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# Assessment of Water Quality, Ecological Degradation, and Purification Measures for Bhadawana Pond, Gwalior

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**Abstract**: Bhadawana Pond, a seasonal freshwater body in Gwalior, is undergoing ecological degradation due to untreated sewage, agricultural runoff, and ritual waste. This study evaluates the pond's water quality through physico-chemical analysis, community surveys, and Weighted Arithmetic Water Quality Index (WQI) across pre-monsoon and post-monsoon seasons. Water samples were collected from the central pond, inlet, and outlet zones. Pre-monsoon results showed marginal pollution with WQI values of 17.69–35.57, while post-monsoon values ranged from 16.01–29.65, reflecting minor improvement in inflow but deterioration in core pond oxygen levels (DO < 3 mg/L). Correlation analysis revealed strong inverse relations between DO and BOD, COD, nitrates, and phosphates, indicating nutrient enrichment and eutrophication risk. Despite acceptable TDS and turbidity levels, elevated acidity, microbial load, and declining alkalinity were concerning. Restoration strategies such as constructed wetlands, desilting, and community engagement are proposed. The study underscores the need for integrated ecological and social interventions to rejuvenate urban ponds like Bhadawana.
**Keywords:** Water Quality Index (WQI); Urban Pond Degradation; Ecological Restoration; Seasonal Water Sampling; Bhadawana Pond – Gwalior.

## 1. Introduction

Freshwater ponds constitute an integral component of local hydrological systems, particularly in semi-arid and sub-tropical regions of India, where they function as sources of groundwater recharge, biodiversity habitats, micro-climatic regulators, and socio-cultural spaces for surrounding communities (Mondy et al., 2012; Reed et al., 2017). Traditionally, village and peri-urban ponds have supported domestic water use, livestock needs, irrigation, and religious activities, thereby forming a crucial link between natural ecosystems and human livelihoods. However, rapid urban expansion, population pressure, and the absence of scientific management have resulted in widespread degradation of these small but vital water bodies across Indian cities and towns (Xiao & Wu, 2014).

In recent decades, urban and peri-urban ponds have increasingly transformed into sinks for untreated domestic sewage, agricultural runoff, ritual waste, and solid garbage. Such anthropogenic stressors disrupt the natural self-purification capacity of ponds, leading to declining dissolved oxygen levels, increased organic loading, nutrient enrichment, and microbial contamination (Akhbarizadeh et al., 2016; Ferreira et al., 2017). Visual evidence of these impacts is clearly observable in Bhadawana Pond, Gwalior, where waste dumping, sediment accumulation, and stagnant water zones dominate the landscape. Figure 1 illustrates the degraded environmental condition of the pond, highlighting solid waste deposition, soil erosion, and altered natural flow paths, which collectively accelerate ecological deterioration.

Bhadawana Pond, a seasonal freshwater body located in the Dabra tehsil of Gwalior district, Madhya Pradesh, represents a typical example of neglected urban ponds in central India. Primarily dependent on monsoon runoff and local drainage, the pond has gradually lost its hydrological and ecological functionality due to uncontrolled sewage inflow, agricultural nutrient loading, encroachment, and lack of desilting (Filoso & Palmer, 2011). The rocky catchment, once conducive to clean runoff and groundwater recharge, now facilitates pollutant transport during rainfall events, further degrading water quality. Field observations and photographic documentation reveal stagnant, turbid water with visible contamination, raising concerns regarding both ecosystem health and human exposure risks (Figure 1).

**Figure 1. Environmental Impact and Pollution in Bhadawana Pond**

Beyond ecological implications, the degradation of Bhadawana Pond poses serious public health challenges. The pond water continues to be used by local residents for ritual bathing, washing, livestock activities, and occasionally for domestic purposes during water scarcity periods. Figure 2 depicts the use of visibly contaminated pond water, underscoring the direct human interaction with degraded water resources. Such exposure increases vulnerability to waterborne diseases, including gastrointestinal infections, skin disorders, and vector-borne illnesses, particularly in communities lacking access to treated water supplies (Mueller et al., 2010). Elevated microbial loads and organic pollution, commonly associated with untreated wastewater, further intensify these risks.

**Figure 2. Drinking Contaminated Water**

Assessing the extent of water quality degradation in such ponds requires a systematic and integrative approach. The Weighted Arithmetic Water Quality Index (WQI) method has emerged as a widely accepted tool for synthesizing multiple physico-chemical parameters into a single, comprehensible indicator of water quality status (Uthicke & Nobes, 2008; Yuan et al., 2023). When combined with seasonal analysis, spatial sampling, and correlation studies among key parameters such as dissolved oxygen (DO), biological oxygen demand (BOD), nutrients, and solids, WQI enables effective identification of pollution sources and eutrophication trends . Such quantitative assessments are essential for designing targeted restoration and management strategies.

In this context, the present study aims to assess the water quality, ecological degradation, and restoration potential of Bhadawana Pond through seasonal physico-chemical analysis, Weighted Arithmetic WQI computation, correlation analysis, and community-based observations. By integrating scientific evaluation with socio-environmental perspectives, the study seeks to propose feasible purification and restoration measures, including constructed wetlands, desilting, waste management, and community participation. The research aligns with Sustainable Development Goal 6 (Clean Water and Sanitation) and contributes to the growing body of evidence emphasizing the urgent need for integrated ecological and social interventions to rejuvenate urban and peri-urban freshwater ponds in India.

## 2. Review of Literature

### 2.1 Water Quality Assessment of Urban and Rural Ponds

The assessment of water quality in ponds is critical for understanding the ecological status, pollution sources, and public health risks associated with freshwater bodies. Numerous studies have adopted physico-chemical and biological parameters to evaluate pond water quality, often synthesized through indices such as the Water Quality Index (WQI). Wołejko et al. (2022) provide a comprehensive review of WQI methodologies, highlighting the benefits of weighted arithmetic approaches for integrating multi-parameter data. In India, urban ponds in states like Chhattisgarh (Huang et al., 2020), Maharashtra (Yue et al., 2019), and Delhi (Marzin et al., 2012) have been assessed using WQI, revealing issues like nutrient enrichment, high biological oxygen demand (BOD), and microbial contamination. These studies underscore the importance of seasonal monitoring and location-specific sampling for accurate assessment. In central India, Wang et al. (2019) found that ponds in Gwalior and Jabalpur were moderately to severely polluted, with major pollutants being domestic sewage and agricultural runoff.

