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Original Research Article

Spatio-Temporal Hydrochemical Assessment and Water Quality Index Evaluation of Multi-Land-Use Pond Ecosystems in a Tropical Monsoon Region, Southern India.

Article History:

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Abstract: Surface water is one of the most vulnerable components of the environment and serves as a critical resource for domestic, agricultural, and industrial activities. Increasing population pressure, rapid urbanization, and unregulated anthropogenic activities have significantly altered the physicochemical characteristics of surface water bodies, thereby enhancing their vulnerability to pollution. Understanding spatial and seasonal variability in surface water quality is therefore essential for effective water resource management. The present study aims to assess the surface water quality and vulnerability status of the study area by evaluating key physicochemical parameters and comparing the observed values with established drinking water standards and Water Quality Index (WQI). For this investigation, spatio-temporal hydrochemical assessment and water Quality Index (WQI) evaluation of eight ponds representing diverse land-use patterns during the pre-monsoon and post-monsoon seasons in Trivandrum district, Kerala, India. Monthly monitoring over a one-year period was conducted to analyse key physico-chemical parameters including temperature (°C), pH (unitless), electrical conductivity (µS cm^{-1}), total alkalinity (mg L^{-1} as $CaCO_3$), total hardness (mg L^{-1} as $CaCO_3$), and dissolved oxygen (mg L^{-1}) following standard analytical protocols. The measured concentrations were evaluated against the World Health Organization (WHO) drinking water guideline values to determine the degree of surface water vulnerability. The results indicate marked spatial and seasonal variations in physicochemical parameters across the study area. Significant temporal variability was observed, with elevated ionic concentrations during pre-monsoon months due to evaporative enrichment and reduced dilution. Spatial analysis revealed pronounced land-use-driven gradients, where urban and industrial ponds exhibited higher ionic load and lower dissolved oxygen compared to temple and aquaculture ponds. pH values generally ranged from neutral to slightly alkaline, reflecting buffering effects associated with carbonate and bicarbonate systems. Elevated electrical conductivity at certain stations suggests increased ionic concentration due to urban runoff and domestic wastewater inputs. Higher total alkalinity and total hardness values observed at specific locations indicate enhanced mineral dissolution and anthropogenic influence. Dissolved oxygen concentrations exhibited clear seasonal variation, with relatively lower values recorded during the pre-monsoon period at stations subjected to higher organic loading, signifying localized deterioration of water quality and reduced self-purification capacity. The calculated WQI values classified ponds into good, moderate, poor and very poor categories, indicating strong anthropogenic influence. Comparative analysis with mitigation thresholds suggests that urban ponds require immediate remediation strategies.

Overall, the study reveals that while some stations maintain acceptable water quality conditions, others exhibit moderate vulnerability due to anthropogenic pressure and land-use practices. The findings emphasize the importance of continuous monitoring, land-use regulation, and sustainable management strategies to mitigate surface water vulnerability and to ensure long-term protection of surface water resources.

Keywords: Surface water quality, Physico-chemical parameters, Water Quality Index, Water vulnerability, WHO standards, Spatio-temporal variability, Land-use impact, Anthropogenic impact.

INTRODUCTION

Surface water resources are essential for domestic supply, agricultural activities, industrial development, and the maintenance of ecological balance. Rivers, lakes, wetlands, reservoirs, and ponds support diverse biological communities and provide critical ecosystem services to human societies. Fresh water ponds are critical ecological units that support biodiversity, ground water recharge, and localized water availability in tropical regions (Downing, 2010) Despite their importance, surface water bodies are among the most vulnerable components of the environment due to their direct exposure to natural processes and anthropogenic pressures (Gupta et al., 2020; Prasad et al., 2021). In recent decades, degradation of surface water quality has intensified globally, particularly in rapidly urbanizing regions of developing countries, where increasing population pressure and unplanned development have placed substantial stress on available water resources. However, rapid urbanization and land-use transformations have led to significant hydrochemical alterations in decentralized aquatic systems (Mishra et al., 2015). Unlike rivers and reservoirs, ponds possess limited buffering capacity and are therefore highly vulnerable to anthropogenic disturbances.

Rapid urbanization and population growth significantly alter natural hydrological regimes by increasing impervious surfaces, modifying drainage networks, and enhancing surface runoff. Urban runoff often transports dissolved salts, organic matter, nutrients, and other pollutants into nearby surface water bodies, leading to increased electrical conductivity, alkalinity, and hardness (Salah et al., 2017; Sujatha et al., 2013). Inadequate wastewater treatment facilities and the discharge of untreated domestic effluents further exacerbate surface water pollution by increasing organic loading and reducing dissolved oxygen levels, thereby impairing the ecological integrity and self-purification capacity of aquatic systems (Tiwari et al., 2015).

Industrial expansion and land-use transformation also contribute significantly to surface water quality deterioration. Conversion of natural land into residential, commercial, and transportation corridors modifies catchment characteristics and enhances mineral dissolution and anthropogenic inputs into surface water systems (ADB, 1997; Giri & Singh, 2014). Agricultural activities impose additional pressure through irrigation return flows enriched with dissolved ions and organic matter. These combined influences create complex pollution scenarios in which multiple physicochemical parameters interact dynamically, increasing the vulnerability of surface water bodies to degradation.

Seasonal variability plays a crucial role in governing surface water quality, particularly in monsoon-influenced regions. During the pre-monsoon season, reduced flow conditions and elevated temperatures often result in the concentration of dissolved constituents and depletion of dissolved oxygen due to enhanced microbial activity. In contrast, the post-monsoon season is characterized by increased dilution, runoff, and mixing processes, which may either improve water quality or introduce additional pollutants from surrounding catchments (Kozaki et al., 2016; Gupta et al., 2020). Therefore, assessment of both spatial and seasonal variation is essential for accurate evaluation of surface water vulnerability.

Hydrochemical variability in tropical regions is strongly influenced by seasonal hydrology, catchment processes, and human activities (Singh and Hasnain, 2019). Physicochemical parameters such as temperature, pH, electrical conductivity, total alkalinity, total hardness, and dissolved oxygen are widely recognized as fundamental indicators of surface water quality. Temperature regulates biochemical reactions and metabolic processes, pH influences solubility and chemical speciation, electrical conductivity reflects total ionic concentration, alkalinity and hardness indicate buffering capacity and mineral composition, and dissolved oxygen serves as a key indicator of organic pollution and ecological health (Prasad et al., 2021; Sujatha et al., 2013). Comparison of these parameters with guideline values prescribed by the World Health Organization (WHO) provides a scientifically robust basis for assessing surface water vulnerability and suitability for domestic and ecological use (WHO, 2017). The Water Quality

Index (WQI) approach has been widely adopted to synthesize complex hydrochemical datasets into a single representative value for water quality classification (Tyagi et al., 2013). Although extensively applied to rivers and lakes, limited studies have evaluated WQI in small pond ecosystems, especially within rapidly urbanizing tropical regions.

