River Basin is a strategic priority for both state and national authorities.

The Periyar River Basin has experienced escalating environmental stress in recent decades. Rapid industrialisation, particularly within the Eloor–Edayar industrial corridor, has led to the persistent discharge of chemical effluents, heavy metals, and organic contaminants into the river. Additional factors such as municipal sewage, agricultural runoff, sand extraction, land use changes, and dam-controlled flow regimes have further degraded water quality and altered sediment transport processes. Multiple studies have documented elevated concentrations of nutrients, heavy metals, and organic pollutants in the water and sediments of the Periyar, indicating both ongoing pollution and legacy contamination preserved in riverbed deposits (Saranya et al., 2020; Chandni et al., 2026).

The construction of reservoirs and dams in the Periyar Basin has severely impacted natural sediment transport. Sediment entrapment in reservoirs reduces downstream sediment delivery, alters channel morphology, and restricts the movement of sediment-bound nutrients to floodplains, estuaries, and the Vembanad Lake system. These changes increase reservoir sedimentation, reduce downstream sediment availability, and modify the basin's sediment and nutrient budgets, all of which affect riverine and estuarine ecosystem functioning. Understanding these variations is thus critical for determining sediment and nutrient loads and promoting sustainable river basin management (Sudheer et al., 2019).

Recent ecological disturbances, such as frequent fish mortality events and localized hypoxia, have increased concerns regarding nutrient enrichment, oxygen depletion, and pollutant discharges in the Periyar River (Maya et al., 2007; Aditya et al., 2023). These incidents highlight the significant impact of episodic nutrient and sediment influxes, often triggered by monsoon floods or industrial discharge events, in causing short-term water quality degradation. Additionally, climate variability and projected increases in rainfall intensity are likely to intensify runoff-driven nutrient and sediment transport, emphasizing the need for improved basin-scale monitoring and management (Costa et al., 2022).

Although various studies have examined water quality, sediment geochemistry, industrial contamination, and localised pollution in the Periyar River Basin, comprehensive basin-scale assessments quantifying nutrient and sediment loads remain limited. Most earlier studies have focused on water quality metrics or specific contaminants, with insufficient emphasis on the spatial and seasonal dynamics of pollutant transport across the basin. Quantifying nutrient and sediment load by integrating concentration data with hydrological information is essential for identifying pollution hotspots, understanding source contributions, evaluating seasonal transport processes, supporting regulatory compliance, and developing evidence-based strategies for river restoration and sustainable watershed management.

The main aim of this report is to quantify nutrient and sediment loads in the Periyar River Basin, examine their spatial and seasonal variability, identify the major sources and controlling processes influencing their transport, and provide a scientific basis for pollution control, river restoration, and integrated watershed management.

### 1.1. Scope and Methodology

The present study is based exclusively on secondary data analysis from various government and institutional agencies, aiming to generate a basin-scale understanding of nutrient and sediment dynamics within the Periyar River basin. The scope and methodological approach focus on the systematic compilation, screening, harmonization, and interpretation of multi-source data sets to quantify nutrients and sediment loads, and examine their spatial and seasonal variability.

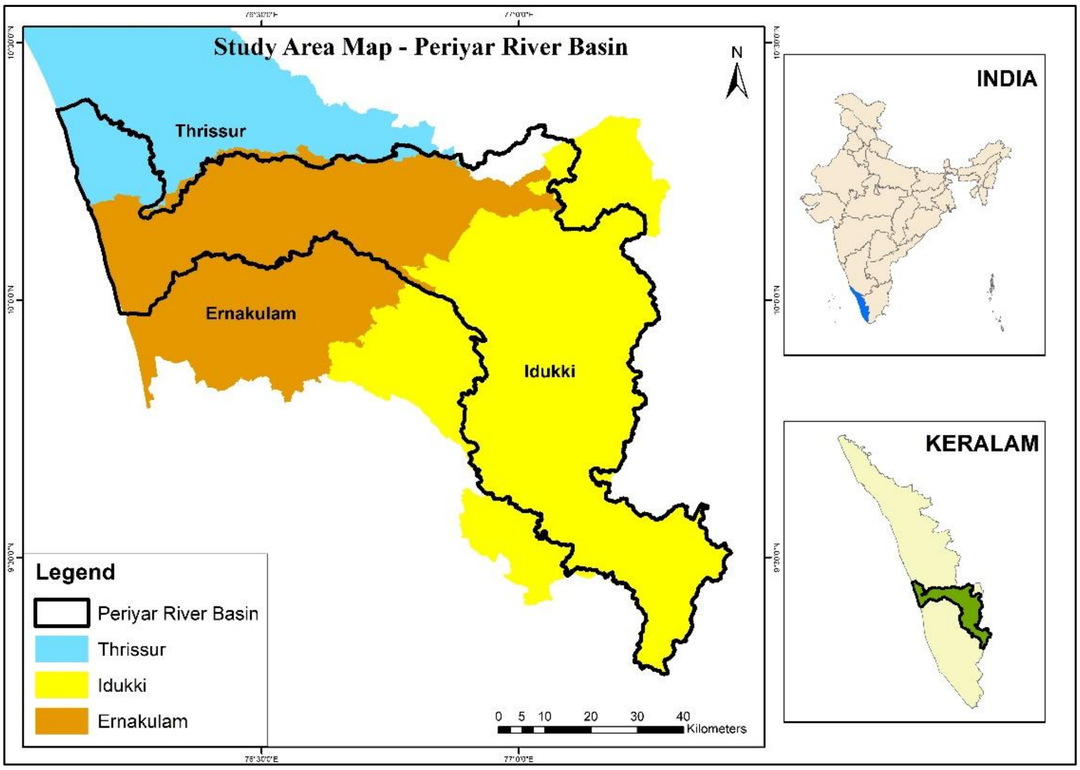


Figure 1. Study Area Map

The study spans the entire Periyar River basin, from the upstream regions of the Western Ghats to agricultural, urban, and industrial boundaries, including large tributaries, regulated river segments downstream of reservoirs, and downstream stretches that influence the Vembanad Lake System. The assessment is based on measured parameters at monitoring sites, as represented in the available secondary datasets, to capture spatial variability in nutrient and sediment transport and to identify river and priority areas for special management focus.

### 1.1.1. Temporal Framework

The analysis focuses on seasonal variability in the transport of nutrients and sediments under a monsoon-dominated hydrological regime. Secondary data sets are organized and analyzed during the pre-monsoon, monsoon, and post-monsoon periods to reflect the hydrologically distinct conditions governing runoff, erosion, and pollutant transport. When multi-year data sets are available, the interannual variability and long-term trends of nutrient and sediment loads are examined.

### 1.1.2. Data Sources and Parameters

The current study uses hydrological and water quality datasets from several government agencies to evaluate nutrient dynamics, sediment transport, and overall environmental conditions in the Periyar River Basin. Nutrient and water quality metrics were gathered from the KSPCB. In contrast, sediment load and discharge datasets were obtained from the CWC, specifically from the Neeleswaram gauge station in the Periyar River.

The analysed parameters include physicochemical indicators such as pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), and turbidity; nutrient parameters including ammoniacal nitrogen, nitrate, phosphate, and total Kjeldahl nitrogen (TKN); microbiological indicators such as total coliform and faecal coliform; and sediment load observations derived from the Central Water Commission (CWC) Neeleswaram gauge station. The relevance of these parameters, as well as the accompanying analytical results, are described in further detail in the next sections of this study.

Secondary data from different agencies are subject to systematic screening to assess completeness, temporal alignment, analytical coherence, and spatial representativeness. The differences in monitoring frequency, analytical methods, and reporting formats are reviewed, and data sets are adjusted to a common temporal and spatial framework to the extent possible.

Table 1. Data sources and parameters used in the study

| Sl. No | Data Category | Data Source | Parameters/Variables |
|---|---|---|---|
| 1 | Surface Water Quality | Kerala State Pollution Control Board (KSPCB) | pH, DO, BOD, COD, EC, TDS, TSS, Turbidity |

| | | | |
|---|---|---|---|
| 2 | Nutrients | Kerala State Pollution Control Board (KSPCB) | Ammoniacal Nitrogen ($NH_4^+$-N), Nitrate ($NO_3^-$-N), Phosphate ($PO_4^{3-}$), TKN |
| 3 | Microbiological Parameters | Kerala State Pollution Control Board (KSPCB) | Total Coliform, Faecal Coliform |
| 4 | Hydrological Data | Central Water Commission (CWC) | River Discharge |
| 5 | Sediment Data | Central Water Commission (CWC) | Sediment Concentration |

#### 1.1.2.1. Nutrient & Sediment Load Estimation Approach

Nutrient and sediment loads are estimated using flow-weighted calculation approaches that integrate reported concentration data with corresponding discharge records. Instantaneous loads are calculated for available pair concentration-displacement observations, while seasonal loads are derived by aggregating event-based or period averaged estimates. Where the discharge data are continuous, but the concentration data are intermittent, statistical concentration-discharge relationships are developed to estimate loads during unmonitored periods, especially during high-flow monsoon conditions.

### 1.1.3. Spatial Analysis and Interpretation

Geographic Information System tools are applied to integrate secondary hydrological, water quality, sediment, and land use data. The basin and subbasin boundaries are defined to support the spatial aggregation of loads and the comparative assessment of sub-catchments. Spatial indicators, including total load size and load standardized by catchment area, are used to identify persistent and seasonally dominant contaminant hotspots. The results are interpreted in relation to hydrological variability, land use patterns, urban and industrial pressures, agricultural activities, and reservoir capture effects. Uncertainty related to the use of secondary data, including variability in sample frequency, analytical methods, and time coverage, is evaluated qualitatively and explicitly during interpretation. The results of this assessment are intended to inform basin-scale understanding of nutrient and sediment processes and support subsequent planning and management activities.

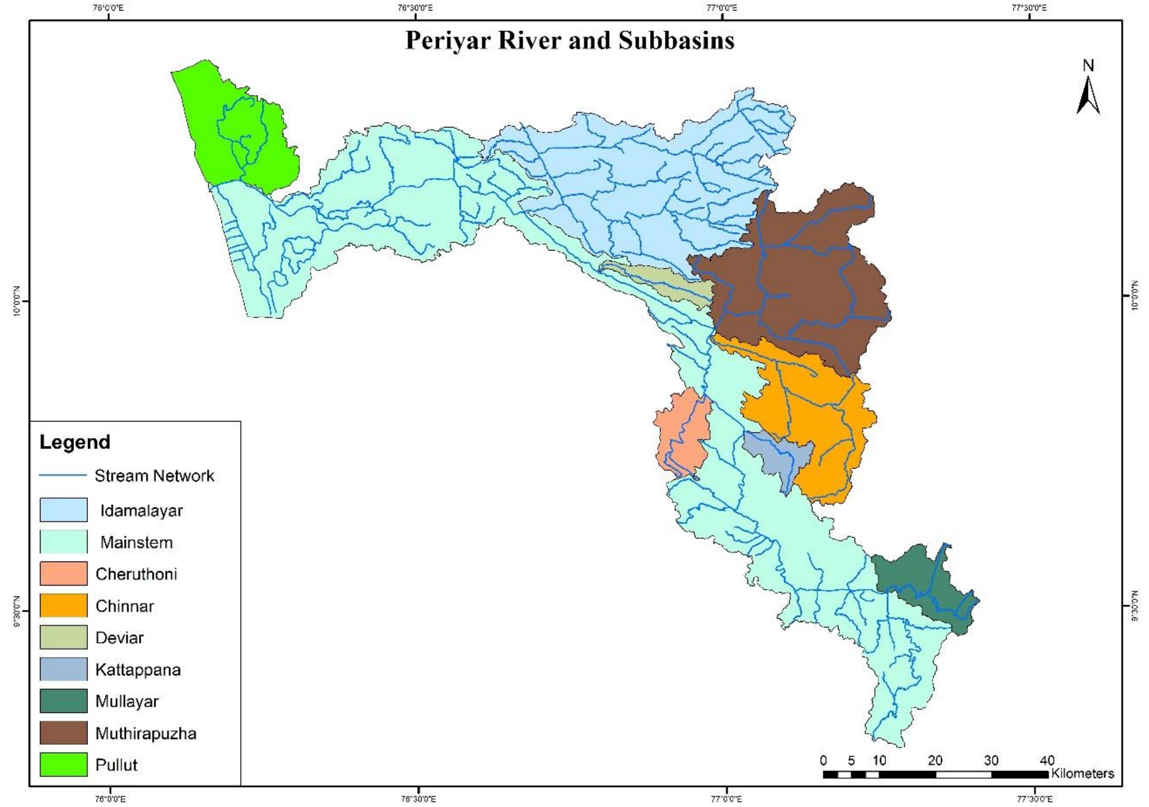


Figure 2. Subbasins and named stream network

## 2. Overview

### 2.1. Nutrient and Sediment Dynamics in River Basins

River basins are integrated systems in which nutrients and sediments are constantly mobilised, transported, stored, and altered by interactions between climate, hydrology, geomorphology, biogeochemical processes, and human activities. Nutrient transport is closely connected to sediment dynamics because suspended sediments serve as both transport media and temporary storage sites for nutrients and other pollutants. Nitrogen and phosphorus are the principal nutrients that cause eutrophication in freshwater habitats, and sediment movement significantly affects their mobility, retention, and downstream delivery. Understanding these interactions is critical for assessing water quality, ecological functioning, and contaminant transport at the river basin scale (Ying et al., 2025).

Nitrogen is a highly mobile and abundant nutrient in river systems, occurring in both inorganic and organic forms, including nitrate, nitrite, ammonium, dissolved organic nitrogen, and particulate organic nitrogen. Nitrate is the most common type in agricultural and urban catchments due to its high solubility and mobility in soils and groundwater. Natural processes such as biological nitrogen fixation and organic matter mineralisation introduce nitrogen into river systems, as can anthropogenic sources such as fertiliser application, livestock manure, municipal sewage, and industrial effluents. Groundwater-surface water interactions help to support nitrogen transfer during low-flow periods. Elevated nitrogen loading causes eutrophication, algal blooms, oxygen depletion, and worsening of water quality, especially in downstream reservoirs and estuaries (Xia et al., 2018; Wang et al., 2022).

Phosphorus transport differs from that of nitrogen due to its strong affinity for soil minerals and fine particles. It is carried in two forms: dissolved (mainly orthophosphate) and particulate (associated with suspended silt and organic materials). In many river basins, especially those dominated by agriculture and extensive erosion, a significant fraction of yearly phosphorus export occurs during high-flow periods, when runoff and sediment transport are at their peak. As a result, monsoon-driven runoff is primarily responsible for regulating phosphorus loading. Sediment-bound phosphorus can accumulate in riverbeds, floodplains, reservoirs, and other depositional environments before being released under reducing conditions or during sediment resuspension, contributing to internal phosphorus loading and the persistence of eutrophic conditions even when external nutrient inputs are reduced (Timis et al., 2022; Yang et al., 2024).

Although iron (Fe) and manganese (Mn) are not the major nutrients involved in eutrophication, they play an important role in regulating phosphorus availability in aquatic sediments. Under oxic conditions, phosphorus is strongly adsorbed onto iron and manganese oxides, limiting its release into the water column. However, under reducing conditions, the dissolution of these oxides releases previously bound phosphorus into the surrounding water, a process known as internal phosphorus loading. As a result, the geochemistry of iron and manganese significantly affects phosphorus cycling, nutrient availability, and the persistence of eutrophic conditions in rivers, reservoirs, and other slow-flowing aquatic habitats (Pan et al., 2019; Chen et al., 2024).

Silicon is an essential macronutrient for diatom growth in freshwater and estuarine habitats. River management and reservoir impoundment can alter downstream silicon transport by altering natural sediment dynamics, potentially influencing phytoplankton community composition (Humborg et al., 2000). However, dissolved silica was not included in the current assessment. As a result, silicon is presented only to provide context for nutrient cycling and is not considered part of the nutrient load analysis.

Carbon is another key component of river biogeochemistry, appearing in dissolved organic, particulate organic, and inorganic forms. Organic carbon is directly linked to sediment transport because fine particles provide sites for adsorption and microbial digestion. The transport and transformation of carbon affect oxygen consumption, organic matter decomposition, and overall river metabolism. The current work focuses on carbon dynamics in connection to organic matter transport and water quality rather than broader carbon cycle mechanisms (Liu et al., 2023; Li et al., 2025).

Sediment transport is a critical mechanism that connects upland erosion to downstream deposition, influencing channel structure, floodplain dynamics, and aquatic ecosystems. Suspended particles limit water clarity and light penetration while transporting nutrients, phosphate, trace metals, and organic material. Hillslope erosion, bank erosion, channel scour, and remobilisation of previously deposited material are all major contributors to sedimentation. Reservoirs in regulated river systems disrupt natural sediment continuity by retaining sediments upstream and limiting downstream sediment delivery. These alterations alter channel morphology, decrease floodplain fertility, limit reservoir storage capacity, and affect nutrient flow to downstream ecosystems (Kondolf et al., 2014).

The significant temporal variability of nutrient and sediment transport in river basins distinguishes it. In monsoon-dominated catchments, a significant share of yearly nutrient and sediment export occurs during a few high-flow periods. These episodic transport events frequently dominate annual load budgets and cause short-term degradation of water quality, such as eutrophication, hypoxia, and fish mortality. As a result, load-based assessments that combine concentration data with river discharge provide a more accurate depiction of nutrient and sediment transport than concentration measures alone, especially in highly seasonal river systems (Kim et al., 2021; Raghunath et al., 2026).