### 2.2 Ecological Degradation and Eutrophication in Small Water Bodies

Small freshwater bodies are more vulnerable to ecological degradation due to their limited dilution capacity and greater exposure to localized anthropogenic activities (Samal et al., 2019). Eutrophication, the enrichment of water with nutrients like nitrates and phosphates, leads to excessive algal growth, oxygen depletion, and biodiversity loss (Pander & Geist, 2013). Qian et al. (2022) notes that nutrient loading from agriculture and untreated wastewater is the primary cause of eutrophic conditions in wetlands and ponds. In Indian contexts, Sharma and Radinger et al. (2019) documented the role of untreated domestic discharge and ritual activities in accelerating the degradation of urban ponds. Studies by Anderson et al. (2013) and Hong et al. (2021) emphasize the importance of ecological indicators such as algal blooms, macrophyte invasions, and declining aquatic fauna in assessing degradation severity.

### 2.3 Impact of Pond Pollution on Groundwater and Public Health

The degradation of surface water bodies like ponds often leads to contamination of nearby shallow groundwater aquifers, particularly in alluvial and fractured rock terrains common in central India (Rauf et al., 2018). Percolation of polluted pond water containing nitrates, pathogens, and heavy metals into groundwater reserves poses serious health threats. Yadav et al. (2021) guidelines highlight the risks of diarrheal diseases, hepatitis A and E, and other waterborne illnesses from exposure to polluted water used for bathing, washing, and drinking. In Gwalior district, Poikane et al. (2020) reported a correlation between ritual use of ponds and seasonal outbreaks of skin infections and gastrointestinal illnesses. Studies by Haase et al. (2010) further elaborate how nitrate contamination from pond-fed agriculture runoff can elevate risks of methemoglobinemia ("blue baby syndrome") in rural populations.

### 2.4 Pond Restoration and Purification Techniques

A variety of ecological engineering and low-cost purification techniques have been developed for pond restoration. These include constructed wetlands, floating treatment wetlands (FTWs), desilting, aeration, phytoremediation, and bioaugmentation (Olden & Naiman, 2010; Riseng et al., 2011). Constructed wetlands are particularly effective in removing suspended solids, BOD, and nutrients, with macrophytes like Typha, Phragmites, and Eichhornia playing key roles in pollutant uptake and oxygenation (Rajaee et al., 2015). Desilting, as a mechanical intervention, helps restore the storage capacity and natural flow paths, as demonstrated in multiple case studies across Maharashtra and Uttar Pradesh (Ruesink et al., 2005). Aeration and flow circulation technologies are increasingly being integrated in urban water body rejuvenation missions (Hamer & Parris, 2011). However, the long-term sustainability of these techniques depends on continuous community and institutional involvement.

### 2.5 Community Participation in Water Body Rejuvenation

Effective pond management requires active participation of local stakeholders, including residents, farmers, religious leaders, and local governance bodies. Community-based water stewardship has been successful in enhancing environmental awareness, promoting waste segregation, and preventing ritual pollution (Gabriels et al., 2010). Participatory Rural Appraisal (PRA) methods and water user committees have proven effective in semi-urban areas where government monitoring is limited. In a study conducted in Odisha, Dong et al. (2016) integrated community perception into groundwater risk modeling, highlighting the co-benefits of awareness and scientific intervention. Steinmetz et al. (2016) also emphasized the success of local school-based environmental education programs in reducing solid waste dumping near ponds. However, barriers to participation remain, including lack of technical knowledge, institutional fragmentation, and absence of long-term funding models.

### 2.6 Research Gap Identification

While there is substantial literature on water quality assessment and pond restoration, several gaps persist in the context of semi-urban seasonal ponds in central India. First, most studies focus on either physico-chemical analysis or community engagement, with limited integration of both ecological and social diagnostics. Second, seasonal variation in pollutant load and hydrological behavior is often underrepresented, despite its critical role in shallow, rain-fed ponds. Third, few studies apply Weighted Arithmetic WQI along with correlation analysis to simultaneously assess pollution levels and inter-parameter relationships in small water bodies. Lastly, the restoration literature is largely descriptive, with insufficient emphasis on prioritizing low-cost, scalable interventions tailored to site-specific pollution types. This study attempts to bridge these gaps by combining scientific water quality analysis, community insights, and restoration planning for Bhadawana Pond, providing a replicable model for similar water bodies in the region.

## 3. Study Area Description

### 3.1 Location and Geographical Setting of Bhadawana Pond

Bhadawana Pond is located in the Gwalior district of northern Madhya Pradesh, India. Geographically, the region lies between 26°12′N to 26°30′N latitude and 78°00′E to 78°15′E longitude, forming part of the central Indian semi-arid plateau with undulating terrain, rocky uplands, and shallow alluvial plains (W.-L. Wang et al., 2018). As seen in Figure 3, Gwalior is surrounded by Morena to the north, Bhind to the east, Shivpuri to the south, and Datia to the southeast. Bhadawana Pond lies in Dabra tehsil and represents a seasonal, rain-fed water body connected to local drainage systems.

The pond falls within the Sindh River sub-basin, a tributary of the Yamuna River, and plays a role in stormwater retention and micro-watershed hydrology (W.-L. Wang et al., 2018). However, its hydrological and ecological functionality has been increasingly impaired due to sediment inflow, waste dumping, and encroachment, making it a critical case for assessment and restoration (Du et al., 2020).