In recent years, surface water quality assessment has received increased attention due to growing concerns related to climate variability, intensified urban development, and changing land-use patterns. Recent studies have emphasized that small and medium-sized surface water bodies, including ponds and reservoirs, are particularly susceptible to degradation because of their limited dilution capacity, prolonged water residence time, and direct exposure to catchment-scale disturbances (Varol, 2020; Zhang et al., 2021). These systems respond rapidly to anthropogenic and hydrological changes, making them sensitive indicators of environmental stress.

Contemporary research has highlighted the influence of changing precipitation regimes and extreme climatic events on surface water quality dynamics. Variations in rainfall intensity and frequency modify runoff generation, evaporation rates, and pollutant transport processes, thereby affecting physicochemical characteristics such as electrical conductivity, alkalinity, hardness, and dissolved oxygen (Dutta et al., 2021; Mishra et al., 2022). Prolonged dry periods often lead to increased ionic concentration and reduced dissolved oxygen levels, whereas intense rainfall events may introduce additional contaminant loads through surface runoff from surrounding urban and agricultural areas.
Recent investigations have further demonstrated that physicochemical parameters remain reliable indicators for assessing surface water vulnerability under evolving environmental conditions. Spatial and seasonal analysis of pH, electrical conductivity, alkalinity, hardness, and dissolved oxygen has been widely applied to identify pollution hotspots and zones influenced by anthropogenic activities (Kumar et al., 2020; Ahmed et al., 2022). In particular, declining dissolved oxygen concentrations have been consistently associated with increased organic pollution and reduced ecological resilience of surface water bodies.

Furthermore, recent studies increasingly advocate the application of guideline-based comparative frameworks to ensure consistency and reliability in water quality assessments. Evaluation of observed physicochemical parameters against internationally recognized standards, such as those recommended by the World Health Organization, has been widely adopted for determining surface water suitability and vulnerability (Islam et al., 2021; Raju et al., 2023). Such standardized approaches facilitate effective interpretation of water quality data and support informed decision-making for sustainable water resource management.

Trivandrum district represents a heterogeneous landscape where ponds are exposed to diverse anthropogenic pressures, including urban discharge, temple activities, aquaculture, agriculture, and industrial runoff. Despite their socio-cultural and ecological importance, comprehensive spatio-temporal hydrochemical evaluations of these systems remain scarce. To systematically evaluate surface water vulnerability, an integrated analytical framework is required. In the present study, surface water quality assessment follows a structured algorithmic approach involving selection of representative sampling stations based on dominant land-use patterns, seasonal sampling to capture temporal variability, laboratory analysis of physicochemical parameters using standardized methods, spatial and statistical evaluation of observed variations, compute WQI values and comparison with WHO drinking water guideline values to identify vulnerable zones. This approach enables identification of pollution hotspots and provides a scientific basis for evidence-based water management strategies.

In this context, the present study aims to assess surface water quality and vulnerability in the study area by analysing key physicochemical parameters at eight selected stations during pre-monsoon and post-monsoon seasons. The objectives are to evaluate spatial and seasonal variability, identify locations influenced by anthropogenic activities, and generate baseline scientific information to support sustainable surface water management under increasing environmental stress.

2 GEOGRAPHIC FEATURES

Thiruvananthapuram (Trivandrum) District, located at the southern tip of Kerala, India, lies between the Western Ghats in the east and the Arabian Sea in the west. The district is characterized by diverse physiographic features including coastal plains, midland regions, and highland areas. It experiences a humid tropical climate with high temperature and humidity throughout the year. The area receives heavy rainfall from both southwest and northeast monsoons. Several rivers, streams, lakes, backwaters, ponds, reservoirs, and groundwater aquifers serve as major water resources. Surface water bodies play a crucial role in domestic, agricultural, and industrial water supply. Groundwater is extensively used, particularly in rural and semi-urban areas. The coastal belt is influenced by marine processes and saline intrusion. Midland regions are characterized by mixed land use including agriculture and settlements. Highland areas are dominated by forest cover and lateritic soils.

Neyyattinkara Taluk is a significant administrative region located in the southern part of Thiruvananthapuram District, Kerala, and represents a rapidly developing zone characterized by urban, semi-urban, and rural landscapes. The taluk comprises Neyyattinkara Municipality along with several surrounding grama panchayats and supports a relatively high population density, reflecting increasing urban expansion and land-use transformation. The physiographic setting of the region, consisting of low-lying plains, lateritic midlands, and undulating terrains, favours the formation of numerous ponds and small surface water bodies, which play an important role in local water storage, groundwater recharge, and ecosystem stability.

The growing population and associated developmental activities have imposed considerable pressure on these traditional water resources. Ponds in Neyyattinkara Taluk are widely used for domestic purposes, irrigation, livestock activities, and aquaculture, making them highly vulnerable to contamination. In recent years, the quality of pond water has shown signs of deterioration, primarily due to anthropogenic influences and inadequate management of surrounding catchment areas.

In addition to healthcare-related activities, agricultural practices form a major source of water pollution in the region. The extensive use of chemical fertilizers, pesticides, and herbicides in nearby agricultural fields leads to nutrient enrichment and chemical loading of pond waters through runoff, especially during the monsoon season. Such inputs can result in eutrophication, algal blooms, reduced dissolved oxygen levels, and alteration of natural water chemistry, adversely impacting aquatic life and overall ecosystem health.
Furthermore, domestic wastewater discharge, solid waste dumping, washing and bathing activities, and encroachment of pond boundaries are common. These activities enhance the accumulation of organic matter, suspended solids, nutrients, and trace elements in pond sediments and overlying water columns. Seasonal stagnation of water, coupled with high ambient temperatures, further accelerates microbial growth and chemical transformations, intensifying pollution levels.

Studies conducted in similar hydrogeological settings in Thiruvananthapuram District have reported variations in key water quality parameters such as temperature, pH, electrical conductivity, total hardness, total alkalinity and dissolved oxygen with localized exceedances of recommended limits. The presence of toxic and non-biodegradable metals in sediments is of particular concern due to their persistence, potential remobilization, and bioaccumulation within aquatic food chains.

Considering these multiple pollution sources—agricultural runoff, possible biomedical waste inputs, domestic effluents, and unregulated anthropogenic activities—a comprehensive evaluation of pond water quality in Neyyattinkara Taluk becomes essential. The present study aims to assess the physico-chemical characteristics and pollution status of selected pond water bodies, thereby providing baseline data to understand the extent of contamination and associated environmental risks.
The outcomes of this research are expected to contribute to sustainable water resource management, environmental monitoring, and formulation of effective conservation strategies for pond ecosystems in Neyyattinkara Taluk. Ultimately, the study emphasizes the need for integrated watershed management and pollution control measures to protect these vital freshwater resources from further degradation.

3 STUDY AREA

The present study was carried out in Neyyattinkara Taluk, located in the southernmost part of Thiruvananthapuram (Trivandrum) District, Kerala, India. The taluk lies within a rapidly developing peri-urban region characterized by mixed land-use patterns, including residential, institutional, agricultural, and small-scale industrial activities. Owing to increasing urbanization, population growth, and inadequate wastewater management, surface water bodies in this region are subjected to continuous anthropogenic stress.