Overall, nutrient and sediment dynamics in river basins reflect complex interactions between hydrological processes, geomorphology, land use, agricultural activities, wastewater inputs, and river control. Understanding these interactions is critical for estimating nutrient and sediment loads, identifying pollution hotspots, assessing seasonal transport processes, and devising effective pollution control, river restoration, and long-term watershed management plans. Building upon the natural processes governing nutrient transport, anthropogenic activities have substantially altered nutrient cycling within most river basins, increasing both nutrient availability and downstream pollutant loads.

## 2.2. Human Influence on Natural Nutrient Cycling

The natural nutrient cycles in river basins are governed by interactions between geological weathering, soil formation, vegetation absorption, microbial processes, and hydrological transport. Under unrestricted conditions, these processes work in relative balance, with nutrients retained within the catchment through biological assimilation and soil storage, and only limited quantities exported to river systems. Human activities have significantly changed this balance by accelerating nutrient inputs, changing transport pathways, and disrupting natural retention and transformation mechanisms, leading to a widespread nutrient enrichment of inland and coastal waters (Cui et al., 2021; Tanaka et al., 2021).

One of the most important anthropogenic influences on the nutrient cycle is agricultural intensification. The widespread use of synthetic nitrogen and phosphorus fertilisers has greatly increased the availability of nutrients in soils and often exceeds crop harvest capacity. Excessive nutrients are easily mobilized through surface water runoff, soil erosion, and subsurface leaching, especially during rainfall events. Nitrogen, particularly in the form of nitrate, is highly mobile and can be transported through groundwater flow, contributing to sustained nutrient loading of rivers even during low-flow periods. Phosphorus losses are more closely associated with soil erosion and sediment transport, resulting in episodic but high-energy nutrient flows during storm and monsoon events. Numerous studies in temperate and tropical river basins have shown that agricultural catchments have significantly higher nutrient export rates compared to forested or minimally disturbed basins (Vitousek et al., 2009; Bouwman et al., 2011).

Urbanization is another major driver of the altered nutrient cycling. The expansion of urban areas increases impermeable surfaces, reduces infiltration, and increases stormwater flow, leading to a rapid transport of nutrients and organic matter to receiving waters. Municipal wastewater discharge, especially when treatment infrastructure is inadequate or overloaded, is a continuous source of nitrogen, phosphorus, and organic carbon in river systems. Even if secondary or tertiary treatment is implemented, residual nutrient concentrations in treated effluents can remain considerable on the basin scale. Urban stormwater discharge further contributes nutrients from atmospheric deposition, household waste, detergents, and organic waste, creating complex and spatially heterogeneous nutrient loading patterns in urban-influenced river habitats (Fan et al., 2025).

Industrial activity also changes the natural nutrient cycle, both directly and indirectly. Some industries emit nutrient-rich effluents containing ammonia, phosphates, and organic matter, while others indirectly contribute nutrients by changing land cover, water abstraction patterns, and flow regimes. Industrial effluents may introduce nutrients in chemical forms different from those derived from agricultural or domestic sources, affecting their bioavailability and their transformation pathways within river systems. In addition, co-discharge of contaminants, including trace metals and other industrial pollutants can inhibit the microbial processes responsible for nutrient cycling, thereby changing nitrification, denitrification, and decomposition of organic matter (Zaman et al., 2025).

Hydrological changes associated with dams, reservoirs, and water diversions have a profound impact on the nutrient cycle at the basin level. Reservoirs alter natural flow patterns, increase water residence time, and promote sedimentation, thereby increasing nutrient retention in impoundments. Although this can reduce downstream nutrient transport in some cases, reservoirs also function as zones of nutrient transformation and retention, where prolonged water residence times and sediment accumulation promote internal nutrient cycling. Under anoxic conditions, iron- and manganese-bound phosphorus may be released from bottom sediments, contributing to internal phosphorus loading. Stratification, anoxic bottom waters, and sediment-water interactions can result in the release of phosphorus and ammonium from sediments, which can then be exported during removal or high flow events. These processes disrupt natural upstream-downstream nutrient transport and complicate the prediction of nutrient loads under regulated flow conditions (Maavara et al., 2020; Yang et al., 2021).

Land use changes, especially deforestation and the conversion of natural landscapes into agriculture or urban land, further disrupt nutrient cycling by reducing vegetation cover, soil stability, and nutrient absorption capacity. The loss of river vegetation reduces natural buffer zones that absorb nutrients before reaching river channels, while increased soil exposure increases erosion and nutrient mobilization. In tropical river basins, deforestation combined with high precipitation intensity can dramatically increase the export of nutrients and sediments, which exceeds the assimilation capacity of river systems and downstream wetlands (Tikuye et al., 2023).

Globally, anthropogenic activities have substantially increased nitrogen and phosphorus fluxes to rivers, lakes, and coastal waters, resulting in widespread eutrophication and water quality degradation (Wurtsbaugh et al., 2019).

Overall, human activities modify nutrient cycling by increasing nutrient inputs, altering transport pathways, disrupting natural retention processes, and changing sediment-nutrient interactions. These changes increase nutrient and sediment loads, accelerate eutrophication, and degrade water quality. Understanding these processes is therefore essential for interpreting observed nutrient and sediment loads, identifying dominant pollution sources, and developing effective strategies for river restoration and sustainable watershed management.

### 2.3. Agricultural and Industrial context

Agricultural and industrial activities are two of the most influential anthropogenic drivers that shape the dynamics of nutrients and sediments in river basins. These sectors alter natural biogeochemical cycles by increasing nutrient inputs, transforming land cover and soil properties, modifying hydrological pathways, and generating both point-source and non-point-source pollution. The combined influence of agriculture and industry often results in complex spatial and temporal patterns of nutrient enrichment and sedimentation, especially in densely populated and economically active river basins (Kypritidou et al., 2024).

Agricultural land management practices strongly influence sediment transport and erosion. Planting operations, the removal of natural vegetation, and cultivation on slopes increase soil erosion and sediment delivery to nearby watercourses. In regions influenced by the monsoon, intense rainfall affecting exposed agricultural soils can produce substantial sediment yields over short periods. Irrigation practices, canal networks, and field drainage systems further alter the natural flow pathways, facilitating the rapid transport of sediments and dissolved nutrients from fields to river channels. Consequently, agricultural catchments often show significant seasonal variations in nutrient and sediment load, with a large proportion of annual exports occurring in a limited number of high-flow events (Oduor et al., 2023).

Industrial activities largely contribute to nutrient loading through point-source effluent discharges and urban-industrial runoff. Depending on the industrial procedures used, industrial effluents may contain high levels of nitrogen, phosphorus, organic waste, and suspended particles. Fertiliser manufacturing, food processing, chemical industries, and certain mineral-processing businesses are all significant sources of nutrient enrichment. Even when effluent treatment facilities are in place, inadequate removal of nutrients and suspended solids can lead to ongoing pollutant inputs to flowing waters, resulting in persistent water quality degradation and increased nutrient loads at the basin scale (Maupin & Ivahnenko, 2011).

Industrial growth is also associated with significant land modification, such as excavation, filling, and construction operations, which increase soil disturbance, sediment formation, and changes in natural drainage patterns. Industrial zones along river corridors frequently occupy floodplains and low-lying areas, diminishing natural sediment storage capacity and allowing the direct transport of sediments, fertilisers, and other industrial pollutants into river channels during storms. These mechanisms affect sediment transport dynamics, nutrient mobility and bioavailability, and the long-term buildup of pollutants in riverine and reservoir sediments (Das et al., 2025).

Hydropower reservoirs and dams further affect nutrient and sediment dynamics by controlling river discharge, trapping sediment, and modifying downstream transport processes. Increased water residence times promote sediment deposition and nutrient retention within reservoirs. In contrast, anoxic conditions at the sediment-water interface can stimulate the release of sediment-bound phosphorus by reducing iron and manganese oxides, thereby increasing internal phosphorus loading. As a result, reservoirs alter downstream nutrient and sediment budgets, complicate predictions of pollutant transport, and affect the ecological functioning of downstream river reaches and estuaries (Maavara et al., 2020).

The interaction between agricultural and industrial pressures can increase the nutrient and sedimentary effects at the basin level. In many river systems, non-point-source agricultural pollution dominates nutrient inputs during wet seasons, while industrial and urban point-sources provide continuous baseline loads throughout the year. This combination leads to both chronic nutrient enrichment and acute periodic loading, complicating water quality management and source distribution. Sediments transported from agricultural areas can absorb nutrients and industrial contaminants, facilitating their downstream transportation and long-term storage in river beds, reservoirs, and flood plains (Nuruzzaman et al., 2025).

At the basin level, the cumulative effects of agricultural intensification and industrial expansion often lead to changes in nutrient ratios, an increase in sediment flow, and disruptions in natural retention processes. These changes can reduce the assimilation capacity of river systems, promote eutrophication, and increase the frequency of water quality degradations. Reservoirs and impoundments can trap sediments and associated nutrients, modify downstream sediment transport, and create favourable conditions for internal nutrient loading through prolonged water residence times, sediment accumulation, and redox-driven phosphorus release (Maavara et al., 2020).

In general, the agricultural and industrial context of a river basin plays a central role in determining the loading patterns of nutrients and sediments. Therefore, effective interpretation of observed nutrient and sediment loads requires consideration of land-use practices, fertilizer application, industrial discharge characteristics, and hydrological variability. Basin-scale assessments that integrate agricultural and industrial influences are essential for identifying dominant sources, granting priority to mitigation measures, and supporting sustainable river basin management.

## 3. Sources of Nutrient and Sediment Loads

Nutrient and sediment load sources in river systems can be classified into two main types: point sources and non-point (diffuse) sources. This classification is based on the spatial characteristics of pollutant inputs and the pathways through which nutrients and sediments enter the river network. Point sources are linked to distinct, recognizable discharge sites, while non-point sources arise from extensive regions within the catchment and are mainly transported via runoff and erosion mechanisms. The proportional contributions of these two source types differ among river basins and hydrological conditions, affecting both the volume and duration of nutrient and sediment transport to rivers.

### 3.1. Point Sources

Point sources are specific and identifiable sites from which nutrients and sediments are directly released into river systems by pipelines, channels, or regulated discharges. These discharges are generally continuous or periodic and come from clearly defined sources, including municipal wastewater outfalls, industrial effluent discharge points, wastewater treatment facilities, and controlled releases from reservoirs or holding structures. Point sources, due to their localised characteristics, can generate significant spatial variations in water quality and can significantly affect river chemistry, especially under low-flow periods when dilution is constrained.

Municipal sewage discharge constitutes a major point source of nutrient loading in Indian rivers. Domestic wastewater typically contains elevated concentrations of ammonium, organic nitrogen, soluble phosphorus, and organic matter derived from human excretion and household activities (Bowes et al., 2020). In the Periyar River Basin, studies have identified untreated and partially treated domestic sewage as a significant contributor to nutrient enrichment, particularly in the downstream reaches near densely populated urban centres (Aditya et al., 2024).

Even when wastewater treatment facilities are functioning, processed effluents frequently constitute significant point sources at the basin level. Secondary and tertiary treatment methods reduce the organic load but may not eliminate dissolved nitrogen and phosphorus. Indian case studies indicate that effluents from wastewater treatment facilities often contain residual nitrate and phosphate, which lead to constant baseline nutrient loading when many outfalls flow into the same river system. In arid seasons, treated effluent can constitute a significant fraction of river flow, hence enhancing its impact on downstream nutrient levels and biological conditions (Zhang et al., 2021).

Industrial effluents constitute a complex group of point sources owing to their fluctuating composition and the chance for complex and variable pollutant composition. Effluents from fertiliser production, chemical businesses, food processing facilities, pulp and paper mills, and metal-processing sectors may exhibit high levels of nitrogen, phosphorus, suspended particles, and organic matter. The Eloor-Edayar industrial corridor along the Periyar River has been thoroughly examined and reported as a significant contributor to industrial pollution. Numerous studies have documented increased nutrient levels, suspended solids, and polluted sediments downstream of industrial discharge sites, signifying the continuing impact of industrial effluents on the quality of river water and sediments (Dsikowitzky et al., 2014; Arun et al., 2024).

Stormwater drainage systems in metropolitan areas may serve as point sources at their discharge locations. Stormwater runoff, produced across distributed urban surfaces, is frequently directed to rivers through concentrated outfalls. During precipitation events, these outfalls discharge surges of suspended sediments, particulate phosphorus, organic matter, and various contaminants deposited on roadways, building sites, and impermeable surfaces. Event-driven flows significantly contribute to short-term nitrogen and sediment loads in Indian urban waterways and can induce critical water quality degradation during monsoon seasons.

Regulated discharges from reservoirs, industrial retention basins, and managed canal systems represent an additional type of point-source input. These discharges can mobilise sediments and nutrient-laden streams that have accumulated during storage intervals. In regulated river systems, intermittent drawdown or emergency releases may transport concentrated amounts of suspended sediments, ammonium, and phosphorus downstream. Such releases may also remobilise sediment-bound phosphorus, particularly under changing redox conditions, contributing to internal nutrient loading downstream. Discharges of contaminated water into the Periyar River have been associated with sharp reductions in dissolved oxygen levels and reported events of fish mortality, highlighting the ecological importance of these uncommon point-source emissions (Aditya et al., 2024).

Point-source discharges are frequently associated with co-pollutants, including trace metals and synthetic organic compounds, which interact with nutrients and sediments in aquatic ecosystems. Some trace metals, particularly iron and manganese, influence phosphorus retention and release within sediments, whereas other metals primarily represent indicators of industrial contamination. Research on the Periyar-Vembanad system indicates that industrial point sources contribute to metal-laden sediments, which can adsorb phosphorus and organic matter, later serving as secondary sources during sediment resuspension. These interactions complicate nutrient cycling and extend water quality degradation beyond the duration of active discharge (Yao et al., 2024; Saravanan et al., 2024).

Point sources deliver concentrated and frequently predictable nutrient and sediment inputs to river systems; however, their effects can reach well beyond the immediate discharge locations. Understanding the location, volume, and composition of point-source discharges is crucial for analysing observed nutrient and sediment loads, especially in basins characterised by substantial urban and industrial growth.

### 3.2. Non-Point Sources (Diffuse Sources)

Non-point sources, also known as diffuse sources, originate from spatially scattered regions throughout the watershed, rather than from specific discharge points. Surface runoff, soil erosion, subsurface flow, and remobilization of stored materials are the main ways that nutrients and sediments from these sources enter river systems. In contrast to point sources, non-point inputs exhibit significant variability in both spatial and temporal dimensions, heavily influenced by rainfall intensity, land use, soil properties, and topographical features. Consequently, non-point sources frequently serve as the primary contributors to nutrient and sediment loads during periods of high flow and monsoonal conditions.

Agricultural lands are recognized as the predominant non-point source of nutrients in numerous river basins. Excessive use of nitrogen and phosphorus-based fertilisers, connected with insufficient crop absorption, results in nutrient buildup in soils. Surplus nutrients are mobilised during precipitation events through runoff and leaching. Nitrogen, especially as nitrate, is efficiently transmitted by subsurface flow and shallow groundwater, leading to a constant nutrient supply to rivers even beyond the monsoon season. Phosphorus losses are tightly associated with soil erosion and sediment movement, resulting in irregular yet significant nutrient fluctuations during rain events. Studies from Indian river basins repeatedly demonstrates that agricultural catchments discharge substantially greater nutrient loads than forested or lightly disturbed regions (Kronvang et al., 2020).

In Kerala and other areas adjacent to the Western Ghats, agricultural non-point source pollution is significantly affected by intense rainfall and steep topography. Farming on inclined terrains, monoculture methods, and regular soil exposure increase erosion rates and sediment transport to streams. Investigations of rivers in Kerala, particularly the Periyar basin, reveal that monsoon precipitation transports significant amounts of fine sediments and accompanying nutrients from agricultural lands, thereby significantly enhancing seasonal maximums in suspended sediment concentration and total phosphorus loads (Kumar et al., 2020).

Urban regions serve as substantial non-point sources of nutrients and sediments. Runoff from roads, rooftops, building sites, and open areas transfers sediments, organic matter, nutrients, and various pollutants into drainage systems. Monsoon storms can cause urban runoff to produce sudden overflows of suspended sediments and particle nutrients, especially from building sites and unpaved areas. Research on Indian urban rivers indicates that this runoff significantly contributes to brief but intense loading events that degrade downstream water quality (Shah & Joshi, 2017).

Deforestation and alterations in land use become additional non-point sources of nutrient and sediment discharge. The elimination of natural vegetation diminishes soil stability, degrades nutrient absorption, and increases vulnerability to erosion. The degradation of riparian buffers increases the direct influx of fertilisers and sediments into river channels. In tropical river basins, deforestation associated with heavy rainfall can significantly elevate sediment yields in short time periods. Research in the Western Ghats has identified that alterations in land cover have been associated with increased sediment transport and modified nutrient dynamics in downstream river segments (Sinha & Eldho, 2018).

Non-point sources also cause the remobilization of legacy nutrients and sediments retained in riverbeds, floodplains, and reservoirs. Sediments accumulated during previous high-load intervals frequently contain adsorbed sediment-bound phosphorus, organic nitrogen, and associated contaminants. Following floods or channel disturbances, these sediments may be resuspended and transferred downstream, serving as delayed nutrient sources. In the Periyar-Vembanad system, sediment analyses have exhibited that riverbed and floodplain sediments act as significant secondary nutrient sources, maintaining high concentrations despite diminished external inputs (Nisari & Sujatha, 2021). Non-point sources contribute diffuse yet significant nutrient and sediment load to river systems, frequently exceeding point sources in total annual export. Their dispersed characteristics, dependence on hydrology, and engagement with landscape processes make them especially difficult to assess and manage. Comprehending non-point source dynamics is essential for analysing basin-scale nutrient and sediment loads and for developing efficient catchment-level management strategies.