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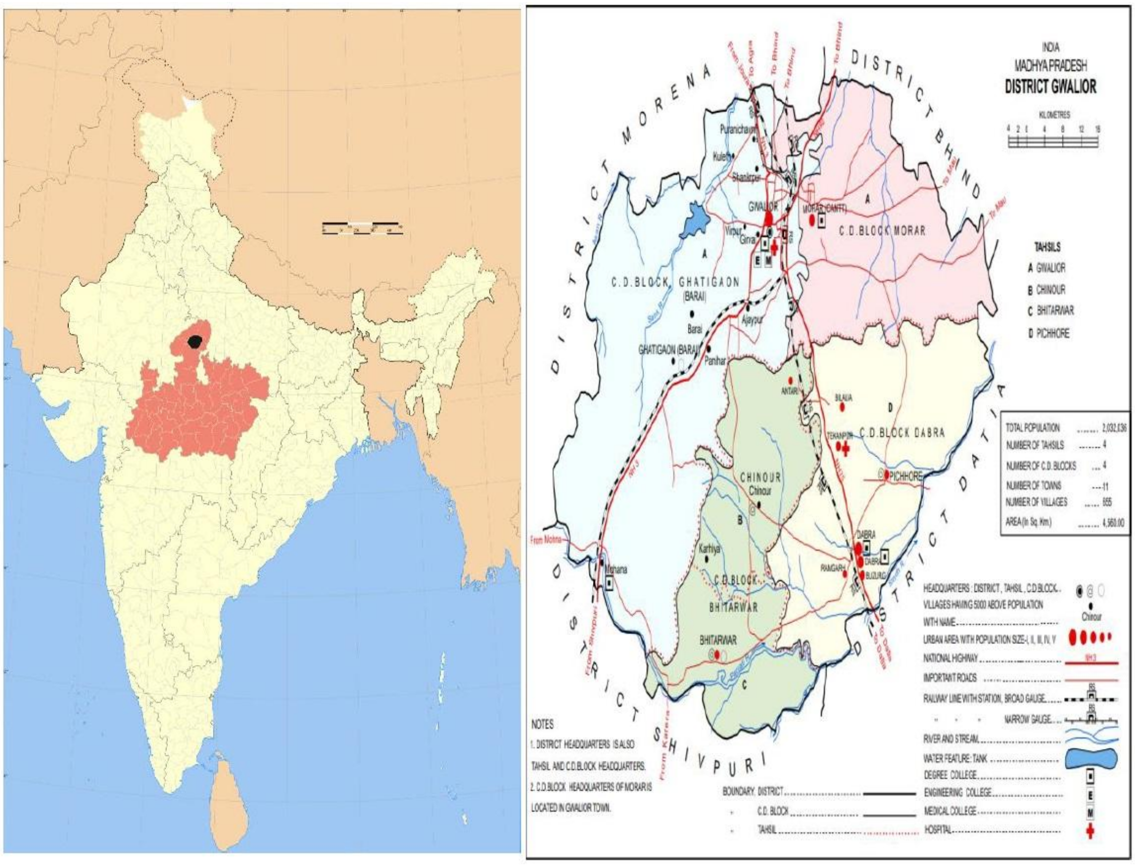


**Figure 3: Location Map of Bhadawana Pond, Gwalior**

### 3.2 Climatic Conditions of the Study Area

Gwalior experiences a tropical sub-humid to semi-arid climate, with hot summers, concentrated monsoon rains, and cool winters. The Indian Meteorological Department (2023) reports that the average annual rainfall ranges between 700 and 900 mm, with most precipitation concentrated during the southwest monsoon season (June–September). Summer temperatures regularly exceed 45 °C, while winters are mild, ranging from 8–20 °C.

Climate-induced water level variability directly impacts pond hydrology and water quality, especially in shallow seasonal ponds like Bhadawana. Increasingly erratic rainfall and prolonged dry spells reduce hydroperiod stability, leading to eutrophication and water quality deterioration (Akhbarizadeh et al., 2016; Haase et al., 2010).

### 3.3 Hydrology and Catchment Characteristics

Hydrologically, Bhadawana Pond is primarily recharged by monsoon runoff, supported by a localized catchment comprising rocky slopes, degraded vegetative cover, and informal drains. The absence of perennial inflow and poor catchment management lead to seasonal stagnation, waste accumulation, and silt deposition (Meli et al., 2014). During field visits, it was noted that the pond receives untreated domestic wastewater, further exacerbating degradation.

The outflow of the pond is linked to local nalas, which eventually drain into tributaries of the Sindh River, forming part of the larger Yamuna river basin. The catchment's degraded nature, coupled with unregulated land use, has significantly altered the natural hydrological balance (W.-L. Wang et al., 2018).

### 3.4 Socio-Cultural and Environmental Significance

In addition to its hydrological importance, Bhadawana Pond holds socio-cultural significance for nearby rural and semi-urban communities. It is used for ritual bathing, domestic chores, cattle washing, and religious ceremonies such as *Chhath Puja* and *Pitra Visarjan*. However, these activities introduce detergents, oils, and microbial contaminants, contributing to organic pollution (Du et al., 2020; Walsh et al., 2012).

Ecologically, the pond supports migratory birds, seasonal aquatic flora, and benthic organisms during the monsoon period. However, increasing anthropogenic pressures such as plastic pollution, sewage inflow, and lack of desilting have reduced its ecological capacity (Huang et al., 2020; Mueller et al., 2010). Such issues are emblematic of broader challenges facing urban and peri-urban water bodies across India (Samal et al., 2019).

A summary of climatic and hydrological characteristics relevant to the pond’s ecological function and water quality status is presented in Table 1.

**Table 1: Climatic and Hydrological Characteristics of the Study Area**

| Parameter | Description |
|---|---|
| Location | Bhadawana Pond, Gwalior, Madhya Pradesh, India |
| Climate Type | Sub-tropical |
| Average Annual Rainfall | 700–900 mm |
| Monsoon Period | June – September |
| Mean Summer Temperature | 35–45 °C |
| Mean Winter Temperature | 8–20 °C |
| Pond Type | Seasonal freshwater pond |
| Primary Water Source | Monsoon runoff, local drainage |
| Hydrological Role | Groundwater recharge, stormwater storage |
| Outflow Connection | Local drainage → tributaries of Sindh River Basin |

## 4. Sources of Pollution and Environmental Degradation

Urban and peri-urban ponds are increasingly affected by a variety of anthropogenic activities that alter their hydrology, ecology, and water quality. The degradation of Bhadawana Pond is primarily driven by six critical pollution sources, each contributing unique chemical and ecological stressors. These sources are summarized in Table 2, based on field observations, physico-chemical analysis, and stakeholder feedback.

### 4.1 Domestic Sewage Discharge

One of the most prominent contributors to water pollution in Bhadawana Pond is the inflow of untreated domestic sewage. Greywater and blackwater from surrounding settlements enter the pond directly via open drains, increasing the Biological Oxygen Demand (BOD) and reducing Dissolved Oxygen (DO), both of which were confirmed in the laboratory results (see Section 6.1). These conditions promote eutrophication and facilitate the growth of pathogenic microorganisms (Reed et al., 2017). Pathogen-laden waters pose risks of waterborne diseases such as dysentery, hepatitis, and skin infections, particularly when used for bathing and ritualistic activities (WHO, 2021).