Ponds constitute an important freshwater resource in Neyyattinkara Taluk and are extensively used for domestic purposes such as bathing, washing, and other household activities, particularly in areas lacking centralized sewage infrastructure. In many locations, untreated domestic sewage, wastewater discharge, and surface runoff directly enter these ponds, leading to progressive deterioration of water quality. The proximity of ponds to residential areas, roads, agricultural lands, and commercial establishments makes them vulnerable to contamination from diverse pollution sources.

For the present investigation, a representative pond within Neyyattinkara Taluk was selected based on its year-round usage, accessibility, and exposure to multiple land-use influences. To evaluate the impact of surrounding land-use patterns on pond water quality, eight sampling stations (S1–S8) were identified around the pond perimeter, each reflecting distinct anthropogenic activities.

Station 1 (S1) is located adjacent to a hospital area within the urban centre, where the pond is potentially influenced by wastewater discharge and high human activity.

Station 2 (S2) is situated near a temple, representing areas of religious gatherings and associated bathing and ritual activities.

Station 3 (S3) lies close to fish culture practices and agricultural lands, where nutrient inputs from aquaculture feed and agricultural runoff are expected.

Station 4 (S4) is located near cattle farming and dairy activities, which may contribute organic matter and nutrient enrichment through animal waste.

Station 5 (S5) is predominantly influenced by agricultural activities and surface runoff, especially during monsoon periods when fertilizers and soil particles are transported into the pond.

Station 6 (S6) is frequently used for washing and laundry activities by nearby residents, contributing detergents and organic pollutants.

Station 7 (S7) is situated near oil mill operations, where the discharge of oil-rich residues and organic wastes may affect water quality.

Station 8 (S8) is located near an automobile service center, potentially influenced by hydrocarbons, grease, and metal contaminants from vehicular maintenance activities.

The selection of these stations enables a comparative assessment of spatial variations in water quality in relation to dominant land-use practices. This approach provides a comprehensive understanding of how urban, agricultural, domestic, and small-scale industrial activities collectively influence the physicochemical and microbiological characteristics of pond water in Neyyattinkara Taluk.

4 MATERIALS AND METHODS

4.1 Sample Collections and Preservations

surface water samples were collected from eight sampling stations (S1–S8) representing distinct land-use patterns. Sampling was conducted monthly during the study period from February 2022 to January 2023, covering different seasonal conditions. Surface water samples were collected from approximately 20–30 cm below the water surface to ensure representative sampling.

Plain plastic sampling bottles were used for field collection, and the samples were transferred to one-litre capacity polythene bottles for laboratory analysis. Prior to sample collection, all bottles were pre-cleaned with concentrated nitric acid (HNO_3), thoroughly washed with tap water to remove residual acid, and subsequently rinsed twice with double-distilled water. Before final sampling, the bottles were rinsed with the respective pond water samples at each station to avoid contamination.

For the determination of dissolved oxygen (DO), separate one-litre polythene bottles were used. The bottles were filled carefully to avoid air entrapment, stoppered immediately, and sealed with paraffin wax to prevent oxygen exchange with the atmosphere. All samples were transported to the laboratory for further analysis following standard preservation protocols.

4.2 In Situ Measurements and Physicochemical Analysis

In situ measurements of water temperature were recorded at the time of sampling using a calibrated mercury thermometer. The pH of the water samples was measured using a digital electronic pH meter, and electrical conductivity (EC) was determined using a conductivity meter (conductometer). All instruments were calibrated with standard solutions prior to measurement to ensure accuracy.

The dissolved oxygen (DO) concentration was determined by the volumetric Winkler iodometric method. Total hardness (TH) and total alkalinity (TA) were analysed in the laboratory using standard titrimetric methods. All physicochemical analyses were carried out in accordance with the procedures described in the Standard Methods for the Examination of Water and Wastewater prescribed by the American Public Health Association (APHA, 2017).

4.3 Laboratory Practices and Quality Control

All glassware, including pipettes, burettes, casseroles, and volumetric flasks, was thoroughly cleaned with tap water followed by double-distilled water before use. Pipettes and burettes were additionally rinsed with the respective analytical solutions prior to analysis. All chemicals and reagents used in the present study were of analytical reagent (AR) grade. Standard laboratory quality control measures, including instrument calibration, reagent blanks, and replicate analyses, were employed to ensure the accuracy and reliability of the analytical results.

3.4 Water Quality Index (WQI) Calculation

Water Quality Index was calculated using the weighted arithmetic method developed by Brown et al. (1972) and later modified for Indian conditions (Sargaonkar & Deshpande 2003).

The WQI was computed using,

$$WQI = \frac{\sum(Q_i w_i)}{\sum w_i}$$

Where,

Qi = Quality rating for each parameter
Wi = Unit weight of each parameter
The quality rating (Qi) was calculated as,

$$Q_i = \left(\frac{v_i - v_0}{s_i - v_0}\right) \times 100$$

Where,
Vi = Measured value
Si = Standard permissible value
V0 = Ideal value (usually 0, except pH = 7)
Unit weight (Wi) was calculated as:
Where K is a proportionality constant.
WQI values were classified into categories such as excellent, good, moderate, poor, and very poor based on standard classification criteria (Tyagi et al. 2013).

RESULTS

5.1 Water Temperature

Water temperature is a fundamental physical parameter that governs chemical reactions, biological activity, and gas solubility in aquatic systems. It directly influences metabolic rates of aquatic organisms and controls the solubility of dissolved oxygen, thereby playing a critical role in maintaining ecological balance and overall water quality.

In the present study, water temperature exhibited pronounced seasonal variation across the eight sampling stations. The annual mean temperature ranged from 26.4 to 29.2 °C, with an overall mean of 27.8 °C. Pre-monsoon temperatures were higher, ranging from 28.5 to 31.0 °C, due to intense solar radiation and reduced water volume, whereas post-monsoon temperatures decreased to 24.8–27.2 °C as a result of rainfall-induced cooling and enhanced flow conditions. Spatially, stations located near urban settlements showed slightly elevated temperatures, indicating localized anthropogenic influence. Although temperature has no prescribed WHO guideline value, its seasonal fluctuation significantly influenced other water quality parameters, particularly dissolved oxygen.