Because point and non-point sources differ significantly in temporal behaviour, spatial distribution, and transport mechanisms, identifying their respective contributions is critical for estimating nutrient and sediment loads. Point sources typically provide continuous baseline loads, but non-point sources dominate episodic transport during monsoon-driven runoff events. Quantifying these source-specific load contributions provides a scientific foundation for identifying pollution hotspots and prioritising basin-scale management efforts.

## 4. Current Status and Trends

The current status and long-term trends in sediment and nutrient dynamics in the Periyar River Basin shed light on the river system's changing hydrological and biological conditions. Monsoon variability, land-use changes, reservoir regulation, agricultural operations, and extreme hydro-meteorological events such as the 2018 Kerala floods all significantly impact sediment movement, nutrient loading, and water quality. Understanding these changes is critical for assessing watershed stability, nutrient transport pathways, reservoir sustainability, and the basin's overall ecological health. This section investigates the current state and temporal variability of sediment and nutrient dynamics in the Periyar River Basin utilising hydrological data, sediment load records, and relevant studies.

### 4.1. Surface Water Quality Assessment

Nutrient loads are important indicators of water quality and ecosystem health, as they indicate the amount of nutrients delivered through the river system over time. The Periyar River Basin's nutrient dynamics are regulated by agricultural operations, urban runoff, domestic wastewater, industrial discharges, and hydrological variability. The following section examines the primary nutrient parameters and their spatial distribution to determine potential sources, environmental implications, and management priorities for the basin.

Surface water quality assessment provides the basis for understanding the regional and seasonal variability of physicochemical conditions, nutrient dynamics, and organic contamination in the Periyar River Basin. A combination of natural hydrological processes, geological characteristics, land use, agricultural activities, urban development, industrial discharges, and climate variability determines river water quality. As a result, rigorous monitoring of key water quality indices is critical for assessing the river's biological status, detecting pollution hotspots, and understanding the processes governing nutrient transport and sediment-associated pollutant dynamics.

The present assessment is based on surface water quality data collected by the Kerala State Pollution Control Board (KSPCB) at monitoring stations throughout the Periyar River Basin during the pre-monsoon (April 2022), southwest monsoon (July 2022), and post-monsoon (November 2022) for the Nutrient Load estimation and the pre-monsoon (April 2025), southwest monsoon (July 2025), and post-monsoon (November 2025) for the recent surface water quality analysis. The selected monitoring periods capture the basin's key hydrological variables and enable assessment of seasonal changes in river discharge, runoff, and pollutant transport.

The examined parameters were divided into five groups for interpretation: (i) physicochemical characteristics, (ii) organic pollution indicators, (iii) nutrient parameters, (iv) microbiological indicators, and (v) supporting hydrochemical parameters. This classification offers a systematic framework for assessing water quality while focusing on the primary nutrients responsible for eutrophication, nitrogen and phosphorus.

In addition to concentration-based assessment, nutrient loads were estimated for nitrate-nitrogen ($NO_3$-N), ammonia-nitrogen ($NH_3$-N), total Kjeldahl nitrogen (TKN), and phosphate-phosphorus ($PO_4$-P) at the Kerala Water Authority (KWA) Intake (Location 8 in Figure 3), Aluva, using concurrent river discharge observations. The Neeleswaram gauge station of the Central Water Commission (CWC), which provides discharge data for the basin, is located approximately 26 km upstream along the river course; therefore, the KWA Intake at Aluva represents the nearest downstream location suitable for nutrient load estimation. The combined interpretation of nutrient concentrations and loads provides a more comprehensive understanding of nutrient transport, seasonal variability, and pollution dynamics than concentration data alone, thereby supporting basin-scale pollution assessment and management within the Periyar River Basin.

Table 2. Surface water sampling locations (KSPCB)

| Sl No | Location Name | Latitude | Longitude | Upstream/Downstream |
|---|---|---|---|---|
| 1 | R.Periyar Near Aluva- Eloor | 10.071905 | 76.281246 | Downstream |
| 2 | R.Periyar at Kalady | 10.158507 | 76.438102 | Downstream |
| 3 | Periyar at SDP Aluva | 10.100825 | 76.346109 | Downstream |
| 4 | Periyar at Muppathadam | 10.083386 | 76.319817 | Downstream |
| 5 | Periyar at Pathalam(Vettukadavu) | 10.080819 | 76.317908 | Downstream |
| 6 | Periyar at Kalamassery | 10.063382 | 76.311915 | Downstream |
| 7 | Periyar at Purappillikkadavu | 10.145934 | 76.279859 | Downstream |
| 8 | Periyar at KWA intake,Aluva,Ernakulam | 10.113842 | 76.360296 | Downstream |
| 9 | Periyar River at Kulamavu | 9.802226 | 76.886838 | Upstream |
| 10 | Periyar River at Panamkutty Bridge | 9.952175 | 76.980463 | Upstream |

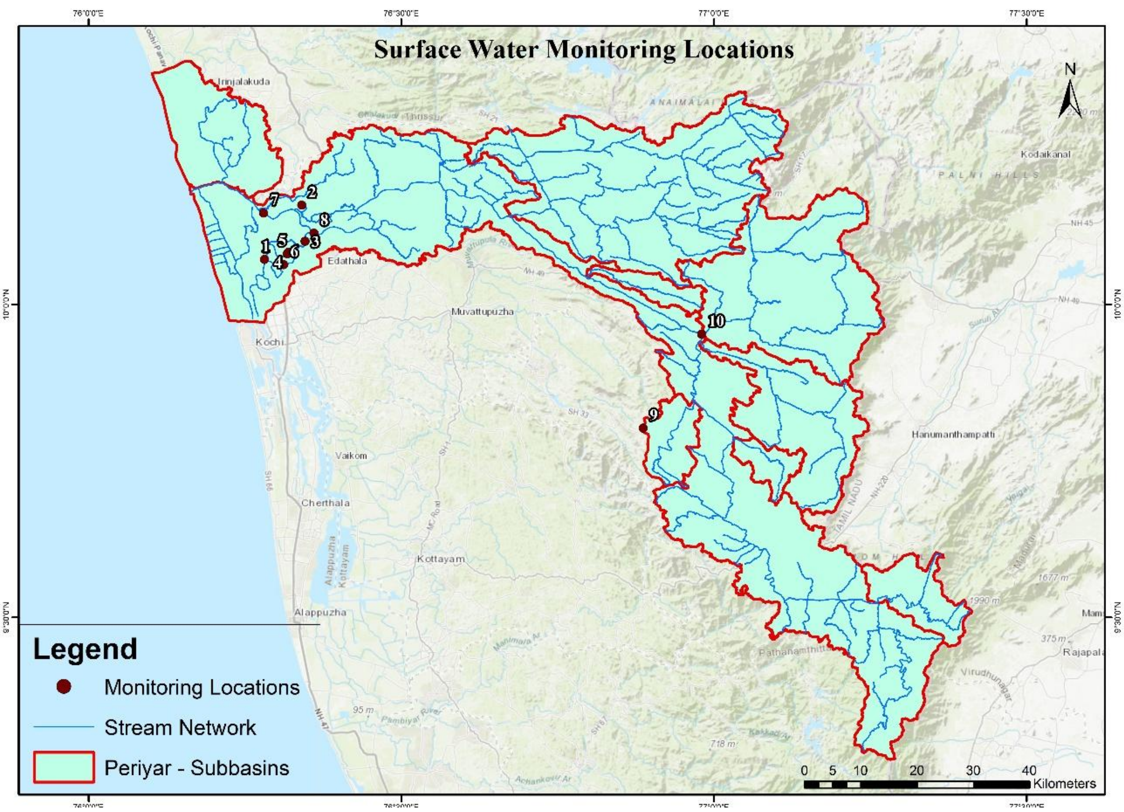


Figure 3. Surface water sampling locations in the Periyar River Basin

### 4.1.1. Physicochemical Characteristics

Physicochemical features give a fundamental understanding of the hydrochemical state of river systems, influencing nutrient transport, sediment dynamics, and overall water quality. pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, and total suspended solids (TSS) reflect the effects of natural geological processes, hydrological conditions, weathering, and human activities such as agriculture, urbanisation, and industrial development. Together, these parameters provide useful information about river water's chemical composition, sediment transport processes, and the potential impact of human activities on aquatic ecosystems.

The physicochemical status of the Periyar River Basin was evaluated using surface water quality data collected by the Kerala State Pollution Control Board (KSPCB) during the pre-monsoon (April 2025), southwest monsoon (July 2025), and post-monsoon (November 2025) seasons from monitoring stations located across the basin. The seasonal assessment enables the study of the influence of monsoonal hydrology on river water quality, as well as the identification of geographical and temporal differences driven by natural processes and anthropogenic activities. The observed values were compared to the applicable Central Pollution Control Board (CPCB) Designated Best Use Water Quality Criteria and the Bureau of Indian Standards (BIS IS 10500:2012) drinking water requirements, where applicable. Table 3 shows the parameters investigated in this category, together with their respective guideline values.

Table 3. Physicochemical parameters, permissible limits and regulatory references

| **Parameter** | **Unit** | **Permissible/Guideline Value** | **Regulatory Reference** |
|---|---|---|---|
| pH | - | 6.5–8.5 | CPCB Designated Best Use Criteria (Class A–C); BIS IS 10500:2012 |
| Electrical Conductivity (EC) | µS/cm | No specific CPCB standard | BIS IS 10500:2012 (Indirect indicator through TDS) |

| | | | |
|---|---|---|---|
| Total Dissolved Solids (TDS) | mg/L | 500 (acceptable); 2000 (permissible in absence of alternate source) | BIS IS 10500:2012 |
| Turbidity | NTU | 1 (acceptable); 5 (permissible) | BIS IS 10500:2012 |
| Total Suspended Solids (TSS) | mg/L | No CPCB/BIS standard for ambient river water | CPCB Water Quality Monitoring Protocol |

#### 4.1.1.1. pH

During the year 2025, the pH in the Periyar River Basin ranged from 6.3 to 8.7. Mean pH values were highest before the monsoon (7.70), declined during the southwest monsoon (6.87) due to rainfall-induced dilution and runoff, and slightly increased after the monsoon (7.07).

Most monitoring stations complied with the CPCB, and BIS suggested a pH range of 6.5-8.5. During the pre-monsoon, slightly alkaline (pH 8.6) and slightly acidic (pH 6.3) conditions were recorded at Periyar at Pathalam (July) and at Periyar at Aluva-Eloor (November).

The elevated pre-monsoon pH in the downstream industrial corridor could be attributed to reduced river flow, increased photosynthetic activity, and anthropogenic influences. In contrast, the lower pH observed during and after the monsoon is likely due to dilution, runoff, and increased decomposition of organic matter. Although these exceedances were minor, deviations from the permissible range can affect nutrient availability, metal solubility, and the efficiency of biological processes in aquatic environments. Overall, the pH values show that the river remained neutral to slightly alkaline, creating ideal conditions for aquatic species to flourish.

#### 4.1.1.2. Electrical Conductivity

Electrical conductivity (EC) is an indicator of water's total dissolved ionic content and accounts for geological weathering, salinity, wastewater discharge, industrial effluents, and agricultural runoff. EC values in the Periyar River Basin varied seasonally, ranging from 42-10,300 µS/cm during the pre-monsoon, 42-132 µS/cm during the southwest monsoon, and 44-200 µS/cm during the post-monsoon.

The highest EC values were routinely reported at Periyar at Pathalam (Vettukadavu), with an extraordinarily high value of 10,300 μS/cm during the pre-monsoon, followed by 132 μS/cm during the monsoon and 200 μS/cm during the post-monsoon period. The elevated pre-monsoon EC suggests a significant concentration of dissolved ions, most likely due to reduced river discharge and industrial and urban impacts in the downstream reach. In contrast, the sharp decrease in EC during the monsoon reflects dilution from rainfall and increased river discharge. In contrast, the mild increase during the post-monsoon suggests a steady increase in dissolved salt concentration as flow conditions stabilise. Although there is no explicit CPCB recommendation for EC in surface waters, the unusually high pre-monsoon value at Pathalam suggests localised ionic enrichment. It requires further investigation into suspected industrial effluent discharge, saline intrusion, or other anthropogenic causes.

#### 4.1.1.3. Total Dissolved Solids (TDS)

Total Dissolved Solids (TDS) are the concentrations of dissolved inorganic salts and organic matter in water and indicate the extent of mineralisation and anthropogenic influence. TDS levels in the Periyar River Basin varied from 30 to 7,500 mg/L during the pre-monsoon, 24-74 mg/L during the southwest monsoon, and 25-115 mg/L during the post-monsoon.

The highest TDS concentrations were observed at Periyar in Pathalam (Vettukadavu), reaching 7,500 mg/L during the pre-monsoon period, while R. Periyar near Aluva-Eloor also had an excessive concentration of 3,910 mg/L. These findings are far above the BIS tolerable level of 500 mg/L and the permissible limit of 2,000 mg/L for drinking water, indicating a significant dissolved salt enrichment in the downstream industrial stretch. During the southwest monsoon and post-monsoon periods, TDS levels at all monitoring stations were substantially below the permissible range due to increased river discharge and rainfall.

The very high pre-monsoon TDS levels recorded at Pathalam and Aluva-Eloor point to localised anthropogenic influences, which could be due to industrial effluent outflow, urban wastewater inputs, or saline water intrusion in the basin's lower reaches. In contrast, the generally low TDS values reported during the monsoon and post-monsoon periods indicate high water quality throughout the basin and demonstrate the major influence of seasonal hydrology on dissolved ion concentration.

#### 4.1.1.4. Turbidity

Turbidity is an essential indicator of suspended particulate matter in water, reflecting the effects of soil erosion, surface runoff, sediment transport, and anthropogenic disturbances within a river basin. Turbidity levels in the Periyar River Basin ranged from 1.0 to 2.1 NTU pre the monsoon, 1.0 to 5.8 NTU during the southwest monsoon, and 1.0 to 3.5 NTU post the monsoon.

The southwest monsoon produced the highest turbidity levels, with a maximum of 5.8 NTU reported at Periyar in Kalamassery, exceeding the BIS-premissible limit of 5 NTU for drinking water. Turbidity was also elevated at SDP Aluva (4.5 NTU), Kalady (4.3 NTU), and Muppathadam (4.2 NTU), showing that sediment was transported more efficiently during the monsoon. Turbidity levels at all monitoring stations stayed within BIS guidelines during the pre- and post-monsoon seasons.

Turbidity levels rise during the monsoon season due to increased surface runoff, bank erosion, and the transport of fine sediments from agricultural and urban areas. Localised anthropogenic disturbances in the downstream industrial corridor may contribute to higher turbidity levels. Turbidity increases in the Periyar River Basin, reducing light penetration, limiting primary productivity, and facilitating the transfer of sediment-bound nutrients and pollutants, all of which influence water quality and eutrophication processes.

#### 4.1.1.5. Total Suspended Solids (TSS)

Total Suspended Solids (TSS) quantify the concentration of suspended particulate matter in the water column and are essential indicators of sediment transport, erosion, and particulate pollution. TSS concentrations in the Periyar River Basin varied from 10 to 19 mg/L before the monsoon, 10-15 mg/L during the southwest monsoon, and 10-27 mg/L after the monsoon.

The highest TSS concentrations were found at the Periyar River at Panamkutty Bridge (19 mg/L) during the pre-monsoon, at Muppathadam (15 mg/L) during the southwest monsoon, and at Kalady (27 mg/L) during the post-monsoon. The lowest TSS content (10 mg/L) was continuously reported at R. Periyar near Aluva-Eloor, indicating that suspended sediment levels are minimal there.

Although there is no precise CPCB or BIS guideline value for TSS in surface waters, the observed amounts indicate that suspended sediment levels are generally low across the basin. The localised increase after the monsoon season, particularly at Kalady, could be due to residual runoff, bank erosion, and remobilisation of deposited sediments. Since suspended particles carry particulate nutrients, organic matter, and other contaminants, higher TSS can enhance the downstream transport of sediment-bound pollutants and alter river water quality. Overall, TSS levels indicate moderate sediment transport conditions, with localised increases reflecting seasonal hydrological processes rather than widespread sediment pollution.

### 4.1.2. Organic Pollution Indicators

Organic pollution indicators provide important information on the ecological health of river systems and the impact of biodegradable and non-biodegradable organic waste on water quality. Dissolved oxygen (DO), biochemical oxygen demand (BOD), and chemical oxygen demand (COD) are commonly used parameters for assessing the oxygen balance of aquatic ecosystems and determining the effects of domestic sewage, industrial effluents, agricultural runoff, and other human activities. Together, these parameters describe the extent of organic contamination and a river's capacity to support aquatic life.

The organic pollution status of the Periyar River Basin was determined using surface water quality data obtained from the Kerala State Pollution Control Board (KSPCB) during the pre-monsoon (April 2025), southwest monsoon (July 2025), and post-monsoon (November 2025) seasons. The observed values were compared to the relevant Central Pollution Control Board (CPCB) Designated Best Use Water Quality Criteria and Bureau of Indian Standards (BIS IS 10500:2012) criteria, wherever applicable. Table 4 shows the parameters considered in this category, together with their respective recommended values.