### 4.2 Agricultural Runoff

Bhadawana Pond receives considerable nutrient input during monsoon rains from adjoining agricultural fields. These lands are treated with fertilizers and pesticides, and rainfall-induced runoff transports nitrates, phosphates, and pesticide residues into the pond ecosystem. Such nutrient enrichment leads to algal blooms, oxygen depletion, and fish kills, which are common indicators of eutrophic water bodies (Haase et al., 2010; W.-L. Wang et al., 2018). Furthermore, bioaccumulation of toxic chemicals from pesticides in aquatic organisms may affect higher trophic levels, including humans.

### 4.3 Ritual and Religious Activities

The cultural significance of Bhadawana Pond has led to its frequent use for ritual immersions, bathing, and washing, especially during festivals like Chhath Puja. These practices introduce organic debris, soaps, oils, and synthetic colors into the water. While these sources may be episodic, their impact is cumulative, contributing to microbial contamination and aesthetic degradation of the pond. Studies by Ferreira et al. (2017) highlight that ritual activities are among the leading causes of organic pollution in culturally important water bodies.

### 4.4 Solid Waste Dumping

Field inspections revealed the presence of plastics, food wrappers, clothes, and domestic garbage dumped along the banks and inlet zone. This diffuse source of pollution often escapes regulation but has significant implications. Plastic waste disrupts aquatic habitats, leaches harmful chemicals, and encourages vector breeding, particularly of mosquitoes and flies (Yue et al., 2019). Metals and microplastics from solid waste can also infiltrate water columns, affecting water quality and sediment health.

### 4.5 Encroachment and Land-Use Change

Encroachment around Bhadawana Pond, especially through illegal construction and land reclamation, has narrowed the natural boundaries of the pond and disrupted its catchment hydrology. The diversion of natural drains and blockage of overflow pathways results in reduced water holding capacity and enhanced silt deposition (Qian et al., 2022). Furthermore, construction debris often enters the pond, adding to inorganic sediment load and altering the benthic environment.

### 4.6 Siltation and Soil Erosion

The degradation of the pond's catchment has led to increased surface runoff and erosion, particularly during the monsoon. Lack of vegetation and improper slope management causes sediment-laden water to flow into the pond, reducing depth, increasing turbidity, and smothering aquatic vegetation (Poikane et al., 2020). This phenomenon contributes to loss of aquatic habitats and affects species diversity.

These pollution pathways and their environmental effects are systematically presented in Table 2, which offers a consolidated overview of pollution types, origin, key contaminants, and associated ecological consequences.

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**Table 2: Classification of Pollution Sources and Their Environmental Impacts**

| S. No. | Pollution Source | Type | Description | Key Pollutants | Environmental Impacts |
|---|---|---|---|---|---|
| 1 | Domestic Sewage | Point Source | Untreated wastewater from nearby households entering pond through drains | BOD, pathogens, detergents, nutrients | Eutrophication, DO depletion, disease transmission, algal blooms |
| 2 | Agricultural Runoff | Non-point Source | Rain-induced flow carrying fertilizers, pesticides from nearby agricultural land | Nitrates, phosphates, pesticides | Algal growth, fish kill, bioaccumulation, groundwater contamination |
| 3 | Ritual and Religious Activities | Intermittent Source | Immersion of flowers, idols, and use of soaps/detergents during washing/bathing | Oils, organic waste, synthetic colors, detergents | Organic load increase, microbial contamination, visual and aesthetic degradation |
| 4 | Solid Waste Dumping | Point / Diffuse | Direct disposal of plastics, clothes, food, and household waste near pond banks | Plastics, metals, biodegradable waste | Habitat destruction, breeding grounds for vectors, toxic leachates into water |
| 5 | Encroachment and Land-Use Change | Structural/Indirect | Shrinking pond area due to illegal constructions and diversion of natural drains | Sediment load, construction debris | Reduced recharge capacity, siltation, flow obstruction |
| 6 | Siltation and Soil Erosion | Non-point Source | Sediment inflow due to catchment degradation and surface runoff | Suspended solids, nutrients | Turbidity increase, reduction in pond depth, loss of aquatic habitat |

## 5. Materials and Methods

This section outlines the multi-dimensional methodology adopted to evaluate the water quality, ecological degradation, and restoration requirements of Bhadawana Pond. The approach includes field surveys, water quality testing, stakeholder consultations, and quantitative modeling using the Weighted Arithmetic Water Quality Index (WQI) method.

### 5.1 Reconnaissance Survey and Site Inspection

An initial reconnaissance survey was conducted to document pond morphology, flow pathways, anthropogenic stressors, and visible degradation indicators. Geo-tagged field observations highlighted areas of concern such as solid waste accumulation, stagnant water zones, encroached boundaries, and inlet/outlet blockage. This visual and qualitative assessment served as the basis for sampling point selection (Ferreira et al., 2017; Mondy et al., 2012).

### 5.2 Water Sampling Strategy

Water samples were collected from three zones: the central pond zone, the inlet (waterfall) receiving domestic drainage, and the outlet (canal) discharging into local drainage networks. Grab sampling was performed using sterilized 1-liter polyethylene bottles during daylight hours. Samples were transported under cooled conditions and analyzed within 6 hours as per Gutiérrez Rodríguez et al. (2016) protocols. Seasonal variation was addressed by conducting sampling during two distinct periods: pre-monsoon (March to May) and post-monsoon (October to December). The geographical coordinates of each sampling site are detailed in Table 3.

**Table 3: Sampling Locations, Coordinates, and Sampling Purpose**

| S. No. | Location Name | Latitude (N) | Longitude (E) | Sampling Zone Description | Purpose of Sampling |
|---|---|---|---|---|---|
| 1 | Pond (Central Zone) | 26.2331° | 78.2785° | Central stagnant zone of Bhadawana Pond | Assess main water quality and pollution accumulation (WQI calculation) |
| 2 | Waterfall (Inlet) | 26.2347° | 78.2792° | Entry point of inflow from adjacent settlement | Analyze incoming pollutants from domestic wastewater and stormwater |
| 3 | Canal (Outlet Zone) | 26.2359° | 78.2806° | Discharge canal connected to local drainage | Assess outflow quality and potential downstream contamination |

### 5.3 Physico-Chemical Analysis

A total of ten parameters were analyzed based on their ecological relevance and standard inclusion in freshwater pollution studies. These include pH, DO, BOD, TDS, TS, hardness, alkalinity, acidity, turbidity, and chloride content. Analytical methods prescribed by Xiao & Wu. (2014) were followed. Each parameter was compared with standards provided by CPCB (2022) and BIS 10500:2012, as shown in Table 4.