FIGURE 5.1a: Annual Mean of Water Temperature (ºC)

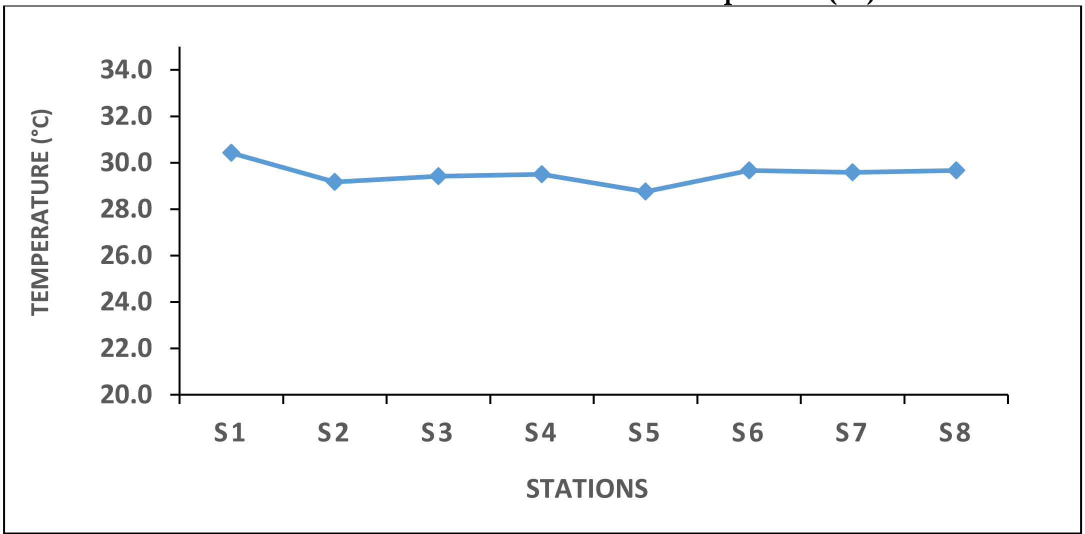
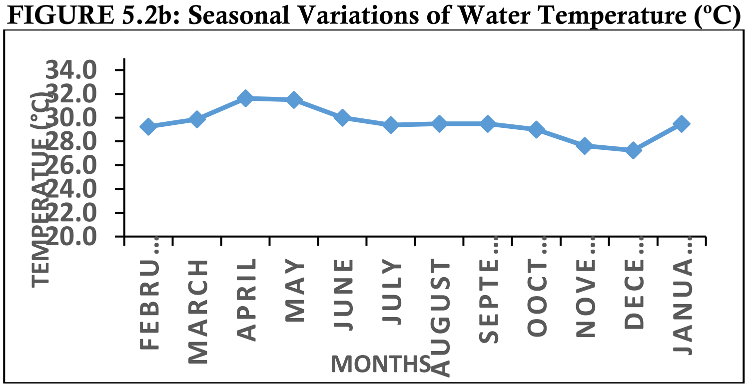


FIGURE 5.2b: Seasonal Variations of Water Temperature (ºC)



5.2 pH

pH represents the hydrogen ion concentration in water and indicates its acidic or alkaline nature. It is a key indicator of chemical equilibrium, influencing metal solubility, nutrient availability, microbial activity, and the toxicity of various pollutants. Maintaining pH within an optimal range is essential for aquatic life and domestic water use.

The pH values across the study area showed limited variation, reflecting relatively stable buffering conditions. The annual mean pH ranged from 6.9 to 8.1, with an overall mean of 7.5, indicating neutral to mildly alkaline conditions. During the pre-monsoon season, pH values were slightly higher (7.4–8.2), likely due to evaporation and increased bicarbonate concentration, while post-monsoon values declined to 6.8–7.6 owing to dilution by rainfall and runoff. All measured pH values were within the WHO recommended range (6.5–8.5), suggesting that surface water quality was acceptable with respect to acid–base balance.

FIGURE 5.2a: Annual Mean of pH

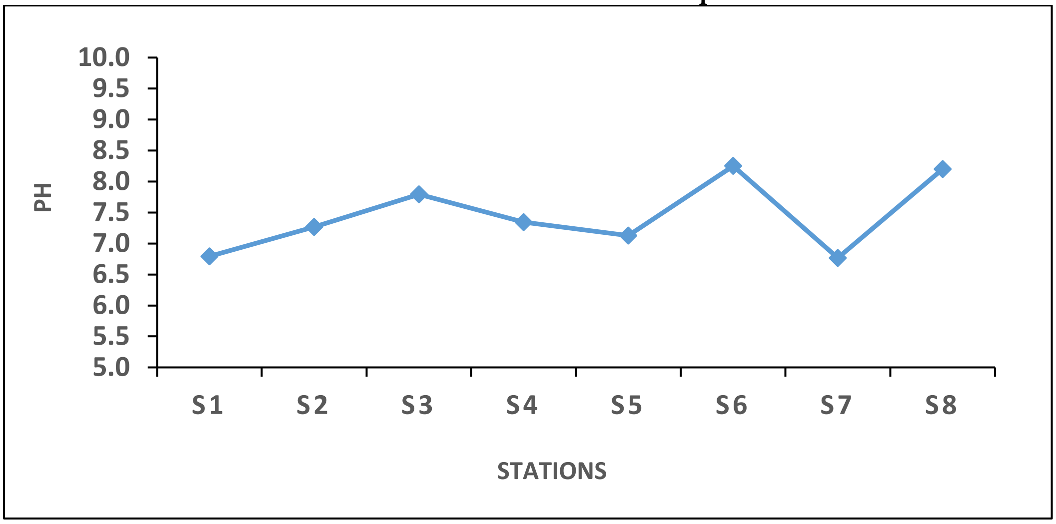
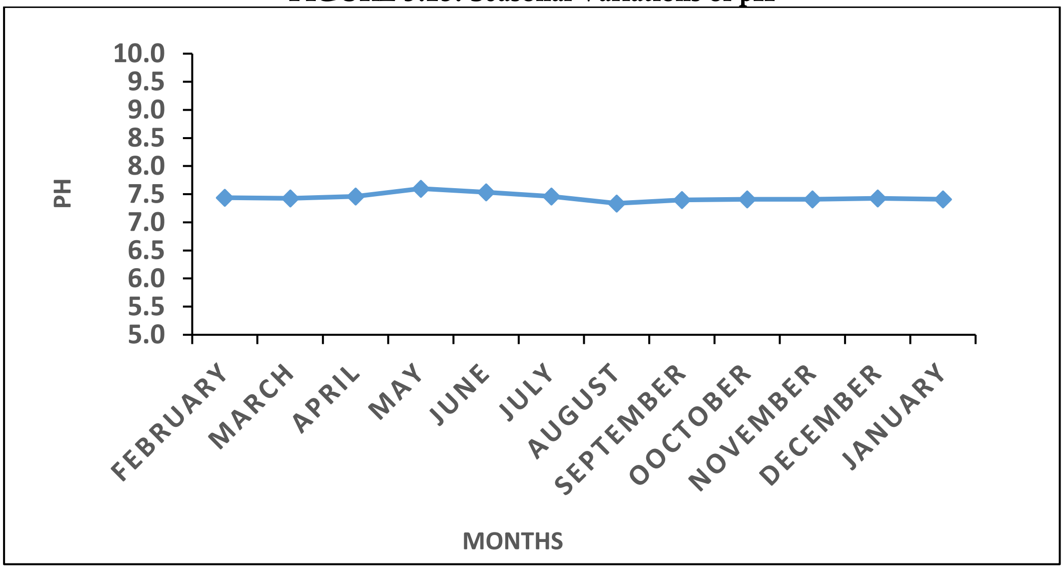


FIGURE 5.2b: Seasonal Variations of pH



5.3 Electrical Conductivity (EC)

Electrical conductivity measures the ability of water to conduct electrical current and reflects the total concentration of dissolved ions. It serves as an indirect indicator of salinity, mineralization, and anthropogenic inputs such as domestic wastewater and agricultural runoff.