Table 4. Organic pollution indicators and guideline values used for assessment

| **Parameter** | **Unit** | **CPCB Designated Best Use Water Quality Criteria*** |
|---|---|---|
| Dissolved Oxygen (DO) | mg/L | ≥ 6 (Class A); ≥ 5 (Class B); ≥ 4 (Class C) |
| Biochemical Oxygen Demand | mg/L | ≤ 2 (Class A); ≤ 3 (Class B & C) |
| Chemical Oxygen Demand (COD) | mg/L | No prescribed CPCB criterion for ambient surface water |

*Source: Central Pollution Control Board (CPCB). Water Quality Standards - Designated Best Use Water Quality Criteria (Updated: 11 October 2019), Ministry of Environment, Forest and Climate Change, Government of India.

#### 4.1.2.1. Dissolved Oxygen (DO)

Dissolved oxygen (DO) is a key indicator of river ecosystem health because it indicates the balance between oxygen replenishment and oxygen consumption caused by organic matter decomposition. DO values in the Periyar River Basin varied from 5.5-7.7 mg/L during the pre-monsoon to 5.8-8.8 mg/L during the southwest monsoon, showing that the basin was generally well-oxygenated.

The lowest DO concentration (5.5 mg/L) was measured at R. Periyar (near Aluva – Eloor). During the pre-monsoon season, Periyar near Aluva-Eloor had relatively low DO (5.8 mg/L), and Periyar at Kalamassery did as well. The highest DO concentration (8.8 mg/L) was recorded in the Periyar at Purappillikkadavu during the southwest monsoon, indicating enhanced aeration due to increased river discharge and turbulent flow.

Throughout the study period, all monitoring stations met the CPCB Class C requirement of ≥4 mg/L, suggesting acceptable dissolved oxygen levels for aquatic life. However, DO readings below the Class A criteria (≥6 mg/L) at downstream locations, particularly in the Aluva-Eloor and Kalamassery reaches, indicate localised oxygen depletion caused by domestic sewage, industrial effluents, and organic pollution. The higher DO concentrations observed during the southwest monsoon indicate that enhanced river discharge and atmospheric reaeration improve the oxygen availability in the river water.

#### 4.1.2.2. Biochemical Oxygen Demand (BOD)

Biochemical Oxygen Demand (BOD) is a measure of biodegradable organic pollution that represents the amount of dissolved oxygen bacteria require to degrade organic materials. BOD readings in the Periyar River Basin ranged from 1.2 to 3.3 mg/L across monitoring stations, indicating mild to moderate organic pollution.

The majority of monitoring stations met the CPCB Designated Best Use standard (≤3 mg/L) during the study period. However, during the southwest monsoon, the BOD concentration in Periyar near Purappillikkadavu was 3.3 mg/L, slightly above the CPCB threshold. During the pre-monsoon, Periyar at SDP Aluva (2.8 mg/L) had a higher BOD value than Periyar at Kalamassery (2.4 mg/L), indicating localised organic loading in the downstream urban-industrial stretch.

The basin's generally low BOD levels indicate limited biodegradable organic pollutants and a good assimilation capacity of the river. The localised rise in BOD at downstream sites is most likely caused by domestic sewage, urban runoff, and industrial activity. In contrast, the minor increase in BOD at Purappillikkadavu during the monsoon may be attributable to the transport of organic matter through surface runoff. Overall, the BOD results show that organic contamination is localised rather than widespread in the Periyar River Basin.

#### 4.1.2.3. Chemical Oxygen Demand (COD)

Chemical Oxygen Demand (COD) is a measure of the total oxygen required to oxidise both biodegradable and non-biodegradable organic materials in water. COD readings in the Periyar River Basin varied from 5.0 to 8.8 mg/L during the pre-monsoon and 5.0 to 9.6 mg/L during the southwest monsoon, indicating that oxidisable pollutants were typically low across the basin.

The highest COD content (9.6 mg/L) was found at Periyar at Purappillikkadavu during the southwest monsoon, followed by Periyar at Pathalam (8.8 mg/L) during the pre-monsoon and Periyar River at Panamkutty Bridge (8.0 mg/L) during the southwest monsoon. The majority of the remaining monitoring sites reported COD levels ranging from 5 to 8 mg/L, indicating relatively low levels of organic and chemical contamination.

Although no CPCB guideline value for COD in ambient surface waters has been defined, the relatively higher values observed at Purappillikkadavu and Pathalam suggest localised inputs of oxidisable organic matter, potentially from domestic sewage, industrial discharges, or surface runoff during the monsoon. Overall, the basin's low to moderate COD values indicate minimal organic pollution and are consistent with the generally favourable dissolved oxygen conditions observed during the sampling period.

### 4.1.3. Nutrient Load Assessment

Nutrient concentrations give useful information on water quality at the time of sampling; however, they do not measure the total amount of nutrients transported by the river. Nutrient load estimation combines nutrient concentration with river discharge to provide a more complete picture of nutrient transport and export within a river basin. Unlike concentration-based assessments, nutrient loads account for fluctuations in streamflow and therefore better represent the amount of nutrients transported to downstream ecosystems, especially during high-flow events. As a result, load estimation is widely regarded as a more reliable method for identifying pollution hotspots, assessing seasonal nutrient transport, and supporting river basin management.

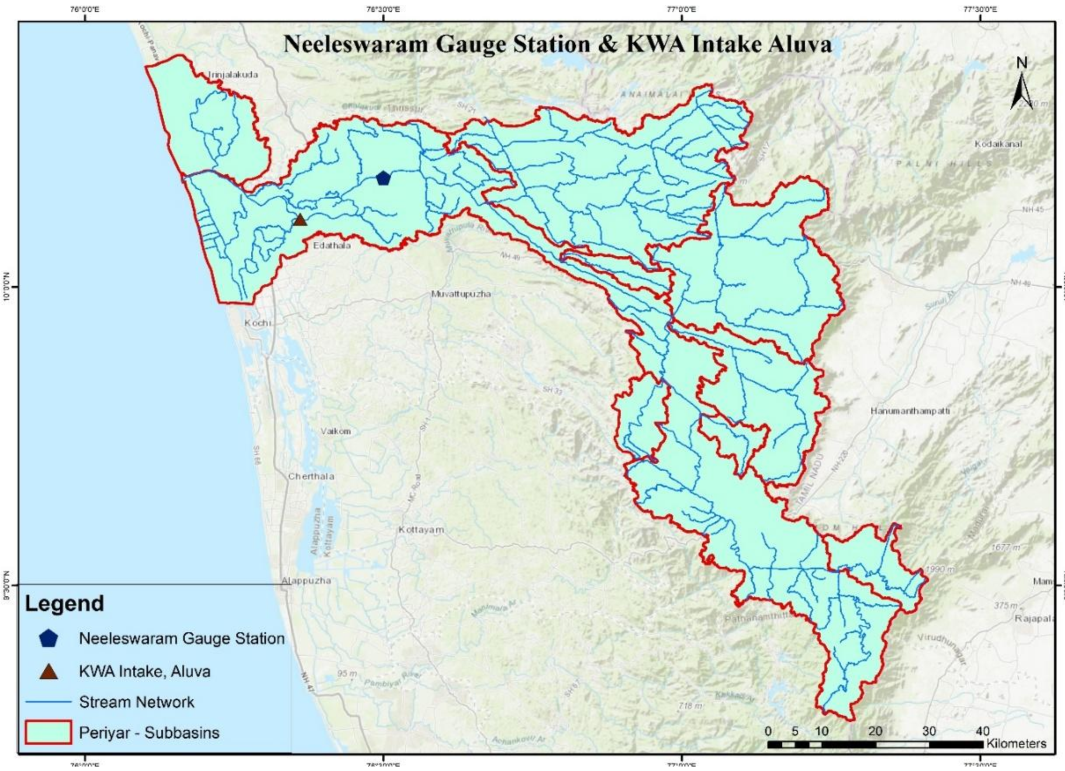


Figure 4. Gauge station and Water Quality monitoring point for nutrient load estimation

The present study assessed instantaneous nutrient loads at the Kerala Water Authority (KWA) Intake in Aluva (Figure 4), which is directly downstream of the CWC river discharge measuring station at Neeleswaram. This site was chosen because it incorporates cumulative upstream fertiliser inputs from the Periyar River Basin while allowing nutrient concentrations to be directly linked to contemporary discharge observations. Water quality data from pre-monsoon (April 2022), southwest monsoon (July 2022), and post-monsoon (November 2022) sampling campaigns were used to estimate nutrient loads for $NO_3$-N, $NH_3$-N, TKN, and $PO_4$-P. Parameters reported as below the analytical detection limit (BDL) were retained at BDL, and associated nutrient loads were not calculated.

#### 4.1.3.1. Estimation of Nutrient Loads

Instantaneous nutrient loads were estimated by integrating the measured nutrient concentrations with the corresponding river discharge observed at the Kerala Water Authority (KWA) Intake, Aluva. The calculations were carried out for nitrate-nitrogen ($NO_3$–N), ammonia-nitrogen ($NH_3$–N), total Kjeldahl nitrogen (TKN), and phosphate-phosphorus ($PO_4$–P) using the relationship:

$$Load\ (kg/day) = C \times Q \times 86.4$$

Where:

C - Measured nutrient concentration in the river water (mg/L)

Q - River discharge at the CWC gauge station, Neeleswaram ($m^3/s$)

86.4 - Unit conversion factor used to convert the product of concentration (mg/L) and discharge ($m^3/s$) into nutrient load expressed as kilograms per day (kg/day). The factor is derived from the conversion of cubic metres to litres (1 $m^3$ = 1000 L) and seconds to days (1 day = 86,400 s).

Table 5 presents the predicted instantaneous nutrient loads at the Kerala Water Authority (KWA) Intake in Aluva. The estimates represent the amount of nutrients transported by the river at the time of sampling, giving a direct assessment of nutrient export from the upstream watershed. Unlike concentration measurements, which reveal the nutrient status of water at a specific point, load estimations include river discharge and hence account for seasonal fluctuations in streamflow. As a result, nutrient loads provide a more accurate assessment of nutrient transport. They are especially valuable for detecting periods of increased nutrient export and for supporting pollution management measures.

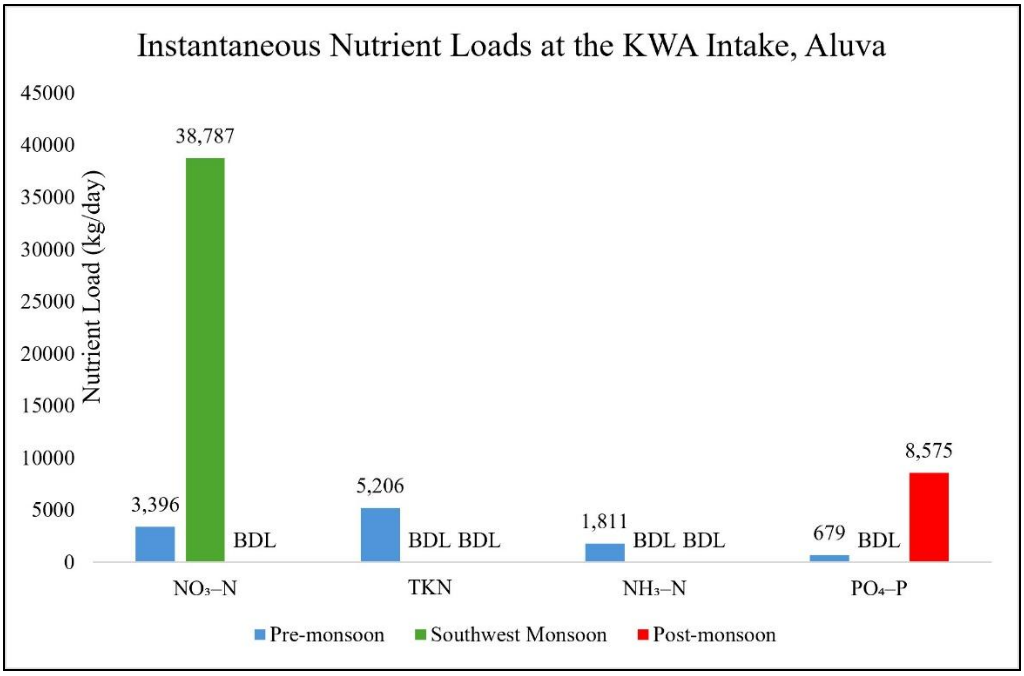


Figure 5. Instantaneous nutrient loads at the KWA Intake, Aluva (2022)

Table 5. Estimated instantaneous nutrient loads at the Kerala Water Authority (KWA) Intake, Aluva

| Sampling Season | Discharge ($m^3/s$) (2022) | $NO_3$–N (mg/L) | $NO_3$–N Load (kg/day) | TKN (mg/L) | TKN Load (kg/day) | $NH_3$–N (mg/L) | $NH_3$–N Load (kg/day) | $PO_4$–P (mg/L) | $PO_4$–P (kg/day) |
|---|---|---|---|---|---|---|---|---|---|
| Pre-monsoon | 262.0 | 0.15 | 3,395.52 | 0.23 | 5,206.46 | 0.08 | 1,810.94 | 0.03 | 679.10 |
| Southwest Monsoon | 774.0 | 0.58 | 38,786.69 | BDL | BDL | BDL | BDL | BDL | BDL |
| Post-monsoon | 236.3 | BDL | BDL | BDL | BDL | BDL | BDL | 0.42 | 8,574.85 |

***BDL:*** *Below Detection Limit. Nutrient loads were not estimated for parameters reported below the analytical detection limit.*

#### 4.1.3.2. Seasonal Variation in Nutrient Loads

The estimated nutrient loads varied significantly with the season, reflecting changes in river discharge rather than in nutrient concentrations alone (Table 5). During the pre-monsoon, low river discharge (262.0 $m^3/s$) led to moderate instantaneous loads of nitrate (3,395.52 kg/day), total Kjeldahl nitrogen (5,206.46 kg/day), ammonia (1,810.94 kg/day), and phosphate (679.10 kg/day).

The southwest monsoon had the largest river discharge (774.0 $m^3/s$), leading to a significant rise in nitrate load to 38,786.69 kg/day, although nitrate concentration increased only slightly. This indicates the major role of streamflow in nutrient transfer, as strong monsoonal discharge significantly increases the mass of nutrients exported downstream. However, TKN, ammonia, and phosphate concentrations during this period were reported to be below the analytical detection limit (BDL), rendering quantification of the associated nutrient loads impossible.

During the post-monsoon, river discharge reduced to 236.3 $m^3/s$, with only phosphate measured, resulting in an instantaneous load of 8,574.85 kg/day. The remaining nutritional parameters were reported using BDL. The increased phosphate load despite the decreased discharge reflects the substantially higher observed phosphate concentration during this sampling period, demonstrating that nutrient concentration can have a considerable impact on load estimates even under low-flow conditions.

Overall, the findings show that the interplay between nutrient concentrations and river discharge strongly influences nutrient transport in the Periyar River Basin. High-flow conditions during the southwest monsoon significantly increase downstream nutrient export, emphasising the need to include discharge in water quality studies. The findings emphasise that concentration-based estimates alone may underestimate the magnitude of nutrient transfer. In contrast, load estimation provides a more accurate basis for assessing nitrogen export and supporting river basin management.

### 4.1.4. Microbiological Indicators

Microbiological indicators (Table 6) are commonly used to determine the hygienic status of surface waters and to detect contamination from human and animal feces. The presence of indicator organisms, such as total and faecal coliforms, suggests potential contamination from untreated or partially treated domestic sewage, livestock waste, and urban runoff. Elevated microbiological contamination endangers public health, especially in areas where river water is used for drinking, leisure, irrigation, and other domestic purposes.

The microbiological health of the Periyar River Basin was assessed using total coliform and faecal coliform concentrations collected by the Kerala State Pollution Control Board (KSPCB) during the pre-monsoon (April 2025), southwest monsoon (July 2025), and post-monsoon (November 2025) seasons. The observed results were compared with the Central Pollution Control Board's (CPCB) Designated Best Use Water Quality Criteria to assess the river's sanitary condition and identify sites of faecal pollution. Table 6 shows the parameters considered in this category, along with the corresponding guideline values.

Table 6. Microbiological indicators and guideline values

| Parameter | Unit | CPCB Designated Best Use Water Quality Criteria* |
|---|---|---|
| Total Coliform | MPN/100 mL | ≤ 50 (Class A); ≤ 500 (Class B); ≤ 5,000 (Class C) |
| Fecal Coliform | MPN/100 mL | No separate CPCB criterion |

**Source**: Central Pollution Control Board (CPCB). Water Quality Standards - Designated Best Use Water Quality Criteria (Updated 11 October 2019).

Note: The CPCB Designated Best Use Criteria specify Total Coliform as the microbiological indicator for classifying surface water. Fecal coliform results are interpreted as supplementary evidence of fecal contamination.

#### 4.1.4.1. Total Coliform

Total coliform concentrations varied significantly across space and over time within the Periyar River Basin. During the pre-monsoon period, total coliform counts ranged from 1,800 to 21,000 MPN/100 mL, with the maximum concentration observed at SDP Aluva in Periyar. Elevated counts were also recorded in Periyar near Aluva-Eloor (7,000 MPN/100 mL), Periyar at Pathalam (7,000 MPN/100 mL), and Periyar at Kalamassery (5,800 MPN/100 mL), all exceeding the CPCB Class C criteria of 5,000 MPN per 100 mL.