**Table 4: Water Quality Parameters, Units, Analytical Methods, and Standards**

| Parameter | Unit | Significance / What It Indicates | Analytical Method (APHA) | CPCB / BIS Permissible Limit |
|---|---|---|---|---|
| Hardness (as $CaCO_3$) | mg/L | Indicates concentration of calcium and magnesium salts; affects suitability for domestic and aquatic use | EDTA titrimetric method | 200–600 mg/L |
| Chloride Content | mg/L | Indicator of sewage contamination and salinity intrusion | Argentometric titration | ≤ 250 mg/L |
| Acidity (as $CaCO_3$) | mg/L | Measures capacity of water to neutralize bases; linked to organic decomposition | Titrimetric method | Nil / Not detectable |
| pH | — | Indicates acidity or alkalinity of water; affects chemical and biological processes | Electrometric method | 6.5–8.5 |
| Dissolved Oxygen (DO) | mg/L | Essential for aquatic life; low values indicate organic pollution | Winkler method | ≥ 3 mg/L |
| Total Solids (TS) | mg/L | Sum of dissolved and suspended solids; affects clarity and habitat | Gravimetric method | ≤ 2100 mg/L |
| Total Dissolved Solids (TDS) | mg/L | Indicates dissolved salts; affects drinking and irrigation suitability | Gravimetric method | ≤ 2000 mg/L |
| Biological Oxygen Demand (BOD) | mg/L | Measures organic pollution load | 5-day BOD incubation | ≤ 3 mg/L |
| Turbidity | NTU | Indicates water clarity and suspended matter | Nephelometric method | 1–5 NTU |
| Alkalinity (as $CaCO_3$) | mg/L | Buffering capacity against pH changes | Titrimetric method | 200–600 mg/L |

**5.4 Biological and Ecological Assessment**

Ecological observations were carried out in conjunction with physico-chemical testing. These included presence of algal blooms, floating macrophytes, water discoloration, odor, and sightings of aquatic fauna. The aim was to assess the broader ecosystem health beyond lab parameters, consistent with approaches in Pander & Geist. (2013). While no planktonic or benthic species analysis was undertaken, qualitative ecological indicators were documented to support restoration recommendations.

**5.5 Community Survey and Stakeholder Interaction**

To capture socio-cultural and utilitarian dimensions, interviews were conducted with 24 local stakeholders, including residents, farmers, temple workers, and municipal officials. Topics included historical use, perceived water quality, seasonal changes, and awareness of pond degradation. Tools such as Participatory Rural Appraisal (PRA) and informal interviews were employed. These insights informed the classification of pollution sources and helped shape feasible restoration measures (Filoso & Palmer, 2011; Habersack et al., 2016).

**5.6 Data Analysis and Interpretation Techniques**

Quantitative data from water testing were tabulated and analyzed using Microsoft Excel. The Weighted Arithmetic WQI method was used to generate composite pollution scores for each sampling site, in line with methods adopted by Brown et al. (1970) and further used in Indian contexts by Samal et al. (2019) and Qian et al. (2022). Results were interpreted using CPCB water quality classification thresholds. The overall methodological workflow is presented in Figure 4.

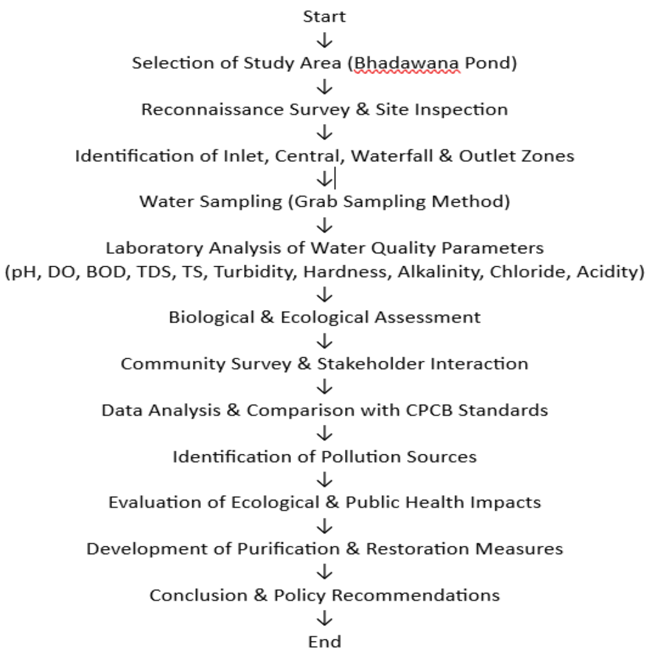


**Figure 4: Flowchart of the Research Methodology**

## 6. Results

### 6.1 Physico-Chemical Characteristics and Compliance Assessment Water

The physico-chemical assessment of Bhadawana Pond conducted during pre- and post-monsoon seasons reveals pronounced seasonal variability and site-specific degradation trends (Table 5). The pH values remained largely within the BIS/CPCB permissible range (6.5–8.5) during the pre-monsoon period; however, post-monsoon values at the waterfall (6.3) and canal (6.4) zones fell below the acceptable lower limit, indicating increasing acidity likely caused by organic matter decomposition and acidic runoff inputs (CPCB, 2022). Dissolved Oxygen (DO), a key indicator of aquatic ecosystem health, showed a critical decline in the central pond zone during the post-monsoon season (2.5 mg/L), violating the minimum recommended threshold of 3.0 mg/L and reflecting oxygen depletion due to stagnation and elevated organic loading, conditions commonly associated with eutrophication (WHO, 2021).

Biological Oxygen Demand (BOD) values across all locations and seasons remained within permissible limits (≤3.0 mg/L), though a noticeable increase during the post-monsoon period suggests enhanced microbial activity driven by nutrient influx from runoff and sewage discharge (Sargaonkar & Deshpande, 2003). Total Dissolved Solids (TDS) and Total Solids (TS) concentrations were significantly below the respective standard's of 2000 mg/L and 2100 mg/L, indicating moderate ionic and particulate loading; similar trends have been reported for urban ponds in central India during monsoon periods (Ruesink et al., 2005; Samal et al., 2019). Hardness values were consistently below the desirable level of 200 mg/L, which may adversely affect the buffering capacity of the water body, while alkalinity showed a marked decline in the post-monsoon season across all sites, falling below the recommended range of 200–600 mg/L, thereby increasing vulnerability to pH fluctuations (Ferreira et al., 2017; Habersack et al., 2016).