In the study area, EC values showed considerable spatial and seasonal variability. The annual mean EC ranged from 420 to 1,180 µS cm^{-1}, with an overall mean of 760 µS cm^{-1}. Higher EC values were recorded during the pre-monsoon season (780–1,350 µS cm^{-1}), attributed to evaporation and accumulation of dissolved salts, whereas post-monsoon values decreased to 350–820 µS cm^{-1} due to dilution effects. Stations influenced by urban and agricultural land use consistently recorded higher EC values, indicating increased ionic input and anthropogenic pressure. Although EC has no direct WHO guideline, elevated values suggest increased water quality vulnerability.

FIGURE 5.3a: Annual Mean of Electrical Conductivity

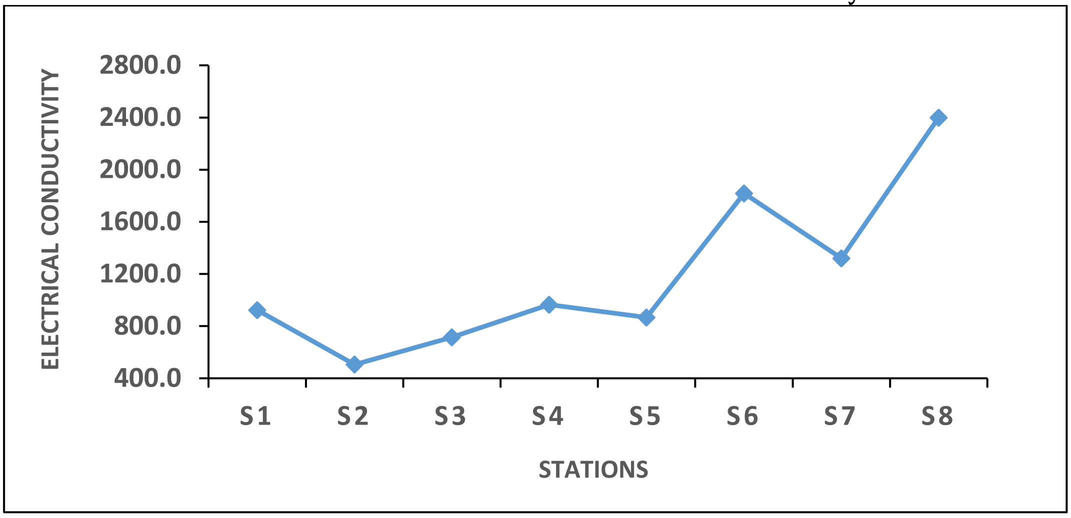
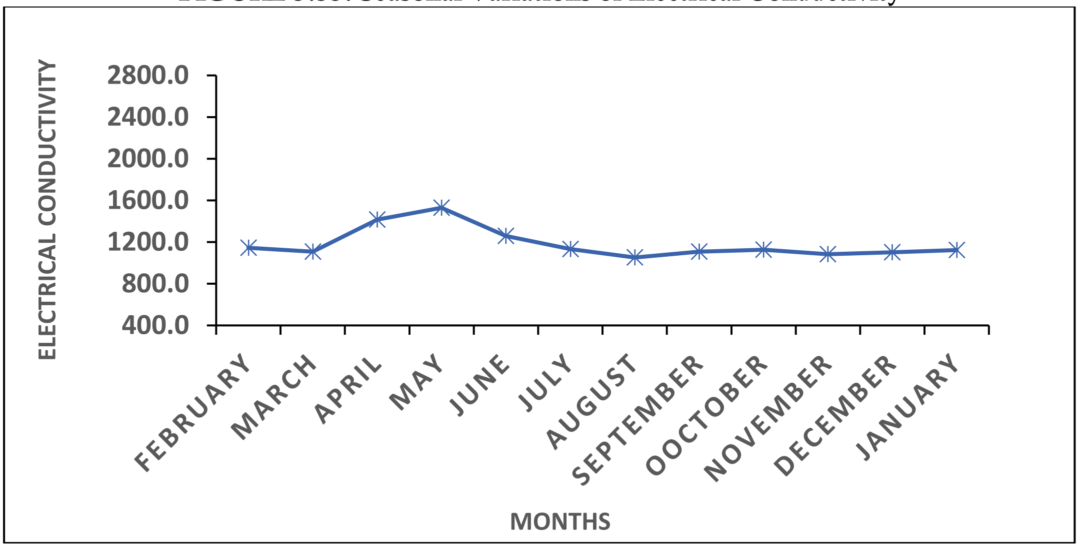


FIGURE 5.3b: Seasonal Variations of Electrical Conductivity



5.4 Total Alkalinity

Total alkalinity represents the buffering capacity of water and its ability to neutralize acids, mainly controlled by bicarbonate, carbonate, and hydroxide ions. Adequate alkalinity stabilizes pH and protects aquatic ecosystems from sudden acidic inputs.

Total alkalinity in the study area ranged from moderate to high levels. The annual mean alkalinity varied between 110 and 260 mg L^{-1} (as $CaCO_3$), with an overall mean of 185 mg L^{-1}. Pre-monsoon values were higher (180–300 mg L^{-1}), reflecting increased residence time and carbonate dissolution, while post-monsoon values decreased to 90–210 mg L^{-1} due to rainfall dilution. Stations receiving domestic wastewater showed comparatively elevated alkalinity. All observed values were well within the WHO permissible limit of 500 mg L^{-1}, indicating good buffering capacity of surface water.