During the southwest monsoon, total coliform values fell dramatically, ranging from 1,500 to 5,400 MPN/100 mL, with only Periyar at Purappillikkadavu (5,400 MPN/100 mL) above the CPCB threshold. Similarly, during the post-monsoon period, concentrations ranged from 1,200 to 6,000 MPN/100 mL, with Periyar at Purappillikkadavu (6,000 MPN/100 mL) being the only station that exceeded the required limit, while Periyar at SDP Aluva (5,000 MPN/100 mL) was exactly at the Class C level.

The higher total coliform counts in the downstream reaches indicate localised fecal contamination from domestic sewage discharge, urban runoff, and human activities. The lower concentrations during the southwest monsoon indicate dilution caused by increased river discharge. In contrast, the higher pre-monsoon counts reflect less dilution due to low-flow conditions. Overall, microbiological pollution was confined to the downstream urban-industrial region of the Periyar River Basin.

#### 4.1.4.2. Fecal Coliform

Fecal coliform values ranged from 260 to 7,900 MPN/100 mL before the monsoon, 200 to 2,400 MPN/100 mL during the southwest monsoon, and 100 to 1,700 MPN/100 mL after the monsoon. Periyar at SDP Aluva had the highest quantities (7,900 MPN/100 mL) during the pre-monsoon, followed by Periyar at Purappillikkadavu during the southwest monsoon (2,400 MPN/100 mL) and post-monsoon (1,700 MPN/100 mL).

Although the CPCB Designated Best Use Criteria do not provide a distinct guideline value for fecal coliform, increased counts at downstream stations support the total coliform results and point to the influence of untreated or partially treated sewage and other fecal sources. The decrease in fecal coliform concentrations during the monsoon and post-monsoon seasons is most likely due to dilution from increasing river discharge. The persistence of elevated fecal indicator bacteria at Purappillikkadavu and along the Aluva-Eloor stretch emphasises the importance of ongoing monitoring and improved control of wastewater discharges in the basin's downstream reaches.

### 4.1.5. Supporting Hydrochemical Parameters

Supporting hydrochemical parameters give information on the overall chemical composition of river water and help assess the impact of geological formations, weathering processes, anthropogenic activities, and seasonal hydrological changes on water quality. Total alkalinity, total hardness, calcium, magnesium, chloride, sulphate, and sodium indicate the river's intrinsic geochemical characteristics, as well as potential inputs from domestic wastewater, industrial effluents, agricultural runoff, and saltwater intrusion. Although these metrics are not the primary indicators of eutrophication, they provide useful information on the hydrochemical properties and overall water quality of the Periyar River Basin.

The supporting hydrochemical parameters were assessed using data gathered by the Kerala State Pollution Control Board (KSPCB) during the pre-monsoon (April 2025), southwest monsoon (July 2025), and post-monsoon (November 2025) seasons. The observed values were compared to the Bureau of Indian Standards (BIS IS 10500:2012) drinking water requirements, when applicable.

Hydrochemical parameters such as total alkalinity, chloride, total hardness, calcium, magnesium, sulphate, and sodium were examined to assess the overall chemical composition of the Periyar River Basin and to identify potential influences of geological weathering and anthropogenic activities. Overall, these measures showed noticeable seasonal variation, with concentrations relatively higher during the pre-monsoon and significantly lower during the southwest monsoon, due to dilution from increased river discharge.

Total alkalinity remained low and reasonably uniform during the research period, ranging from 20-30 mg/L during the pre-monsoon, 20-24 mg/L during the southwest monsoon, and 20 mg/L during the post-monsoon, showing limited buffering capability but constant carbonate chemistry across the basin.

The supporting hydrochemical parameters, chloride, total hardness, calcium, magnesium, sodium, and sulphate, revealed significant regional variation. During the pre-monsoon, chloride concentrations reached 3,543 mg/L, total hardness 1,500 mg/L, calcium 1,000 mg/L, magnesium 500 mg/L, sodium 1,900 mg/L, and sulphate 255 mg/L. The detected chloride, hardness, calcium, magnesium, and salt contents were significantly above the permissible limits set by BIS IS 10500:2012, indicating a localised decline in water quality. In contrast, concentrations at the remaining monitoring stations were generally within the allowed limits. They declined significantly throughout the southwest monsoon and post-monsoon periods, indicating the influence of monsoonal dilution.

The increased concentrations recorded at Pathalam are most likely due to localised anthropogenic impacts, such as industrial effluent discharge and saline water intrusion in the basin's downstream reaches. The fast drop in concentrations during the monsoon suggests that the elevated values are local rather than basin-wide. Overall, the supporting hydrochemical data indicate that the Periyar River Basin has good hydrochemical quality, with localised issues limited to the downstream industrial corridor.

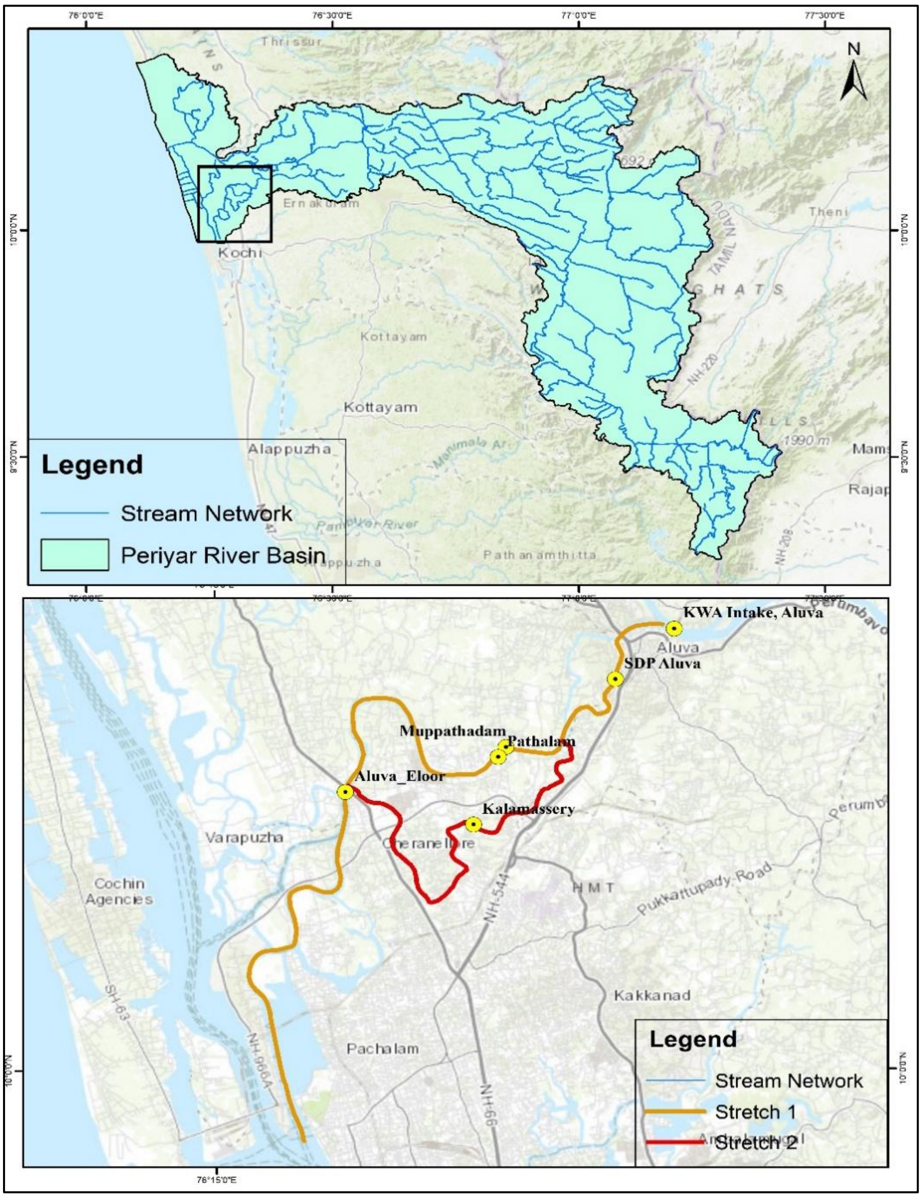


Figure 6. Probable stretches with high organic and nutrient loading

Figure 6 illustrates the probable stretches of the main stem of the Periyar River identified as experiencing nutrient loading based on the analysis of nutrient concentrations. These stretches represent potential nutrient hotspots and indicate priority areas for enhanced monitoring, pollution control, and river restoration interventions.

Figure 7. Field photographs illustrating water hyacinth infestation at selected locations along the Periyar River representing potential nutrient-rich environments

### 4.1.6. Groundwater Analysis

Groundwater quality assessment is critical for determining the appropriateness, sustainability, and ecological condition of subsurface water resources in a river basin. Groundwater in the Periyar River Basin is an important supply of water for household, agricultural, and industrial uses. However, rising anthropogenic pressures, such as agricultural runoff, industrial operations, urbanisation, waste disposal, and excessive groundwater extraction, can have a substantial impact on groundwater quality and hydrochemical properties. The hydrogeological environment of the Periyar basin, combined with extensive interactions between surface water and groundwater systems, makes groundwater particularly susceptible to contamination and nutrient enrichment in some areas.

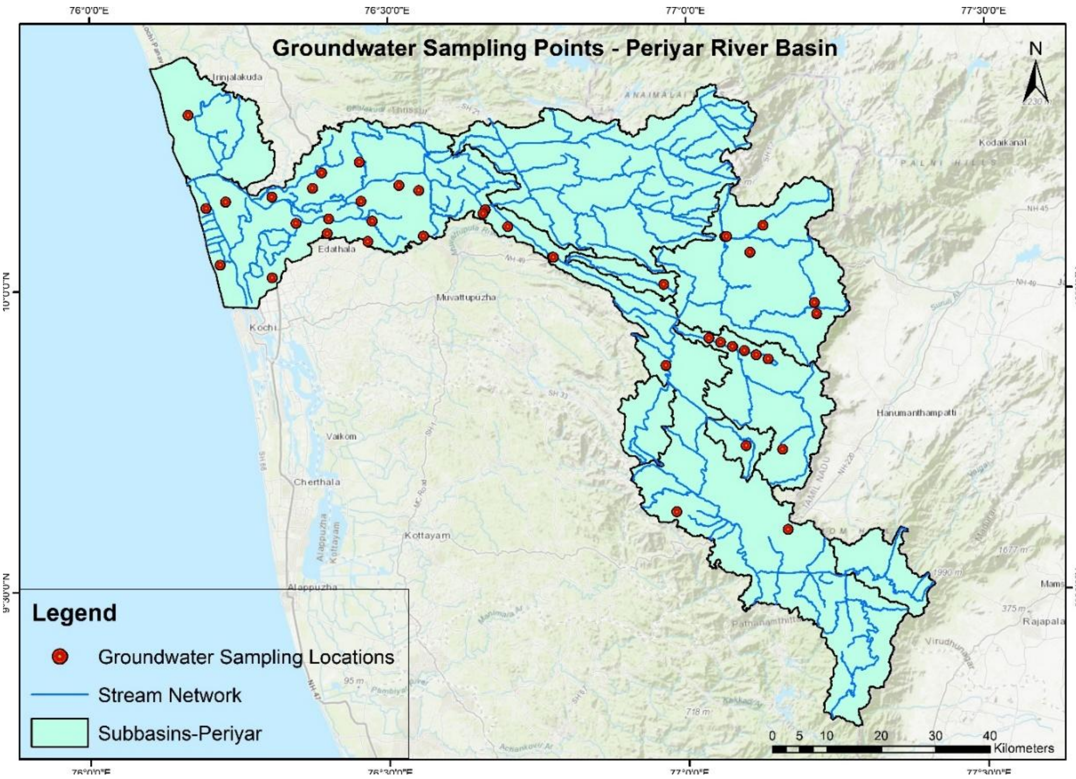


Figure 8. Groundwater sampling locations in the Periyar River Basin

Secondary groundwater quality data from the Kerala State Pollution Control Board (KSPCB) were evaluated to assess groundwater's potential contribution to nutrient loading in the Periyar River Basin. Groundwater is an essential hydrological conduit that transports dissolved nutrients, especially nitrogen species, to rivers via baseflow, thereby enriching rivers even during low-flow periods. As a result, the study focused primarily on nutrient-related factors, such as nitrate and ammonia, as well as other physicochemical features that influence nutrient mobility and groundwater quality. Microbiological markers and heavy metals were used as additional metrics to detect localised contamination and assess the overall appropriateness of groundwater resources. The observed values were compared to drinking water specifications from the Bureau of Indian Standards (BIS IS 10500:2012) and other relevant guideline values, if applicable. This examination improves understanding of groundwater quality, identifies potential pathways of nutrient contamination, and aids in interpreting nutrient loading into the Periyar River.

Table 7. Parameters analysed for groundwater samples - KSPCB

| Sl. No | Parameter | Unit | Acceptable Limit | Permissible Limit |
|---|---|---|---|---|
| 1 | pH | — | 6.5 – 8.5 | No relaxation |
| 2 | EC | µS/cm | — *(not specified)* | — |
| 3 | TDS | mg/L | 500 | 2000 |
| 4 | Chloride ($Cl^-$) | mg/L | 250 | 1000 |
| 5 | Iron (Fe) | mg/L | 0.3 | No relaxation |
| 6 | Sulphate ($SO_4^{2-}$) | mg/L | 200 | 400 |
| 7 | Sodium ($Na^+$) | mg/L | — *(not specified)* | — |
| 8 | Potassium ($K^+$) | mg/L | — *(not specified)* | — |
| 9 | Calcium ($Ca^{2+}$) | mg/L | 75 | 200 |
| 10 | Magnesium ($Mg^{2+}$) | mg/L | 30 | 100 |
| 11 | Alkalinity (as $CaCO_3$) | mg/L | 200 | 600 |
| 12 | Fluoride ($F^-$) | mg/L | 1.0 | 1.5 |
| 13 | Total Hardness (as $CaCO_3$) | mg/L | 200 | 600 |
| 14 | Nitrate ($NO_3^-$) | mg/L | 45 | No relaxation |

### 4.1.6.1. Pre-monsoon

Pre-monsoon groundwater samples from the Periyar basin showed pH fluctuations ranging from alkaline (>8.5) to acidic (<6.5), indicating a diverse hydrogeochemical environment under limited recharge conditions. The acidic nature observed mostly in upstream parts can be attributed to significant lateritic soil leaching, organic acid accumulation, and prolonged water-rock interaction, all of which are characteristics of the Western Ghats topography. Localised alkaline conditions in both upstream and downstream locations may be caused by carbonate mineral dissolution, ion exchange processes, and anthropogenic inputs such as home wastewater and agricultural return flows. During the pre-monsoon period, limited dilution and extended residence time improve geochemical controls, resulting in regional heterogeneity in groundwater pH (Natesan et al., 2022).

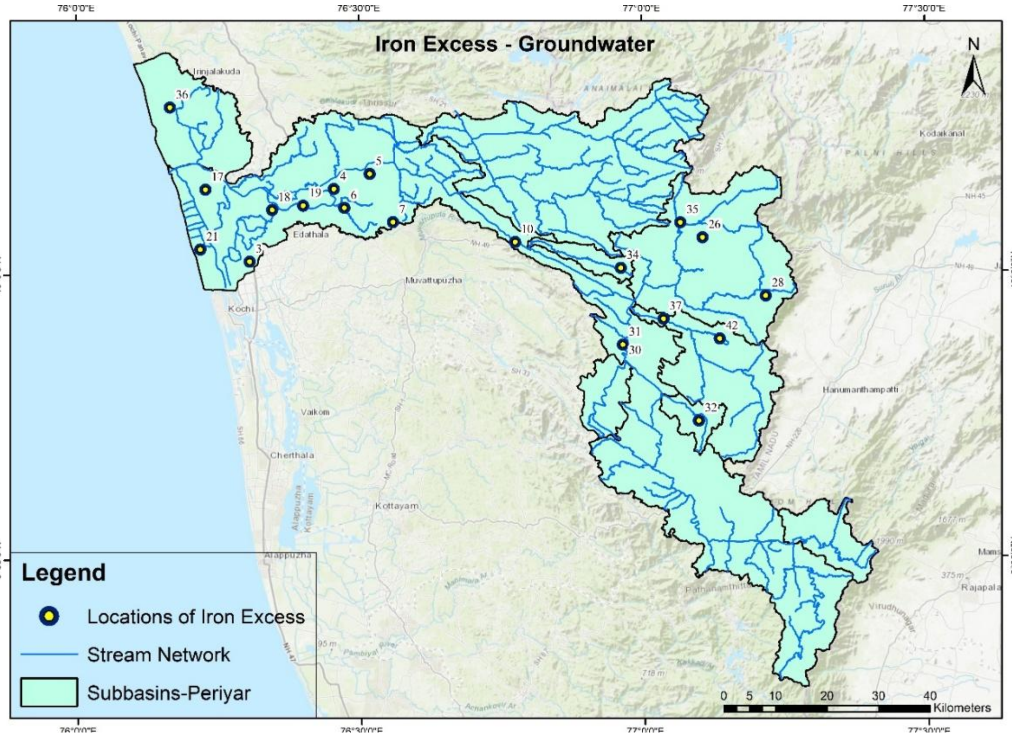


Figure 9. Locations with excess iron concentration in groundwater

Iron (Fe) contents in the majority of samples above permissible limits (Figure 9), indicating that pre-monsoon groundwater in the Periyar basin is primarily iron-rich. This is mostly determined by geogenic processes, such as the weathering of iron-rich lateritic formations and the reductive dissolution of iron-bearing minerals in low oxygen environments. The pre-monsoon period, marked by sluggish groundwater conditions and low recharge, encourages the formation of reducing environments, which increases iron solubility. Furthermore, the presence of organic matter in the soil and human inputs might speed up iron mobilisation. The widespread distribution in both upstream and downstream areas indicate strong lithological control, with possibly secondary contributions from sewage infiltration and localised industrial activities (Kumar et al., 2020; Giri et al., 2023).