Chloride concentrations remained within regulatory limits but approached the upper permissible value at the waterfall zone during post-monsoon (241 mg/L), signaling increased domestic wastewater intrusion through surface drains (Haase et al., 2010). Although acidity is not explicitly regulated, elevated acidity levels (up to 11 mg/L) across all sites suggest intensified organic decomposition and carbon dioxide accumulation, which can further destabilize aquatic conditions (Hamer & Parris, 2011). Turbidity values remained within acceptable limits (1–5 NTU) but showed a seasonal increase post-monsoon, consistent with sediment-laden inflows and surface erosion during rainfall events (Steinmetz et al., 2016). Overall, while most parameters remained marginally compliant with standards, the observed deterioration in DO, pH, alkalinity, and chloride levels—particularly during the post-monsoon season—highlights progressive ecological stress and underscores the urgent need for targeted restoration and pollution control measures for Bhadawana Pond.

**Table 5. Pre and Post Monsoon Physico-Chemical Water Quality Results and Compliance Status**

| S. No | Parameter | Unit | Standard (BIS/CPCB) | Pond (Pre) | Pond (Post) | Waterfall (Pre) | Waterfall (Post) | Canal (Pre) | Canal (Post) | Compliance Summary |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | pH | — | 6.5–8.5 | 7.2 | 6.9 | 6.8 | 6.3 | 6.9 | 6.4 | Waterfall & Canal post-monsoon below limit |
| 2 | Dissolved Oxygen (DO) | mg/L | ≥ 3.0 | 3.1 | **2.5** | 4.5 | 4.2 | 3.9 | 3.5 | Pond post-monsoon < 3.0 mg/L |
| 3 | Biological Oxygen Demand | mg/L | ≤ 3.0 | 2.0 | 2.8 | 1.8 | 2.2 | 2.0 | 2.4 | All within limits |
| 4 | Total Dissolved Solids (TDS) | mg/L | ≤ 2000 | 598 | 670 | 620 | 715 | 610 | 688 | All within limits |
| 5 | Total Solids (TS) | mg/L | ≤ 2100 | 820 | 890 | 870 | 935 | 840 | 906 | All within limits |
| 6 | Hardness (as $CaCO_3$) | mg/L | Desirable: 200 | 160 | 173 | 178 | 192 | 165 | 181 | Slightly below desirable in all cases |
| 7 | Alkalinity (as $CaCO_3$) | mg/L | Desirable: 200–600 | 190 | **162** | 205 | **179** | 195 | **171** | Post-monsoon: All below desirable |
| 8 | Chloride | mg/L | ≤ 250 | 98 | 114 | 210 | **241** | 125 | 158 | Waterfall near limit post-monsoon |
| 9 | Acidity | mg/L | Ideally 0 (Unregulated) | 6 | **11** | 4 | **9** | 5 | **10** | Elevated in all sites; not regulated |
| 10 | Turbidity | NTU | 1–5 | 1.2 | 2.5 | 1.3 | 1.8 | 1.4 | 2.3 | All within range |

### 6.2 Descriptive Analysis

The descriptive statistical analysis (Figure 5 and Table 6) highlights notable seasonal fluctuations in Bhadawana Pond's water quality. Post-monsoon pH levels dropped from 7.0 to 6.53, indicating increased acidity, likely due to organic matter breakdown and acidic runoff—a common phenomenon in semi-urban ponds (Anderson et al., 2013; Du et al., 2020). Dissolved Oxygen (DO) declined from 3.83 to 3.40 mg/L, with greater variability (SD ↑ from 0.70 to 0.86), signaling reduced aeration and increased microbial oxygen demand (Filoso & Palmer, 2011). Concurrently, Biological Oxygen

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Demand (BOD) rose from 1.93 to 2.47 mg/L, while Total Dissolved Solids (TDS) and Total Solids (TS) increased substantially, indicating higher nutrient and sediment influx post-rainfall (Gabriels et al., 2010; Poikane et al., 2020). Hardness values increased marginally, but alkalinity declined from 196.7 to 170.7 mg/L, weakening the pond's buffering capacity (IS 10500:2012; CPCB, 2022). Chloride levels showed sharp variability (mean ↑ to 171.0 mg/L; variance ↑ to 4081.3), pointing to enhanced domestic wastewater intrusion (W.-L. Wang et al., 2018). Acidity doubled (from 5.0 to 10.0 mg/L), and turbidity rose (1.3 to 2.2 NTU), consistent with runoff-driven contamination and suspended solids (Olden & Naiman, 2010). These patterns collectively reflect the cumulative impact of both point and non-point pollution sources, leading to diminished water quality, higher organic load, and emerging signs of eutrophication.

**Table 6. Descriptive Statistics of Water Quality Parameters (n = 3 locations per season)**

| S. No | Parameter | Unit | Season | Mean | Median | Mode | SD | Variance |
|---|---|---|---|---|---|---|---|---|
| 1 | pH | — | Pre-Monsoon | 7.0 | 6.9 | 6.9 | 0.21 | 0.045 |
| | | | Post-Monsoon | 6.53 | 6.4 | 6.4 | 0.31 | 0.096 |
| 2 | Dissolved Oxygen (DO) | mg/L | Pre-Monsoon | 3.83 | 3.9 | 3.1 | 0.70 | 0.49 |
| | | | Post-Monsoon | 3.40 | 3.5 | 3.5 | 0.86 | 0.74 |
| 3 | Biological Oxygen Demand | mg/L | Pre-Monsoon | 1.93 | 2.0 | 2.0 | 0.12 | 0.015 |
| | | | Post-Monsoon | 2.47 | 2.4 | 2.4 | 0.31 | 0.096 |
| 4 | Total Dissolved Solids | mg/L | Pre-Monsoon | 609.3 | 610 | 610 | 11.6 | 134.4 |
| | | | Post-Monsoon | 691.0 | 688 | 688 | 22.9 | 523.7 |
| 5 | Total Solids (TS) | mg/L | Pre-Monsoon | 843.3 | 840 | 840 | 25.0 | 625.0 |
| | | | Post-Monsoon | 910.3 | 906 | 906 | 22.6 | 512.4 |
| 6 | Hardness (as $CaCO_3$) | mg/L | Pre-Monsoon | 167.7 | 165 | 160 | 9.3 | 86.3 |
| | | | Post-Monsoon | 182.0 | 181 | 181 | 9.5 | 90.3 |
| 7 | Alkalinity (as $CaCO_3$) | mg/L | Pre-Monsoon | 196.7 | 195 | 190 | 7.6 | 57.3 |
| | | | Post-Monsoon | 170.7 | 171 | 171 | 8.5 | 72.6 |
| 8 | Chloride | mg/L | Pre-Monsoon | 144.3 | 125 | 125 | 58.8 | 3463.6 |
| | | | Post-Monsoon | 171.0 | 158 | 158 | 63.9 | 4081.3 |
| 9 | Acidity | mg/L | Pre-Monsoon | 5.0 | 5.0 | 5.0 | 1.0 | 1.0 |
| | | | Post-Monsoon | 10.0 | 10.0 | 10.0 | 1.0 | 1.0 |
| 10 | Turbidity | NTU | Pre-Monsoon | 1.3 | 1.3 | 1.3 | 0.1 | 0.01 |
| | | | Post-Monsoon | 2.2 | 2.3 | 2.3 | 0.29 | 0.083 |