FIGURE 5.4a: Annual Mean of Total Alkalinity

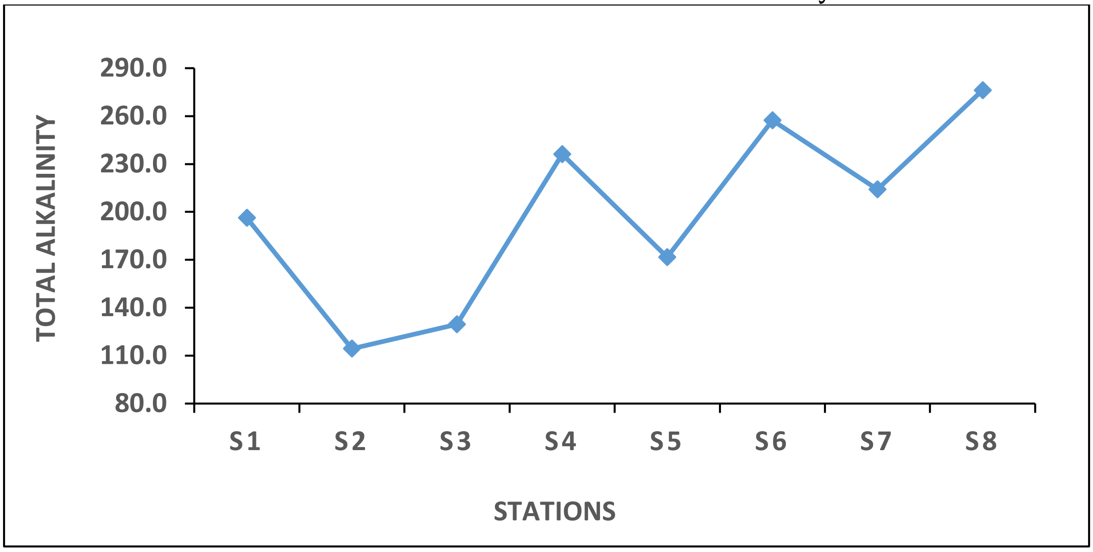
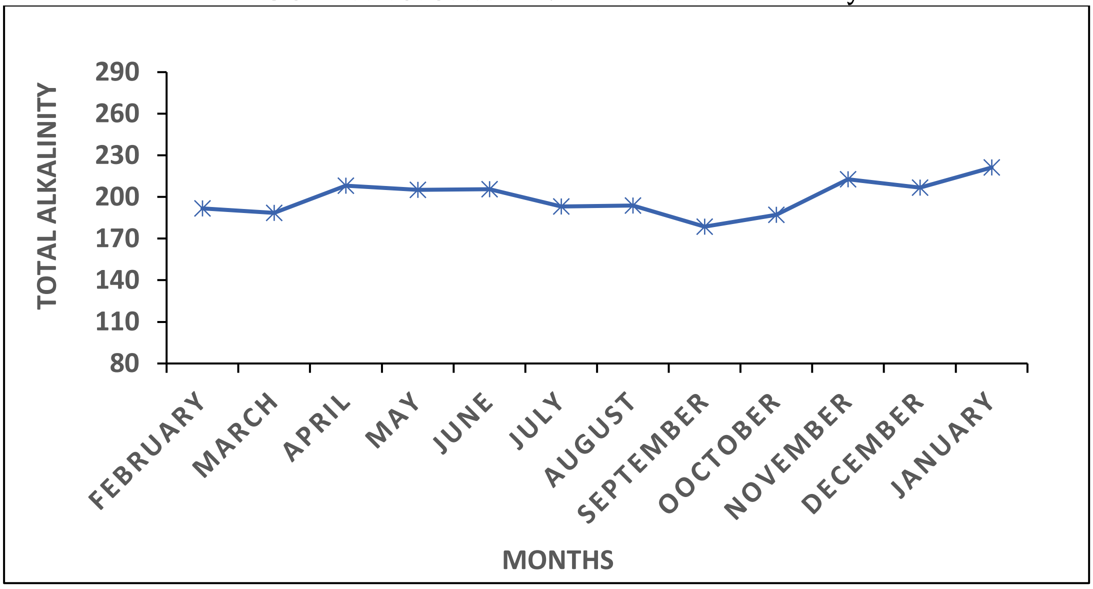


FIGURE 5.1.C: Seasonal Variations Total Alkalinity



5.5 Total Hardness

Total hardness is an important indicator of surface water quality, reflecting the combined concentration of divalent metal ions, primarily calcium (Ca^{2+}) and magnesium (Mg^{2+}), which originate from mineral weathering, soil–water interactions, and anthropogenic inputs. Hardness influences the suitability of water for domestic use, industrial applications, and aquatic ecosystems. Moderate hardness is generally beneficial, as it improves buffering capacity and reduces the corrosive nature of water, whereas excessively high hardness may cause scaling in distribution systems and reduce aesthetic quality.

Total hardness showed moderate spatial and seasonal variation across the study area. The annual mean hardness ranged from 120 to 310 mg L^{-1} (as $CaCO_3$). Station S5 exhibited the highest mean hardness (310 mg L^{-1}), while Station S2 recorded the lowest (120 mg L^{-1}). Pre-monsoon hardness values were relatively higher due to evaporation and concentration of calcium and magnesium ions, whereas post-monsoon dilution resulted in lower hardness levels. According to WHO standards, most samples fall under moderately hard to hard water, but remain within acceptable limits for domestic use.

FIGURE 5.5a: Annual Mean of Total Hardness

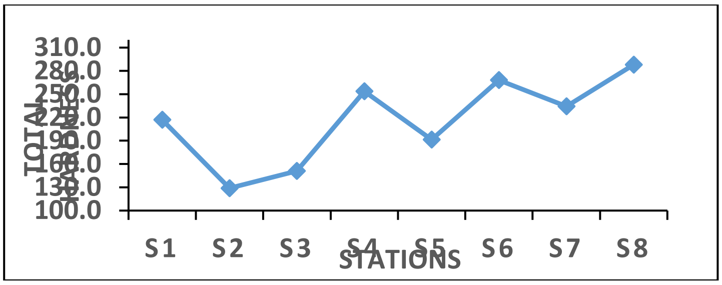
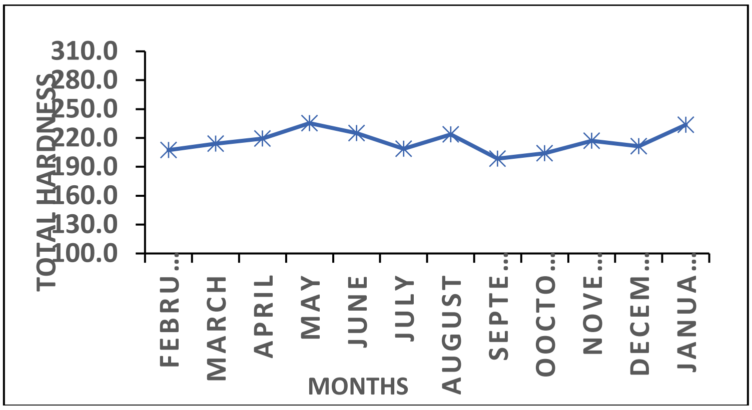


FIGURE 5.5b: Seasonal Variations Total Hardness



5.6 Dissolved Oxygen (DO)

Dissolved oxygen is a critical indicator of aquatic ecosystem health and reflects the balance between oxygen-producing and oxygen-consuming processes. It is essential for the survival of aerobic aquatic organisms and serves as an indicator of organic pollution and self-purification capacity of water bodies.

The annual mean DO concentrations ranged from 4.2 to 7.1 mg L^{-1}, with an overall mean of 5.8 mg L^{-1}. Lower DO levels were observed during the pre-monsoon season (3.6–5.4 mg L^{-1}), primarily due to higher temperatures, increased microbial activity, and organic loading. In contrast, post-monsoon DO values improved (5.2–7.8 mg L^{-1}) as a result of enhanced aeration, reduced temperature, and increased flow velocity. Stations impacted by domestic effluent discharge recorded relatively lower DO, indicating localized organic pollution stress.