Although most other metrics are within the acceptable range of IS 10500:2012, this does not guarantee the lack of anthropogenic interference. In the Periyar watershed, diffuse pollution sources like agricultural runoff, domestic sewage, and industrial activities can still have an impact on groundwater quality, especially in shallow aquifers. During the pre-monsoon season, decreased flushing and prolonged residence times allow for the accumulation of dissolved constituents supplied through fertiliser leaching, septic system leaks, and subterranean movement of contaminants from industrial zones such as the Eloor-Edayar belt. However, the lack of broad exceedance in key ions shows that such impacts are limited or modest in severity (Kumar et al., 2020).

The restricted recharge and dropping water table conditions that characterise the pre-monsoon period reduce direct contact between surface water and groundwater, strengthening the importance of in-situ geochemical processes over external inputs. However, legacy effects from prior monsoonal recharge and pollutant loading may remain in the aquifer system, influencing current groundwater chemistry. This emphasises the significance of seasonal memory effects in groundwater systems, as previous recharge episodes continue to influence water quality under low-flow conditions (Alfio et al., 2024).

The pre-monsoon groundwater quality in the Periyar basin is primarily controlled by natural geochemical processes, particularly lateritic weathering and redox-driven iron mobilisation, with moderate but localised anthropogenic influence from agriculture, sewage, and industrial activities. The increasing iron contents and pH variability highlight the need of longer water-rock contact and reduced dilution, although the general compliance of other parameters indicates that the aquifer system is not yet heavily contaminated. Continuous monitoring across seasons is required to capture the changing impact of natural and anthropogenic variables on groundwater quality in the basin.

#### 4.1.6.2. Post Monsoon

The pH distribution of post-monsoon groundwater samples from the Periyar basin varies spatially, with acidic conditions (<6.5) in three downstream locations and alkaline circumstances (>8.5) in three upstream sites. The acidic nature of downstream regions can be linked to infiltration of organic-rich runoff, organic matter decomposition, and anthropogenic waste input, particularly in areas influenced by urban and industrial operations. Post-monsoon recharge increases the movement of dissolved organic carbon and acids into shallow aquifers, which lowers pH. In contrast, alkaline conditions in upstream regions may be associated with carbonate weathering, base cation enrichment, and less anthropogenic disturbance, indicating natural geochemical regulation. These regional disparities illustrate the simultaneous impact of monsoonal recharge and local lithological variability on groundwater chemistry (Manikandan et al., 2020).

Iron (Fe) values are significantly higher in almost all downstream samples, with only one sample falling within acceptable limits, showing pronounced iron enrichment in post-monsoon groundwater in the lower parts of the Periyar basin. This pattern indicates that monsoon recharge and subsequent infiltration processes move iron from lateritic soils and sediments into the aquifer system. Furthermore, downstream locations, particularly those near urban-industrial zones, may experience improved reducing conditions due to organic matter inputs from sewage and industrial effluents, which aid in the breakdown of iron-bearing minerals. The persistence of high iron concentrations long after the monsoon suggests that both geogenic and anthropogenic factors contribute to iron mobilisation, with redox-controlled processes playing an important role (Zhang et al., 2017).

In contrast, the upstream groundwater samples are of considerably higher quality, with most metrics (except in four samples) falling within the allowed range of IS 10500:2012. This shows that upstream aquifers are less affected by anthropogenic activities and are predominantly controlled by natural hydrogeochemical processes such as mineral weathering and recharge dynamics. However, the rare samples that exceed permitted levels show localised contamination or geochemical abnormalities, which could be linked to agricultural operations, localised waste dumping, or spontaneous mineral dissolution.

The observed difference in upstream and downstream groundwater quality demonstrates the importance of land use, anthropogenic pressure, and hydrological connectivity in determining groundwater chemistry in the Periyar basin. Downstream regions, which are more densely populated and industrialised, are more contaminated by sewage infiltration, industrial effluents, and urban runoff, especially during and after the monsoon, when recharge promotes downstream transit of contaminants. Upstream regions, on the other hand, benefit from less disturbance and more natural recharge, resulting in better groundwater quality. (Aditya et al., 2024).

Overall, post-monsoon groundwater quality in the Periyar basin reflects a system in which monsoonal recharge improves both dilution and contaminant transport, resulting in higher quality in less disturbed upstream areas but increased iron mobilisation and localised acidification in downstream regions. These findings emphasise the necessity of taking seasonal hydrological processes and spatial land-use patterns into account when assessing groundwater quality, as well as the vulnerability of downstream aquifers to anthropogenic contamination.

## 4.2. Sediment Loads Analysis and Inferences

While the previous section focused on nutrient sources and dynamics in the Periyar River Basin, sediment processes also play an equally significant role in regulating nutrient transport, transformation, and fate throughout the system. Sediments serve not only as physical materials carried by flowing water, but also as transporters of particle nutrients, organic matter, trace metals, and pollutants. Sediment transport has a significant impact on nutrient fluxes, water quality, biogeochemical cycling, and the ecological functioning of riverine habitats.

The Periyar River Basin stretches from the steep terrains of the Western Ghats to lowland floodplains and estuary environments, resulting in great geographic heterogeneity in erosion, sediment transport, and deposition. Natural variables, such as monsoonal rainfall, terrain, lithology, and hydrological variability, influence sediment dynamics in the basin, as do anthropogenic activities, including land-use change, agriculture, quarrying, sand mining, reservoir regulation, and urbanization.

Fine-grained suspended sediments, particularly the silt and clay fractions, have high adsorption capacity and thus play a key role in transferring nutrients, including phosphorus, nitrogen compounds, and organic carbon (Cieśla & Gruca-Rokosz, 2024). During heavy rainfall and runoff events, nutrient-rich soil particles from agricultural lands, degraded slopes, and urban areas are mobilised and carried downstream, resulting in high sediment-nutrient coupling in the river system.

Sediment-nutrient interactions are especially important in the Periyar River Basin, which has extensive agricultural activity, reservoirs, plantation regions, and ecologically sensitive downstream ecosystems. Excessive sediment transport during monsoon seasons can raise turbidity, accelerate reservoir sedimentation, alter aquatic ecosystems, and enhance downstream transport of sediment-bound nutrients and pollutants (Vázquez-Tarrío et al., 2023). Furthermore, deposited sediments can act as both nutrient sinks and secondary nutrient sources, releasing nutrients in response to changing environmental conditions.

The sediment load estimated from the gauge station provide useful information about the temporal variability of sediment transport within the basin. Continuous sediment monitoring is therefore essential for understanding erosion processes, nutrient transport pathways, reservoir sedimentation, and the impacts of extreme hydro-meteorological events on the ecological health of the Periyar River system.

Table 8. Neeleswaram CWC Gauge Station – Sediment Loads (1990–2023)

| Sl. No | Year | Sediment Load (t) | Sl. No | Year | Sediment Load (t) |
|---|---|---|---|---|---|
| 1 | 1990 | 205073.41 | 18 | 2007 | 145675.29 |
| 2 | 1991 | 511731.80 | 19 | 2008 | 53838.54 |
| 3 | 1992 | 469613.48 | 20 | 2009 | 120366.67 |
| 4 | 1993 | 193027.15 | 21 | 2010 | 59838.65 |
| 5 | 1994 | 390360.31 | 22 | 2011 | 50530.22 |
| 6 | 1995 | 539846.05 | 23 | 2012 | 36222.86 |
| 7 | 1996 | 337948.98 | 24 | 2013 | 288941.03 |
| 8 | 1997 | 221239.56 | 25 | 2014 | 144892.85 |
| 9 | 1998 | 343980.30 | 26 | 2015 | 75747.75 |
| 10 | 1999 | 113392.65 | 27 | 2016 | 37149.92 |
| 11 | 2000 | 83864.42 | 28 | 2017 | 131693.41 |
| 12 | 2001 | 113077.39 | 29 | 2018 | 2104995.44 |
| 13 | 2002 | 56256.80 | 30 | 2019 | 301931.63 |
| 14 | 2003 | 49391.93 | 31 | 2020 | 225436.10 |
| 15 | 2004 | 98012.57 | 32 | 2021 | 238311.62 |
| 16 | 2005 | 132422.90 | 33 | 2022 | 310637.79 |
| 17 | 2006 | 89659.79 | 34 | 2023* | 8368.29 |

Sediment load records from the gauge station at Neeleswaram provide insight into the hydrological, geomorphological, and ecological behaviour of the Periyar River. The recorded sediment loads exhibit significant interannual variation, ranging from 36222.86 tonnes in 2012 to approximately 2.10 million tonnes in 2018. The sediment load observed during the 2018 flood event (2.10 million tonnes) was significantly higher than the historical record. It was approximately 11 times the long-term average annual sediment load and nearly 4 times the previous peak in 1995. This huge increase reflects the severe landslides, slope failures, bank erosion, and catchment-scale sediment movement caused by Kerala's heavy rainfall and flooding in 2018. The occurrence emphasises the Periyar River Basin's sensitivity to major hydrometeorological disturbances and the significance of sediment monitoring for flood management, reservoir sustainability, and watershed protection. Such substantial oscillations clearly show that monsoonal rainfall intensity, extreme flood events, catchment erosion, and anthropogenic disturbances, such as land-use change, quarrying, sand mining, and river regulation, heavily influence sediment transport in the basin.

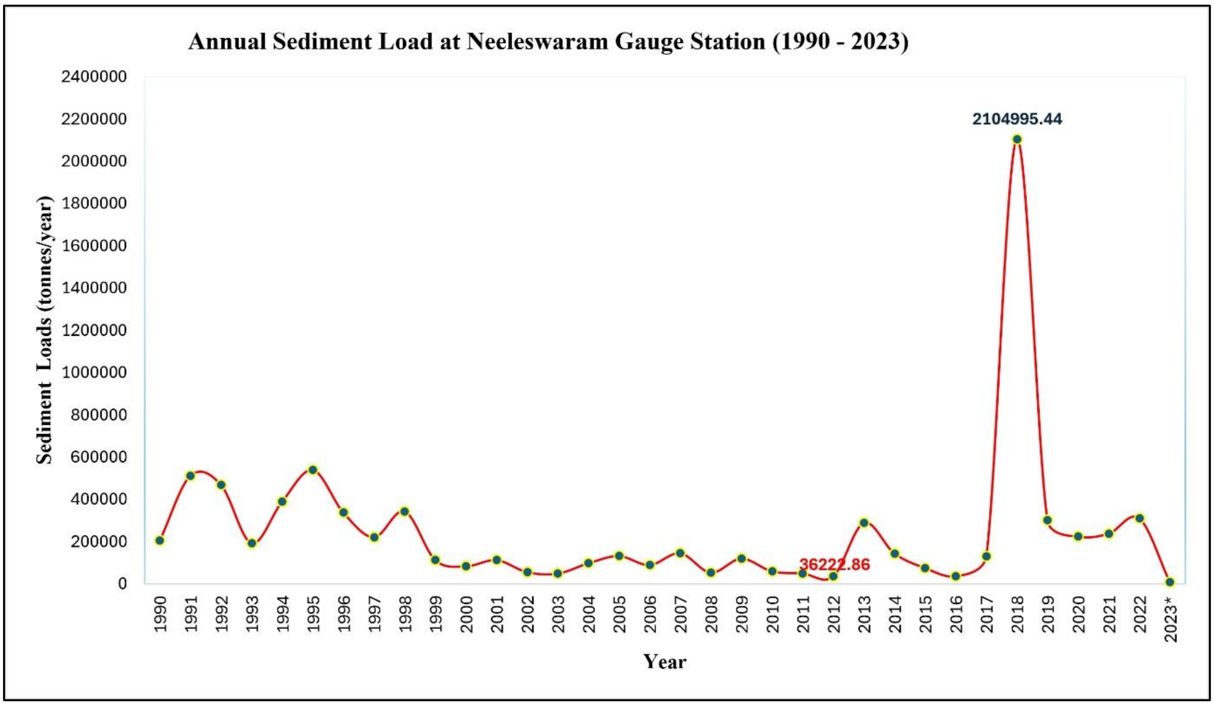


Figure 10. Annual sediment load recorded at the Central Water Commission (CWC) Neeleswaram gauge station on the Periyar River during 1990–2023

Sediment transport is increasingly recognized as an important indicator of watershed stability, river health, and climate resilience. Recent research has found that changes in sediment dynamics directly affect river morphology, nutrient transport, reservoir sustainability, flood behaviour, and ecological productivity in river basins worldwide (Vázquez-Tarrío et al., 2023). Extreme rainfall events in monsoon-dominated tropical basins often lead to rapid erosion and sediment mobilization, with significant geomorphic and biological consequences. Similar patterns can be seen in the Periyar River Basin, particularly during the 2018 Kerala floods, when widespread landslides, slope failures, and riverbank erosion resulted in extremely high sediment transport throughout the basin. The transportation of more than 2 million tonnes of sediment in a single year indicates serious watershed instability and increased geomorphic activity within the river system.

Sediment loads are particularly important in the Periyar basin because they serve as primary carriers of nutrients, organic matter, and pollutants. Fine suspended sediments have a strong adsorption capacity and transport phosphorus, nitrogen compounds, trace metals, and organic carbon downstream during runoff events (Cieśla & Gruca-Rokosz, 2024). This mechanism creates strong sediment-nutrient coupling within the basin, with enhanced sediment transport often leading to higher nutrient fluxes and greater contaminant mobility. This relationship has significant consequences for water quality, aquatic productivity, and ecosystem stability in an ecologically sensitive and heavily used river system like the Periyar.

The Periyar River Basin is home to large plantation crops, urban communities, hydropower projects, reservoirs, industrial areas, and downstream estuarine ecosystems. Under these conditions, excessive sediment transport may affect multiple basin components simultaneously. Elevated sediment loads raise turbidity, restrict light penetration, and change aquatic habitats, harming benthic species and aquatic biodiversity (Vázquez-Tarrío et al., 2023). Sediment-bound nutrients delivered during high-flow events could also contribute to eutrophication in reservoirs, marshes, and estuaries. At the same time, reservoir systems in the basin capture large volumes of suspended particles, diminishing downstream sediment continuity, hastening reservoir siltation, and reducing storage capacity. Similar sedimentation concerns have been reported globally in controlled river systems and hydropower reservoirs, where silt deposition has a substantial impact on reservoir lifespan and operational efficiency.

Sediment load data are extremely useful for river basin management, and long-term sediment monitoring helps identify erosion-prone subbasins, assess the effects of extreme rainfall events, assess watershed degradation, and quantify reservoir sedimentation rates. Sediment records are particularly important for flood risk management because excessive sediment transport changes channel shape, limits channel conveyance capacity, and affects floodplain dynamics. Recent integrated sediment management studies emphasize the importance of integrating hydrological monitoring, sediment transport analysis, reservoir management, and watershed conservation into a single framework for sustainable river basin planning.

In the context of the Periyar River Basin, sediment load records from Neeleswaram can thus serve several management and planning objectives, including:

- Prioritization of soil and water conservation measures
- Reservoir sedimentation assessment
- Flood and landslide risk management
- Regulation of quarrying and sand mining activities
- Nutrient management and eutrophication control

- Riparian restoration planning
- Sustainable land-use and watershed management.

Furthermore, understanding sediment-nutrient coupling is critical for preserving the ecological integrity of downstream wetlands and estuaries linked to the Periyar River. Significant sediment trapping by reservoirs may impede downstream sediment replenishment and affect river morphology and coastal sediment balance. Similar concerns have been raised in recent worldwide sediment management studies, which emphasise the importance of basin-scale sediment governance under changing climatic and anthropogenic conditions.

Overall, the long-term sediment load variability observed in the Periyar River Basin is driven by climate variability, major hydro-meteorological events, land use changes, and river control. Continuous sediment monitoring is thus vital not just for understanding erosion processes but also as a critical scientific tool for integrated river basin management, ecological restoration, reservoir sustainability, and climate adaptation planning in the Periyar River system.

## 5. Existing Practices affecting Nutrient Recycling in Periyar River Basin

Nutrient recycling in river basins happens as a result of intricate interactions between soils, vegetation, sediments, microorganisms, and the flowing water. These mechanisms control how nutrients like nitrogen and phosphorus are stored, altered, and redistributed across the watershed. In the Periyar River Basin, nutrient recycling is driven not only by natural ecological processes but also by human activities that change land use, hydrology, and sediment dynamics. These characteristics influence how well nutrients are kept within the basin or delivered downstream to reservoirs, marshes, and coastal habitats.

Several existing activities in the basin influence these nutrient cycle pathways. Agricultural activities, which are widely practiced throughout the basin, contribute in accumulating nutrients in soils through the use of fertilisers and organic amendments. While crops use a major percentage of these nutrients, others remain in the soil or organic matter. During rainfall events, particularly in the region's extreme monsoon conditions, these nutrients may be mobilised by surface runoff, erosion, or subsurface leaching, finally reaching local streams and river channels. Simultaneously, agricultural soils and plants contribute to nutrient retention and recycling via plant intake, microbial activity, and soil storage.