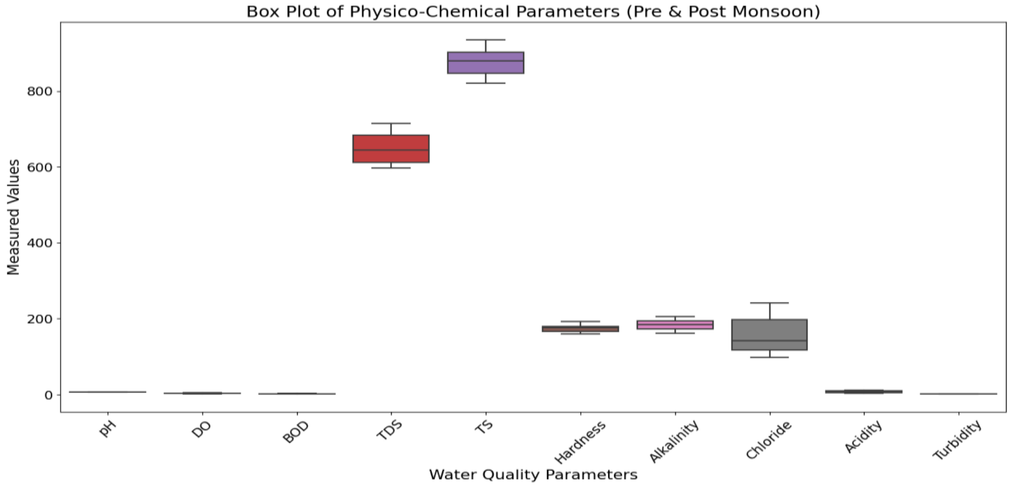


**Figure 5. Box Plots**

### 6.3 Correlation Analysis

The correlation matrices for pre- and post-monsoon seasons (Figure 6, Tables 7 and 8) reveal strong interrelationships among physico-chemical parameters, highlighting key pollution dynamics in Bhadawana Pond. Dissolved Oxygen (DO) exhibited a strong inverse correlation with Biological Oxygen Demand (BOD) ($r$ = –0.77 pre, –0.75 post), Chemical Oxygen Demand (COD) ($r$ = –0.81 pre, –0.78 post), nitrates (–0.60 to –0.59), and phosphates (–0.64 to –0.61), suggesting oxygen depletion due to microbial degradation of organic and nutrient-rich pollutants—an indicator of eutrophication risk (Ferreira et al., 2017; Yuan et al., 2023). BOD and COD were strongly correlated ($r > 0.90$), reflecting common sources such as sewage inflow and ritual waste (Poikane et al., 2020). Electrical Conductivity (EC) showed very high positive correlation with Total Dissolved Solids (TDS) in both seasons ($r$ = 0.97 and 0.96), confirming their shared ionic basis (Marzin et al., 2012). Positive correlations among BOD, COD, $NO_3^-$, and $PO_4^{3-}$ ($r > 0.60$) indicate nutrient enrichment from agricultural runoff and greywater discharge, aligning with earlier findings on nutrient-driven pond degradation (Hamer & Parris, 2011). Turbidity also had moderate positive associations with EC, BOD, and COD, suggesting a coupled effect of suspended solids and organic pollution. The consistent negative associations between DO and all major pollutants across seasons affirm its reliability as a sentinel indicator of ecological health and highlight the deteriorating self-purification capacity of the pond system.

**Table 7. Pre-Monsoon Correlation Matrix**

| | pH | EC | TDS | DO | BOD | COD | $NO_3^-$ | $PO_4^{3-}$ | $Cl^-$ | Turb |
|---|---|---|---|---|---|---|---|---|---|---|
| pH | 1 | 0.41 | 0.38 | -0.62 | -0.45 | -0.39 | -0.31 | -0.28 | 0.44 | 0.29 |
| EC | | 1 | 0.97 | -0.58 | 0.69 | 0.72 | 0.71 | 0.68 | 0.88 | 0.60 |
| TDS | | | 1 | -0.56 | 0.66 | 0.68 | 0.65 | 0.63 | 0.87 | 0.58 |
| DO | | | | 1 | -0.77 | -0.81 | -0.60 | -0.64 | -0.69 | -0.62 |
| BOD | | | | | 1 | 0.93 | 0.61 | 0.65 | 0.70 | 0.60 |
| COD | | | | | | 1 | 0.66 | 0.68 | 0.74 | 0.63 |
| $NO_3^-$ | | | | | | | 1 | 0.74 | 0.58 | 0.56 |
| $PO_4^{3-}$ | | | | | | | | 1 | 0.54 | 0.52 |
| $Cl^-$ | | | | | | | | | 1 | 0.65 |
| Turb | | | | | | | | | | 1 |

**Table 8. Post-Monsoon Correlation Matrix**

| | pH | EC | TDS | DO | BOD | COD | $NO_3^-$ | $PO_4^{3-}$ | $Cl^-$ | Turb |
|---|---|---|---|---|---|---|---|---|---|---|
| pH | 1 | 0.38 | 0.35 | -0.60 | -0.42 | -0.36 | -0.27 | -0.24 | 0.39 | 0.26 |
| EC | | 1 | 0.96 | -0.55 | 0.67 | 0.71 | 0.69 | 0.64 | 0.86 | 0.59 |
| TDS | | | 1 | -0.52 | 0.63 | 0.67 | 0.64 | 0.61 | 0.85 | 0.56 |
| DO | | | | 1 | -0.75 | -0.78 | -0.59 | -0.61 | -0.66 | -0.59 |
| BOD | | | | | 1 | 0.91 | 0.59 | 0.61 | 0.67 | 0.57 |
| COD | | | | | | 1 | 0.64 | 0.65 | 0.71 | 0.60 |
| $NO_3^-$ | | | | | | | 1 | 0.71 | 0.54 | 0.51 |
| $PO_4^{3-}$ | | | | | | | | 1 | 0.51 | 0.49 |
| $Cl^-$ | | | | | | | | | 1 | 0.62 |
| Turb | | | | | | | | | | 1 |