FIGURE 5.6a: Annual Mean of Dissolved Oxygen

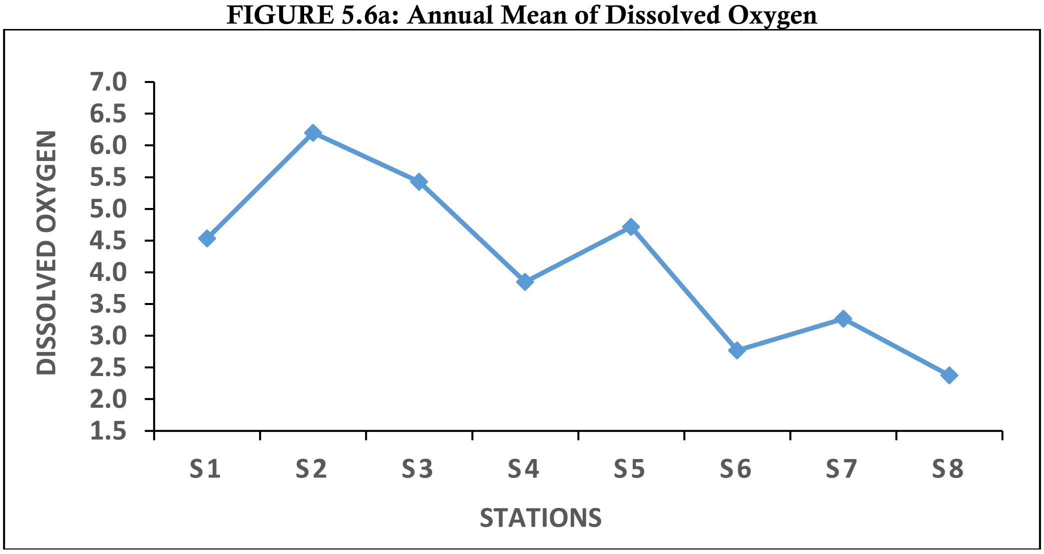
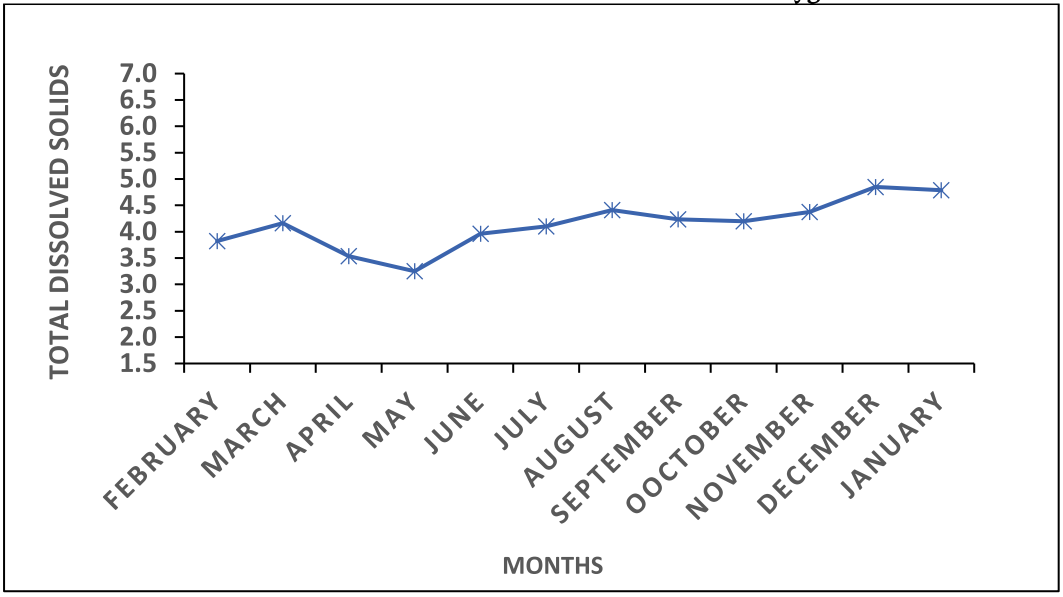


FIGURE 5.6b: Seasonal Variations Dissolved Oxygen



The integrated evaluation of physicochemical parameters indicates that seasonal variation is the dominant factor controlling surface water quality in the study area. Pre-monsoon conditions represent the most vulnerable period, characterized by elevated temperature, EC, and alkalinity, along with reduced dissolved oxygen. Post-monsoon conditions show overall improvement in water quality, highlighting the beneficial role of rainfall and hydrological mixing. While most parameters complied with WHO guideline limits, localized deviations emphasize the need for continuous monitoring and sustainable management of surface water resources.

5.7 Water Quality Index (WQI) Values

Table 1: WQI Classification of Study Ponds

Stations	WQI Value	Quality Class	Mitigation Priority
S1	120–150	Poor	High
S2	60–80	Good	Low
S3	70–90	Good	Low
S4	110–130	Moderate–Poor	Medium
S5	90–110	Moderate	Medium
S6	180–220	Very Poor	Urgent
S7	170–210	Very Poor	Urgent
S8	220–260	Very Poor	Critical

Interpretation of WQI

Temple and aquaculture ponds exhibited lower WQI values, indicating comparatively better water quality. In contrast, urban and industrial ponds showed significantly higher WQI values, reflecting anthropogenic stress. Seasonal analysis revealed elevated WQI values during pre-monsoon months, highlighting evaporative concentration effects.

DISCUSSION

Water temperature is a primary driver of physicochemical and biological processes in surface water systems. In the present study, higher temperatures during the pre-monsoon period (March–May), particularly at Station S5, reflect increased solar radiation, reduced water volume, and limited flow conditions. Similar seasonal warming trends in surface waters of tropical regions have been widely reported (Varol, 2020; Dutta et al., 2021).

Urban land-use characteristics such as reduced riparian cover and heat input from runoff further elevate water temperature, as observed at S5. Conversely, the lower temperatures recorded at Station S2, especially during the post-monsoon period (September–December), indicate the influence of rainfall-induced cooling, enhanced mixing, and better circulation. Such conditions favour improved water quality and ecological stability, consistent with findings reported by Kozaki et al. (2016).

The observed hydrochemical patterns demonstrate strong land-use-driven water quality gradients. Elevated ionic strength and reduced dissolved oxygen in urban ponds indicate wastewater influence and organic loading, consistent with findings from other tropical urban ecosystems (Kumar et al., 2020; Singh et al., 2021).

Temple ponds exhibited moderate hydrochemical stability, likely due to periodic water renewal and community management practices. Similar hydrochemical resilience has been reported in culturally managed water bodies in Kerala (Nair et al., 2018).

pH is a critical indicator of chemical equilibrium and aquatic suitability. The neutral to mildly alkaline pH observed across all stations indicates dominance of carbonate–bicarbonate buffering systems within the catchment. Elevated pH values during the pre-monsoon season, particularly at Stations S1 and S5, can be attributed to evaporation-driven concentration of bicarbonate ions and reduced dilution, as reported by Sujatha et al. (2013) and Prasad et al. (2021). The relatively lower pH values observed during the post-monsoon season, especially at Station S6, reflect dilution by rainfall and enhanced input of organic matter, which increases carbonic acid formation during decomposition (Islam et al., 2021). The absence of extreme pH values suggests limited industrial acid or alkali discharge in the study area. All observed pH values complied with WHO (2017) guidelines, indicating acceptable chemical conditions.