Urban and industrial activity has a further impact on nutrient recycling processes in the basin. Municipal wastewater discharges and industrial effluents provide nutrients and organic matter to river basins. Once added, these nutrients do not just flow downstream; rather, they frequently interact with sediments, aquatic plants, and microbial communities. River sediments, in particular, can operate as temporary storage zones for nutrients, which are then released under changing environmental conditions such as high-flow episodes or sediment resuspension.

The basin's hydrological control has an impact on the dynamics of nutrient recycling. Reservoirs and dams alter natural flow patterns, increase water residence times, and aid in the settling of sediment-associated nutrients. Nutrients in these impounded streams may undergo biological absorption, mineralisation, or other transformations before being transferred downstream. Overall, the interplay of natural ecosystem processes and existing human practices, such as agriculture, urban expansion, industrial activity, and river regulation, has a considerable impact on nutrient recycling in the Periyar river basin. Understanding these relationships is critical for evaluating nutrient transport patterns and devising effective methods for better watershed management and water quality protection.

## 5.1. Agricultural and Land Management Practices in Periyar River Basin

Agriculture is one of the most important land-use systems in the Periyar River Basin, influencing hydrological processes, sediment dynamics, and nutrient cycling. The basin offers a diversified agricultural landscape shaped by elevation, climate, soil characteristics, and water availability. Plantation agriculture dominates the highlands, whereas mixed cropping systems, paddy cultivation, and horticulture farming dominate in the midlands and lowlands. These agricultural activities interact with rainfall patterns, irrigation infrastructure, and land management practices to influence nutrient retention, transformation, and movement within the watershed.

The upper catchment regions of the Periyar River Basin, particularly in the Idukki district, are distinguished by plantation agriculture dominated by crops such as cardamom (*Elettaria cardamomum*), pepper (*Piper nigrum*), tea (*Camellia sinensis*), coffee (*Coffea spp*.), and rubber (*Hevea brasiliensis*). These crops are often grown in perennial plantation systems, sometimes with shade trees and intercrops, resulting in agroforestry-style landscapes. Litterfall and root biomass give considerable amounts of organic matter to the soil, improving soil fertility and promoting internal nutrient recycling processes within plantation ecosystems. However, the rise of plantation agriculture in the Western Ghats has resulted in significant land-use changes, affecting natural forest cover and hydrological channels. Conversion of wooded slopes to agricultural land increases surface runoff and soil erosion, especially during the region's intense monsoon rainfall events (Sreeja et al., 2021). As a result, sediments mobilised from upland agricultural regions frequently convey sediment-bound nutrients like phosphorus and organic matter into river channels and downstream reservoirs.

Recent research into sediment movement in rivers draining the Western Ghats, particularly the Periyar, has revealed the impact of human activities on sediment dynamics. According to research, land-use changes caused by agricultural expansion, reservoir development, and sand mining have had a substantial impact on sediment flows within rivers. Such changes impact the transit and deposition of nutrient-rich sediments, hence influencing nutrient cycle processes within the basin (Das et al., 2025).

Unlike the plantation-dominated highlands, the midland portions of the Periyar Basin, particularly in Ernakulam and Thrissur districts, have more diverse agricultural systems. Coconut (*Cocos nucifera*) plantations are often combined with intercrops, including banana, pineapple, vegetables, spices, and legumes, to form the primary farming systems in these areas. Intercropping inside coconut plantations is commonly used as a tactic for increasing land productivity and farmers' economic resilience. These mixed cropping systems promote continual nitrogen cycling in the soil by decomposing plant debris, turning over roots, and microbial processes. According to the Periyar Agriculture Profiling Report, the basin supports the cultivation of a diversified range of products such as coconut, rubber, pepper, cardamom, banana, tapioca, pineapple, vegetables, and pulses, showcasing the region's agricultural economy (cPeriyar & NRCD, 2025).

Cropping intensity is a crucial aspect of agricultural land management in the basin. Cropping intensity in some areas of the midland agricultural landscape exceeds 100%, meaning that fields are cultivated more than once in a single year. While intensive land usage boosts agricultural yield, it also leads to increased fertiliser application rates and soil disturbance. If proper soil conservation methods are not adopted, increased fertiliser inputs, particularly nitrogen and phosphorus fertilisers, can result in nutrient losses via runoff, erosion, and subsurface leaching (Pandian et al., 2024).

The lower reaches of the Periyar River Basin contain agricultural systems that are uniquely suited to coastal environments. One notable example is the traditional Pokkali rice production system used in Ernakulam district's tidal marshes. Pokkali rice is a salt-tolerant type grown in coastal settings were rice planting alternates with prawn cultivation. This integrated rice-prawn farming technique is based mostly on natural nutrient exchange via tidal water movements, rather than extensive fertiliser inputs. As a result, the Pokkali system encourages natural nutrient regeneration and sustainable nutrient recycling in coastal agroecosystems (Sumithra & Devi, 2025). The technique is widely regarded as an ecologically resilient farming strategy that preserves soil fertility while also enabling agricultural production and aquaculture.

Despite the prevalence of such traditional agricultural methods, agricultural intensification in various areas of the basin has resulted in greater use of chemical fertilisers and agrochemicals. Nitrogen and phosphorus fertilisers are extensively used in plantation and horticulture farming to increase crop productivity. Nutrients that crops do not absorb can, however, be mobilised during rainy events and delivered into surrounding bodies of water. Heavy precipitation events in monsoon-dominated basins like the Periyar cause significant surface runoff, which can transport dissolved nutrients and fine particles from agricultural landscapes into streams and rivers.

Scientific investigations in the Periyar River Basin have revealed the impact of agricultural runoff and land-use activities on nitrogen concentrations in both river water and sediments. Early investigations on nutrient distribution in the Periyar estuary and Cochin backwaters found significant seasonal fluctuations in nitrate, phosphate, and silicate concentrations, which were strongly related to river discharge and terrestrial inputs from the basin (Sankaranarayanan & Qasim, 1969; Kumar et al., 2020). The study found that nutrient concentrations often rise during the monsoon season due to increased runoff from nearby landscapes, especially agricultural regions.

Subsequent hydrochemical investigations have reported elevated nitrate and phosphate concentrations in the Periyar River, reflecting the influence of anthropogenic activities, including agricultural runoff, domestic wastewater discharge, and industrial effluents (Arun et al., 2024). These nutrient inputs can promote eutrophication by stimulating excessive primary productivity and altering nutrient balances in downstream aquatic ecosystems, particularly the Vembanad Lake system, which receives a major proportion of its freshwater inflow from the Periyar River (Venukumar et al., 2024). The transport of dissolved nutrients through groundwater–surface water interactions further increase the potential for sustained nutrient loading, especially in densely populated and industrialised stretches of the basin, where wastewater infiltration and septic system leakage may contribute to groundwater contamination.

Recent studies conducted by research organisations such as the National Centre for Earth Science Studies (NCESS) and the Cochin University of Science and Technology (CUSAT) have looked into nutrient accumulation and sediment geochemistry in the Periyar River and its estuary environment. Studies analysing river and estuarine sediments have found higher quantities of nutrients, organic matter, and heavy metals in the basin's downstream parts, notably in industrially active regions. These investigations show that river sediments act as both sinks and secondary sources of nutrients in the aquatic environment, releasing nutrients back into the water column during sediment resuspension episodes (Arun et al., 2024).

Water quality monitoring programs done by the Kerala State Council for Science, Technology, and Environment (KSCSTE) and the Centre for Water Resources Development and Management (CWRDM) have shown additional geographical differences in water quality throughout the Periyar River. Monitoring results from several sites revealed that water quality is deteriorating in downstream parts of the river, particularly near industrial and urban regions. Several monitoring sites showed elevated turbidity, conductivity, and nutrient contents, demonstrating the cumulative effects of agricultural runoff, industrial discharges, and domestic wastewater inputs (Mukhopadhyay & Valsalan, 2024).

Irrigation strategies have a significant impact on nutrient transfer within the basin. Farmers use a combination of surface water sources (rivers, canals, ponds, and reservoirs) and groundwater retrieved by wells and boreholes. Drip irrigation and micro-sprinkler systems are being used more frequently in plantation-dominated highland areas to improve water use efficiency and reduce water losses. However, conventional flood irrigation methods are still used in some midland agricultural areas, and if not effectively managed, they can contribute to nutrient losses through runoff and soil erosion.

Overall, agricultural and land management methods in the Periyar River Basin are characterised by a complex interaction of plantation agriculture, mixed cropping systems, and traditional farming practices that have been adapted to varied environmental conditions. These agricultural systems play an important role in rural lives and regional food production, but they also have an impact on nutrient cycling, sediment transport, and water quality in the basin. As a result, a thorough understanding of agricultural land-use patterns, fertiliser application, cropping systems, and irrigation practices is required for assessing nutrient loads and developing effective watershed management strategies to reduce agricultural pollution and promote sustainable river basin management.

### 5.2. Wastewater, Industrial and Catchment Practices in Periyar

The nutrient and pollutant loads entering the Periyar River system are also significantly influenced by rapid urbanisation, industrial development, domestic effluent discharge, and catchment-level land-use changes. In particular, the downstream sections of the river are subject to intricate interactions between municipal wastewater, industrial effluents, agricultural discharge, and urban drainage. The basin's water quality conditions, sediment chemistry, and nutrient cycling processes are significantly influenced by these combined influences.

In Kerala, domestic effluent is one of the most prevalent and consistent sources of nutrient inputs to rivers. Decentralised sanitation systems, including septic tanks, soak pits, and localised drainage networks, are the primary methods of managing effluent generated by households, institutions, and commercial establishments throughout the basin. Although these systems offer fundamental sewage containment, they frequently permit the infiltration of nutrient-rich effluents into the soil and groundwater systems of the surrounding area. Eventually, nutrients such as nitrate, ammonium, and phosphate infiltrate nearby streams and rivers through subsurface flow pathways. This process occurs over time.

In wells situated in proximity to densely populated settlements, groundwater investigations have revealed elevated nitrate concentrations, suggesting contamination from domestic effluent sources. This has been observed in certain regions of the Periyar basin. The potential for wastewater-derived nutrients to infiltrate river systems through groundwater–surface water interactions is underscored by these findings.

The transport of nutrients and organic pollutants into the river system is further facilitated by urban drainage networks. In numerous cities and municipalities throughout the basin, wastewater from households and commercial establishments is discharged into open drains that also transport stormwater runoff. These drainage channels transport substantial quantities of organic matter, suspended sediments, nitrogen compounds, and phosphorous into tributaries of the Periyar River during monsoon rainfall events. These processes are especially critical during periods of low river discharge, as the river's dilution capacity is reduced, allowing nutrients to accumulate.

Scientific investigations have shown that anthropogenic inputs from urban runoff and domestic effluent are closely associated with nutrient enrichment in the Periyar River and its estuarine regions. Concentrations of nitrate, phosphate, and silicate in the Periyar estuary have been documented to be between 2.5 and 8.3 μM, 0.5 and 1.8 μM, and 15 and 42 μM, respectively, in regions that are affected by industrial and urban discharges (Maya et al., 2007). These values are considerably higher than those observed in upstream river segments, indicating the significant impact of anthropogenic nutrient inputs on the quality of downstream water. The development of phytoplankton can be facilitated by elevated nutrient levels in the estuary, which can contribute to eutrophic conditions in slow-flowing sections of the river and adjacent estuarine ecosystems.

Nutrient transport and contamination of water bodies are also influenced by the solid waste management practices within the basin. The Kerala State Pollution Control Board reports that the state produces approximately 3011.23 tonnes of solid waste per day, with biodegradable organic waste comprising nearly 73% of this total. The formation of nutrient-rich leachates, which contain nitrogenous compounds, organic carbon, and dissolved phosphorus, can result from the improper disposal of biodegradable waste. These leachates have the potential to infiltrate soil and groundwater systems or be transported to adjacent surface water bodies through stormwater runoff (Kerala State Pollution Control Board, 2024).

Legacy disposal sites continue in presenting environmental challenges in numerous regions of the state, despite the implementation of these initiatives. Large quantities of mixed municipal waste have been amassed at open dumping grounds as a consequence of historical refuse disposal practices. These sites produce leachates that contain heavy metals, organic contaminants, and nutrients, which have the potential to infiltrate the soil and groundwater systems in the vicinity. Consequently, remediation programs have been implemented to recover reusable materials and process old waste deposits through the use of biomining techniques. According to state-level assessments, 44 legacy waste dump sites have been identified, with remediation of 18 sites, which involved approximately 309,197 tonnes of refuse, already completed (Kerala State Pollution Control Board, 2024).

Another significant factor that affects the dynamics of nutrient and contaminant in the Periyar River Basin is industrial activities. The spatial distribution of industries within the basin is significantly different between the upstream and downstream regions. The industrial development of upstream districts, such as Idukki, is relatively limited by the limited availability of developable land, extensive forest cover, and rugged terrain. There are approximately 2,164 operational industrial units in the Periyar Basin region of Idukki district, with 97.69% of them being micro-scale enterprises, according to industrial inventory assessments. Agro-processing, food manufacturing, construction material production, and service-oriented activities, including automobile repair facilities and fabrication units, are the primary activities of these industries.

The agricultural production systems are inextricably entwined with the industrial sector in the upstream basin. The industrial basis is significantly influenced by agro-based industries, including spice processing facilities, food manufacturing enterprises, and tea processing units. The strong correlation between agricultural production systems and local industrial development is exemplified by the fact that agro-food processing industries comprise approximately 62% of the industrial units identified in the basin area of Idukki district.

Despite the fact that these industries are typically modest in scale, they still produce wastewater and organic residues that have the potential to impact nutrient flows within local catchments. Organic matter, suspended solids, and nitrogenous compounds are typically present in the effluents of food manufacturing operations, spice pulverising, and tea processing. If not adequately treated, these effluents may penetrate nearby streams and drainage networks, thereby contributing to nutrient enrichment in downstream water bodies.

Conversely, the Periyar River Basin's downstream regions are home to several of Kerala's most substantial industrial complexes. A diverse array of industries, such as chemical manufacturing plants, fertiliser factories, petrochemical industries, and metal processing units, are situated along the lower reaches of the river in the Eloor–Edayar industrial corridor. These industries generate wastewater that contains a diverse array of chemical pollutants and utilise substantial amounts of water for production processes.

Industrial activities have been consistently identified as a significant source of pollution in the lower Periyar River by environmental studies. Elevated concentrations of heavy metals, including mercury, cadmium, chromium, and lead, have been detected in downstream river segments in the course of sediment analyses conducted in the river. For instance, sediment samples collected in the vicinity of the Eloor–Edayar industrial belt have demonstrated mercury concentrations ranging from 0.12 to 1.85 mg $kg^{-1}$, chromium concentrations between 45 and 210 mg $kg^{-1}$, and lead concentrations between 35 and 118 mg $kg^{-1}$, all of which suggest substantial anthropogenic contamination from industrial sources (Chandni et al., 2026).

River sediments accumulate these heavy metals over extended periods of time, and they can remain in the aquatic environment for decades. Consequently, sediments serve as long-term reservoirs of contaminants that may be remobilised into the water column under specific environmental conditions. The release of sediment-bound metals and nutrients can be triggered by changes in pH, dissolved oxygen concentration, or hydrological disturbances, resulting in secondary pollution of the river system.

Nitrate and phosphate concentrations are elevated in regions that are affected by industrial discharge zones, according to research conducted in the Periyar estuary. The discharge of treated and untreated industrial effluents from adjacent chemical and fertiliser industries has been associated with elevated nutrient concentrations in these areas (Maya et al., 2007). The nutrient accumulation in the river system may be further enhanced by the interaction between nutrient inputs from industrial effluents and domestic wastewater discharges.

Another significant non-point source of nutrient contamination in the basin is urban runoff. The development of extensive impervious surfaces, such as roads, structures, and parking areas, has been the result of rapid urban expansion in downstream districts like Ernakulam. During rainfall events, these surfaces exacerbate surface discharge and decrease infiltration. Stormwater discharge from urban areas frequently contains a combination of pollutants, such as suspended sediments, hydrocarbons, heavy metals, and nutrients that have accumulated on road surfaces.

Wastewater from residential areas, commercial establishments, and industrial facilities is discharged into numerous urban channels in the Kochi metropolitan region. Wastewater and stormwater discharge are transported into the Periyar River and adjacent estuarine systems that are connected to Vembanad Lake by canals like the Edappally Canal and Perandoor Canal. The significance of urban runoff as a source of nutrient loading in the river system has been underscored by studies that have demonstrated that nutrient concentrations in these urban drains are considerably higher than those observed in upstream river segments.

Nutrient transport and sediment dynamics within the basin are also influenced by variations in land use at the catchment level. The conversion of natural vegetation into agricultural land, urban settlements, and industrial infrastructure can result in the alteration of hydrological pathways and the acceleration of soil erosion. Sediment-bound nutrients may be transported into river channels during rainfall events. These sediments have the potential to accumulate in estuarine zones, floodplains, and reservoirs, where they can have an impact on the functioning of aquatic ecosystems and the cycling of nutrients.

The nutrient cycling within the Periyar River Basin is significantly impacted by the combined influence of industrial activities, solid waste management practices, effluent discharge, and catchment-level land-use changes. The excessive primary productivity that can result from increased nutrient inputs from domestic sewage and industrial effluents can contribute to eutrophication and their associated ecological impacts. The balance between nitrogen and phosphorus in aquatic ecosystems may be altered by nutrient enrichment, which can have an impact on the overall functioning of the ecosystem and the phytoplankton communities.