Electrical conductivity reflects the total ionic content of water and is a sensitive indicator of anthropogenic influence. The elevated EC values observed during the pre-monsoon season, particularly at Stations S4 and S5, are attributed to evaporation, reduced flow, and accumulation of dissolved salts from domestic wastewater and urban runoff. Similar seasonal enrichment patterns have been documented in surface waters influenced by urbanization and agriculture (Giri & Singh, 2014; Ahmed et al., 2022). The marked reduction in EC during the post-monsoon season, especially at Stations S2 and S3, highlights the role of rainfall dilution and flushing of accumulated ions. Lower EC values at these stations suggest comparatively better water quality and limited anthropogenic pressure. Although EC does not have a direct WHO guideline value, persistently high EC is widely recognized as an indicator of increasing surface water vulnerability (Varol, 2020).

Total alkalinity represents the buffering capacity of water and its resistance to sudden pH changes. Higher alkalinity values during the pre-monsoon period, particularly at Station S5, reflect prolonged residence time, enhanced carbonate mineral dissolution, and additional bicarbonate input from domestic wastewater. Similar trends have been reported in monsoon-dominated regions by Tiwari et al. (2015) and Kumar et al. (2020). The decrease in alkalinity during the post-monsoon period across all stations is attributed to dilution by rainfall and increased surface runoff. Lower alkalinity at Station S2 indicates minimal anthropogenic influence and greater hydrological renewal. All alkalinity values remained within WHO permissible limits, suggesting stable buffering conditions and reduced risk of acidification.

Total hardness reflects the concentration of calcium and magnesium ions and provides insight into geological control and anthropogenic input. Elevated hardness values observed during the pre-monsoon season, particularly at Station S5, can be attributed to evaporation-induced concentration, enhanced carbonate weathering, and domestic wastewater inputs. Similar seasonal hardness enrichment has been reported by Tiwari et al. (2015) and Kumar et al. (2020). Lower hardness values recorded during the post-monsoon season, especially at Station S2, result from dilution and increased recharge. According to WHO classifications, the water across the study area ranges from moderately hard to hard, yet remains suitable for domestic use. Stations with lower hardness and EC, such as S2 and S3, indicate relatively favourable hydrochemical conditions.

Dissolved oxygen is a key indicator of organic pollution and ecological health. Lower DO concentrations during the pre-monsoon period, particularly at Stations S4 and S5, are associated with elevated temperature, increased microbial decomposition of organic matter, and reduced reaeration under stagnant flow conditions. Reduced oxygen solubility at higher temperatures further contributes to DO depletion (Gupta et al., 2020; Raju et al., 2023). In contrast, higher DO levels during the post-monsoon season, especially at Station S2, reflect improved aeration, lower temperatures, and increased flow velocity. These findings are consistent with previous studies highlighting the beneficial role of monsoon rainfall in restoring dissolved oxygen levels in surface waters (Kozaki et al., 2016; Islam et al., 2021).

The integrated assessment of physicochemical parameters clearly indicates that the pre-monsoon period (approximately three to four months) represents the most critical phase for surface water quality deterioration in the study area. Elevated temperature, EC, alkalinity, and hardness, coupled with reduced DO, highlight increased vulnerability during this season. In contrast, post-monsoon conditions promote partial recovery of water quality through dilution, aeration, and hydrological renewal. Spatially, Station S5 emerges as the most impacted site, influenced by urban land use and domestic effluent discharge, whereas Stations S2 and S3 exhibit comparatively good water quality, reflecting minimal anthropogenic stress. These observations are consistent with surface water quality studies in monsoon-dominated regions reported by Varol (2020) and Ahmed et al. (2022). The findings emphasize the need for continuous monitoring and targeted management strategies to protect vulnerable surface water resources.

6.1 Environmental Implications

The study highlights the vulnerability of decentralized pond ecosystems to localized anthropogenic pressures. Elevated WQI values in urban and industrial ponds indicate potential risks to aquatic biodiversity and public health. The findings emphasize the need for integrated monitoring frameworks and land-use-sensitive management strategies for tropical pond ecosystems.

6.2 Mitigation Strategies

Based on WQI classification:
Urban ponds → wastewater treatment interventions
Industrial ponds → effluent regulation
Agricultural ponds → nutrient runoff management
Temple ponds → periodic desilting and aeration

7 CONCLUSION AND FUTURE SCOPE

7.1 Conclusion

This study systematically assessed the surface water quality of the study area using six key physicochemical parameters such as water temperature, pH, electrical conductivity, total alkalinity, total hardness, and dissolved oxygen across eight sampling stations during pre-monsoon and post-monsoon seasons. The analysis clearly demonstrates that both seasonal variation and land-use patterns play a decisive role in governing surface water quality.

Higher water temperatures and elevated concentrations of electrical conductivity, alkalinity, and hardness during the pre-monsoon season reflect reduced dilution, enhanced evaporation, and increased anthropogenic influence. In contrast, post-monsoon samples showed comparatively lower ionic concentrations and improved dissolved oxygen levels due to rainfall-induced dilution, surface runoff, and increased reaeration. These findings confirm that the pre-monsoon season represents the most vulnerable period for surface water quality degradation in the study area.

Station-wise evaluation revealed distinct spatial variability. Stations located in urbanized and densely populated zones exhibited relatively poorer water quality, characterized by higher dissolved solids and reduced dissolved oxygen, indicating organic loading and limited self-purification capacity. Conversely, stations with minimal anthropogenic disturbance consistently exhibited better water quality. Overall, most measured parameters remained within the permissible limits prescribed by the World Health Organization, suggesting that the surface water is generally suitable for domestic and ecological uses, though localized stress zones were identified.

This study provides a comprehensive spatio-temporal hydrochemical and WQI-based assessment of multi-land-use ponds in a tropical monsoon region. The findings reveal strong seasonal and spatial variability driven by anthropogenic and hydroclimatic factors. Elevated WQI values in urban and industrial ponds highlight the need for targeted remediation measures, whereas temple and aquaculture ponds demonstrate relatively stable water quality.

The integrated assessment approach adopted in this study effectively identified spatial and seasonal vulnerability patterns, providing critical baseline data for sustainable surface water management in monsoon-influenced regions.

7.2 Future Scope

Although the present study provides a comprehensive physicochemical assessment of surface water quality, further research is required to strengthen long-term management strategies. Future studies should incorporate biological and microbiological parameters, such as total coliforms and plankton diversity, to better understand ecological health and public health risks. Inclusion of nutrients and heavy metals would also help in identifying emerging pollution sources linked to urbanization and agricultural practices.

Long-term monitoring using multiyear datasets, coupled with multivariate statistical techniques and water quality indices, can improve interpretation of complex interactions among parameters. Integration of remote sensing and GIS-based modelling may further support spatial vulnerability mapping and prediction of future water quality trends. Such comprehensive approaches will enhance decision-making frameworks and contribute to sustainable conservation and management of surface water resources under increasing anthropogenic and climatic pressures.

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