An integrated river basin management approach that takes into account both point and non-point pollution sources is necessary to address these challenges. It is imperative to implement sustainable urban planning strategies, improve solid waste management practices, expand wastewater treatment infrastructure, and implement stricter regulations for industrial effluent discharges to mitigate nutrient inputs and preserve ecological equilibrium within the basin. In general, industrialisation and urban development have made substantial contributions to the economic expansion of the basin. However, they have also introduced intricate environmental challenges associated with nutrient pollution and effluent management. Therefore, it will be imperative to implement effective management of these pressures to ensure the long-term sustainability of the Periyar River and its associated ecosystems.

## 6. Challenges and Gaps

Despite increasing acceptance of the environmental pressures affecting the Periyar River Basin and the execution of various management measures, significant problems and information gaps remain, limiting effective nutrient pollution and water quality degradation in the basin. The complicated interaction of agricultural runoff, domestic wastewater discharge, industrial effluents, and urban rainwater make identifying and managing nutrient sources very problematic. While numerous studies have demonstrated localised pollution hotspots and nutrient enrichment in downstream river segments and estuarine habitats, a thorough understanding of basin-scale nutrient fluxes and their temporal variability is lacking.

One of the most significant issues in the basin is the fragmentation of monitoring and data collection operations. Water quality monitoring programs are frequently carried out by multiple authorities, with diverse aims, spatial coverage, and monitoring frequencies. As a result, few long-term records reflect seasonal and interannual fluctuations in nutrient contents. Furthermore, many existing studies concentrate on downstream industrial zones, while upstream regions, particularly those dominated by agricultural and plantation landscapes, are comparatively under-represented in scientific research.

Infrastructure restrictions also pose considerable problems to nutrient management in the basin. Despite widespread promotion of decentralised sanitation systems and waste management initiatives, treatment capacity for domestic wastewater and industrial effluents remains insufficient to meet the basin's growing population and expanding industrial operations. Furthermore, non-point pollution sources including agricultural runoff and urban stormwater are difficult to identify and regulate with traditional pollution control methods.

Addressing these difficulties will necessitate greater monitoring program integration, expanded wastewater treatment infrastructure, and the creation of basin-wide nutrient management strategies based on scientific evidence. Identifying these gaps is thus critical for directing future research efforts and designing more effective management measures targeted at restoring and protecting the ecological health of the Periyar River Basin.

### 6.1. Data, Policy and Institutional Issues

To effectively manage nutrient pollution and water quality in river basins, reliable datasets, consistent policy frameworks, and coordinated institutional procedures are required. These difficulties derive from the fragmented structure of environmental monitoring systems, limitations in policy integration across sectors, and institutional complications associated with multi-agency management of river basin resources. One of the most significant issues in the basin is the scarcity of consistent and long-term records on water quality, nutrient loads, and pollutant sources. Although several institutions, including the Kerala State Pollution Control Board (KSPCB), the Central Pollution Control Board (CPCB), research institutions, and academic organisations, conduct monitoring activities in the basin, these datasets are frequently collected for specific regulatory or research purposes rather than as part of an integrated basin-wide monitoring framework. As a result, water quality observations are typically discontinuous in both space and time, making it difficult to determine long-term trends in nutrient concentrations and pollution levels throughout the basin. Furthermore, many existing studies focus on specific hotspots like industrial zones or estuaries, leaving upstream agricultural landscapes and minor tributaries underrepresented in monitoring programs.

Non-point pollution sources like agricultural runoff, urban stormwater, and diffuse wastewater discharge are difficult to quantify and manage. In many situations, current monitoring data only show the concentration of nutrients in river water, not the overall nutrient flux conveyed through the river system. Without reliable estimates of nutrient loads and spatial distribution, it is difficult to create effective pollution control methods or assess the success of management initiatives.

River water quality is influenced by policies and regulatory frameworks from a variety of sectors, including agriculture, industry, urban growth, and environmental protection. However, these sectors are frequently overseen by various policy tools and administrative entities that do not always work together. For example, agricultural policies that support better crop production may unintentionally promote more fertilizer usage, whereas urban development plans may result in settlement expansion and wastewater creation without enough investment in treatment infrastructure. Individual regulatory measures may be limited in their effectiveness if integrated basin-level policies addressing nutrient management across sectors are not implemented.

Institutional coordination is another significant problem in controlling water quality in the Periyar River Basin. Multiple entities are involved in various elements of river basin management, including water resource departments, pollution control boards, municipal authorities, agricultural departments, and local self-government organisations. While each of these entities has a crucial role in regulating various aspects of the basin, collaboration between them is frequently restricted. Differences in institutional mandates, data sharing methods, and managerial agendas can lead to fragmented decision-making and repetitive activities.

In addition, many river management projects are implemented at the administrative or district levels rather than at the river basin level. Because hydrological processes and pollutant movement transcend administrative boundaries, the lack of a fully integrated basin-level governance structure might impede efficient nutrient pollution management. Establishing stronger institutional structures for inter-agency collaboration, data sharing, and basin-wide planning will considerably improve the Periyar River Basin's ability to manage water quality issues.

Addressing these data, regulatory, and institutional gaps is critical for creating evidence-based nutrient management plans and enhancing the long-term ecological health of the river system. To achieve sustainable water resource management in the Periyar River Basin, key measures include strengthening monitoring networks, integrating datasets from numerous organisations, encouraging cross-sectoral policy coordination, and building basin-scale governance frameworks.

## 7. Strategies for Load Management

The Periyar River Basin supports a diverse range of socioeconomic activities, including agricultural production, industrial activities, and urban development, all of which contribute to nutrient and pollution loading in the river. As previously noted, nutrients originate from various sources, including agricultural runoff, residential wastewater discharge, industrial effluents, solid waste leachates, and urban stormwater runoff. These various sources interact within the basin, influencing water quality, sediment chemistry, and ecological conditions in both riverine and estuarine ecosystems. To address these demands, pollution loads entering the river system must be managed comprehensively and holistically. Load management strategies seek to limit the amount of nutrients, sediments, and toxins entering water bodies by combining source control measures, enhanced treatment infrastructure, sustainable land-use practices, and legislative interventions. In complex river basins like the Periyar, where both point and non-point pollution sources are considerable, effective management necessitates coordinated activities from several sectors such as agriculture, urban growth, industrial control, and waste management.

Identifying and prioritising key pollution sources within the basin is a critical component of load control. Targeted interventions in high-impact locations, such as industrial clusters, highly inhabited urban centers, and intensively farmed agricultural landscapes, can considerably reduce pollutant loads into the river system. At the same time, catchment-scale management strategies such as better soil conservation, sustainable agriculture practices, and riparian buffer restoration can all contribute to limiting diffuse nutrient movement over the landscape. In addition to technology and infrastructure solutions, successful load management necessitates supportive institutional frameworks, comprehensive monitoring systems, and community involvement.

This section presents a range of prospective techniques and interventions for decreasing nutrient and pollutant loads in the basin, with a focus on sustainable land management, enhanced wastewater treatment, industrial pollution control, and increased governance systems.

### 7.1. Best Management and Nature-based Practices

In river systems like the Periyar Basin, where nutrient inputs come from agricultural runoff, household wastewater discharge, industrial effluents, and urban stormwater runoff, traditional pollution management techniques are frequently ineffective. Instead, integrated techniques that combine Best Management Practices (BMPs) and nature-based solutions (NbS) are becoming increasingly popular for reducing pollution loads while improving watershed resilience and ecosystem sustainability. BMPs are scientifically tested land and water management techniques that reduce soil erosion, nutrient runoff, and sediment transport in human-dominated landscapes. In contrast, nature-based solutions utilize natural ecosystem processes to regulate hydrological flows and improve water quality (Anawar & Chowdhury, 2020).

Precision nutrient management strategies can dramatically minimise nutrient losses in agricultural landscapes, which are a primary source of diffuse nutrient pollution caused by fertiliser application and soil disturbance. This method involves optimising fertiliser application rates, timing, and positioning based on crop requirements and soil nutrient status, hence avoiding excess nutrient inputs and the possibility of nitrogen and phosphorus runoff. Studies have indicated that optimised fertiliser management systems can reduce nitrogen losses from agricultural fields by 20-40% when compared to traditional fertilisation practices (Liu et al., 2025). Similarly, conservation tillage, which reduces soil disturbance and keeps crop residues on the soil surface, increases soil structure and organic matter content while decreasing erosion and runoff. According to research, conservation tillage strategies can reduce sediment loss from agricultural areas by 50-70%, decreasing sediment-bound phosphorus transport into neighbouring water bodies (Rahman et al., 2021). Another widely recognised method is to develop riparian buffer zones, which are vegetated strips along riverbanks and streams that intercept surface runoff, trap sediments, and absorb nutrients before they reach bodies of water. Vegetation in riparian buffers enhances infiltration and nutrient uptake through plant and microbial processes, and studies have demonstrated that under ideal conditions, these systems can remove up to 70-90% of nitrogen and phosphorus from agricultural runoff.

Natural systems, such as wetlands, also play an important role in regulating nutrient dynamics in river basins. Wetlands enhance water quality through natural processes such as sedimentation, plant absorption, and microbial denitrification. Constructed wetlands, which replicate natural wetland ecosystems, are commonly used as natural wastewater treatment systems, capable of removing 40-90% of nitrogen and phosphorus from wastewater, depending on design and operational conditions (Ge et al., 2019). A notable example is the wastewater-fed aquaculture system in the East Kolkata Wetlands, which treats municipal wastewater using natural ecological processes while supporting aquaculture and agriculture, demonstrating the efficacy of wetland-based solutions for sustainable water management (Tom et al., 2021).

Urban areas also contribute significantly to nutrient and pollution loads via stormwater runoff from impermeable surfaces like roads, parking lots, and buildings. Urban green infrastructure, such as bioswales, rain gardens, permeable pavements, and green roofs, is an effective stormwater management approach that reduces pollutant transfer. These systems collect and infiltrate stormwater runoff, restrict water flow, and promote nutrient uptake by vegetation and soil microbes. According to research, urban green infrastructure can reduce stormwater runoff volumes by 30-60% while also reducing nutrient and sediment transfer into drainage systems (Smith et al., 2023).

Catchment restoration and riverbank stabilisation help to reduce sediment and nutrient loads into river systems. Vegetative stabilisation techniques based on grasses, shrubs, and trees fortify riverbanks and prevent erosion caused by heavy flows, while reforestation and watershed restoration improve infiltration and regulate runoff in upstream catchments. Forested landscapes are especially essential in tropical watersheds because they regulate hydrological processes and minimise sediment movement during heavy rain events. Research has demonstrated that restoring forest cover in damaged catchments can dramatically reduce soil erosion and enhance downstream water quality (Li et al., 2021). Maintaining forest cover in the higher catchments of the Periyar River plays an important role in supporting watershed health and controlling sediment delivery during monsoon rainfall events in locations such as the Western Ghats.

The timely removal of invasive aquatic macrophytes, particularly water hyacinth (*Eichhornia crassipes*), before the onset of the southwest monsoon is another important management measure for the Periyar River Basin. Dense mats of water hyacinth obstruct river flow, reduce channel conveyance, trap floating debris and sediments, and impede the drainage of floodwaters, thereby increasing the risk of localised flooding during periods of high discharge. Early-season mechanical removal of water hyacinth from river channels, drainage canals, and flood-prone stretches can improve hydraulic efficiency, facilitate the unobstructed passage of floodwaters, and reduce the accumulation of organic matter that contributes to nutrient recycling and water quality deterioration. Regular pre-monsoon clearance, coupled with proper disposal or beneficial utilisation of the harvested biomass, should therefore form an integral component of flood management and river maintenance in the Periyar River Basin.

When combined, these best management and nature-based approaches form several barriers that intercept nutrients and pollutants before they enter river systems. Integrating agricultural nutrient management, riparian buffers, wetland restoration, urban green infrastructure, and catchment restoration can provide a comprehensive and long-term approach to reducing nutrient loads while improving ecosystem services like flood regulation, biodiversity conservation, and climate resilience in the Periyar River Basin.

### 7.2. Policy and Stakeholder Interventions

In complex river systems like the Periyar Basin, where pollution comes from a variety of sources, including agriculture, domestic wastewater, industrial activities, and urban runoff, coordinated policy interventions and stakeholder engagement are critical to ensuring the success of load management plans. Policies that limit pollutant discharges, encourage sustainable land-use practices, and facilitate environmental monitoring are critical for managing both point and non-point pollution sources across the basin.

Environmental regulations and water quality standards serve as the legal basis for pollution management and the protection of aquatic ecosystems. In India, the Water (Prevention and Control of Pollution) Act of 1974, as well as subsequent environmental rules, empower authorities like the Central Pollution Control Board (CPCB) and State Pollution Control Boards (SPCBs) to monitor water quality and restrict industrial effluent discharge. These regulatory systems are critical in identifying pollution hotspots and ensuring compliance with environmental norms. However, effective implementation of these policies frequently necessitates improved monitoring systems, increased enforcement power, and greater coordination among regulatory bodies.

Integrated river basin management techniques are widely recognised as an efficient policy framework for managing complex environmental issues in river systems. Such approaches emphasise cross-sector planning, which includes agricultural, urban growth, industry, and environmental conservation. By treating the entire watershed as a management unit, basin-scale governance frameworks allow policymakers to handle the cumulative effects of many pollution sources. International experiences in river basins such as the Rhine and Danube show that coordinated strategies involving many stakeholders and jurisdictions can dramatically reduce nutrient loads and improve water quality over time (Giri, 2020).

Local communities, farmers, industry, municipalities, and civil society organisations all have a significant impact on land-use patterns and pollution control initiatives. Involving these stakeholders in decision-making processes can improve the efficacy of policy interventions and encourage more environmental accountability. For example, community-based watershed management projects have demonstrated that incorporating local stakeholders in monitoring and conservation operations can dramatically increase the adoption of sustainable land-use practices and pollution control measures (Zhou et al., 2022).

Farmers play an important role in implementing agricultural best management practices that limit nutrient runoff, while industry must adopt cleaner production technology and adhere to effluent discharge regulations. Municipal governments are responsible for upgrading wastewater treatment infrastructure and solid waste management systems, which are critical for minimising nutrient inputs from metropolitan areas. At the same time, research institutions and environmental organisations provide significant scientific knowledge and monitoring data that can help guide policy decisions and management methods.

Public awareness and education campaigns are also an important component of stakeholder participation in river basin management. Raising knowledge about the environmental consequences of nutrient pollution can spur behavioural changes in communities and enterprises, resulting in more sustainable resource use practices. Educational activities, citizen science projects, and participatory monitoring programs can all contribute to a shared sense of responsibility for conserving river ecosystems.

Overall, legislative frameworks and stakeholder interventions are essential components of successful load control techniques in the Periyar River Basin. Strengthening regulatory systems, supporting integrated basin governance, and encouraging active participation from local stakeholders can all help to improve pollution control measures and support long-term water quality and ecosystem health.

## 8. Conclusion

The comprehensive analysis of nutrient and sediment dynamics in the Periyar River Basin (PRB) advances our understanding of this critical system, moving from static concentration measures to a dynamic, basin-scale load budgeting framework. The findings show a clear structural divergence across the river continuum: nonpoint agricultural runoff in steep upland terrain drives massive seasonal pulses of particulate nutrients during monsoons, whereas severe urban-industrial point sources in the lower reaches cause chronic, year-round pollution. Furthermore, the basin's extensive reservoir network traps sediment upstream, causing a downstream "sediment famine" that affects river geomorphology and disrupts the biogeochemical balance of the associated Vembanad Lake system.

To bridge the gap between these diagnoses and future action, this report serves as a fundamental plan, outlining essential directions for research, technology, and management:

- **Asset for future research:** This study addresses historical data fragmentation by creating a standardised, cross-agency structure. It provides the precise, load-standardised geographical indicators needed to calibrate predictive hydrochemical models, such as the Soil and Water Assessment Tool (SWAT), which simulate climate change impacts. Furthermore, these quantitative nutrient loads enable marine and freshwater biologists to assess internal loading hazards, forecast legacy contamination in riverbed deposits, and examine how altered nitrogen-to-silicon (N: Si) ratios drive harmful algal blooms and fish deaths in the estuary.
- **Technological implementation and planning**: To move past reactive water management, quantitative load budgets provide a clear path for developing and implementing new technology. This includes installing automated telemetry networks and real-time IoT monitoring stations at crucial high-load sub-basin outlets such as Pathalam, Kalady, and Aluva to detect industrial effluent surges immediately. On an engineering level, it supports the integration of automated reservoir sediment bypass systems and hydro-suction dredging during peak monsoon flows to restore sediment continuity, as well as the connection of real-time water quality sensors to reservoir gates for automated environmental flow (E-flow) releases that dilute downstream pollutants during dry periods.
- **Strategical managerial and policy decisions**: The evidence shifts the focus to proactive, strategic policy decisions grounded in an Integrated River Basin

Management (IRBM) plan of action. It emphasises the critical necessity for a centralised Periyar Basin Authority to manage a common, open-access digital data repository for coordinated environmental planning. Legally, it lays the groundwork for transitioning the Eloor-Edayar industrial zone from outdated concentration norms to tighter Total Maximum Daily Load (TMDL) limits consistent with the river's actual seasonal absorption capacity. On a landscape scale, it justifies the use of targeted nature-based solutions, such as implementing ecological buffers and riparian restoration in upland Idukki agricultural zones to capture fertiliser runoff, and building urban wetlands on the Kochi metropolitan fringe to filter stormwater surges.

In conclusion, by balancing ecological preservation with regional socioeconomic value, this investigation acts as an essential tool for ensuring Kerala's long-term water security and climate resilience.

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