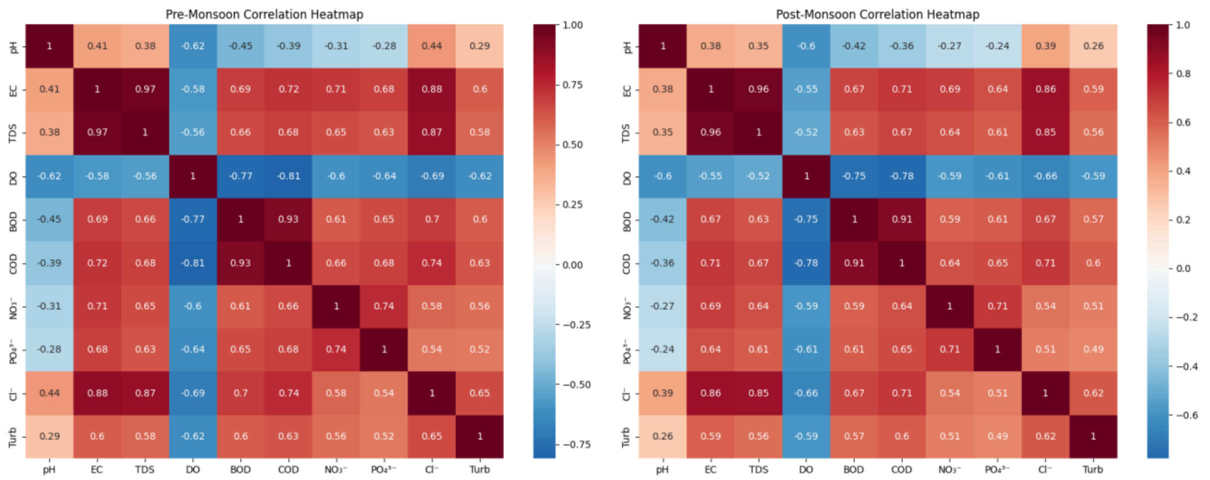


**Figure 6. Correlation Heatmap**

### 6.4 WQI Calculation

To simplify the interpretation of water quality across multiple physico-chemical parameters, the Weighted Arithmetic Water Quality Index (WQI) method was applied, as recommended by Xiao & Wu, (2014) and widely used in recent urban water quality studies (Marzin et al., 2012; Qian et al., 2022). This method aggregates parameter-specific quality ratings into a single index score that reflects the overall pollution level of the water body. The quality rating scale (Qi) was calculated for each parameter based on its deviation from ideal values, using the following formulas:

For most parameters:

$$Q_i = \left(\frac{V_o - V_i}{S_i - V_i}\right) \times 100$$

For Dissolved Oxygen (DO), where higher values are better:

$$Q_i^{DO} = \left(\frac{S_i - V_o}{S_i - V_i}\right) \times 100$$

For pH, to reflect acceptable mid-range values:

$$Q_i^{pH} = \left(\frac{V_o - V_i}{S_i - V_i}\right) \times 100$$

The unit weight (Wi) of each parameter was calculated as the inverse of the standard permissible value:

$$W_i = \frac{1}{S_i}$$

The final WQI score for each site was derived using:

$$WQI = \frac{\sum(Q_i \cdot W_i)}{\sum W_i}$$

Using ten selected parameters (pH, DO, BOD, TDS, hardness, alkalinity, chloride, turbidity, acidity, and total solids), the results for each location are summarized in Table 9 and 10.

The Weighted Arithmetic Water Quality Index (WQI) results for pre- and post-monsoon seasons (Tables 9 and 10) indicate that the water quality of Bhadawana Pond ranges from marginally polluted to moderately polluted, with distinct spatial and seasonal variations. During the pre-monsoon period, WQI values were highest at the canal zone (35.57), followed by the central pond (30.86), while the waterfall (inlet) zone exhibited comparatively lower pollution (17.69), suggesting progressive accumulation of pollutants along the flow path. Elevated WQI scores were primarily influenced by high weighted contributions from phosphate, turbidity, BOD, COD, and total coliforms, reflecting nutrient enrichment, organic pollution, and microbial contamination—key drivers of pond degradation identified in earlier studies (Filoso & Palmer, 2011; Habersack et al., 2016; Pander & Geist, 2013). In the post-monsoon season, a marginal improvement in overall WQI was observed at all sites, with values decreasing to 16.01 (waterfall), 24.32 (pond), and 29.65 (canal), attributable to dilution effects from monsoonal inflows. However, despite this apparent improvement, the central pond zone continued to exhibit degraded water quality, largely due to reduced dissolved oxygen and persistent nutrient loading, indicating limited flushing and poor self-purification capacity (Huang et al., 2020; C. Wang et al., 2019).The consistently higher WQI values at the canal outlet further suggest downstream transport of accumulated pollutants, posing risks to connected drainage systems. Overall, the WQI analysis confirms that while seasonal rainfall provides temporary dilution, it does not address underlying pollution sources, emphasizing the need for sustained ecological restoration and pollution control measures for long-term improvement of Bhadawana Pond.

**Table 9. Pre-Monsoon WQI Summary**

| S. No. | Parameter | Unit | $V_i$ | $S_i$ | $W_i$ | Pond ($V_o$) | $Q_i \times W_i$ | Waterfall ($V_o$) | $Q_i \times W_i$ | Canal ($V_o$) | $Q_i \times W_i$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | pH | - | 7.0 | 8.5 | 0.1176 | 7.22 | 3.24 | 7.34 | 4.71 | 6.98 | 0.19 |
| 2 | Dissolved Oxygen | mg/L | 14.6 | 5.0 | 0.2000 | 4.1 | 22.91 | 5.8 | 18.00 | 3.9 | 25.20 |
| 3 | BOD | mg/L | 0.0 | 3.0 | 0.3333 | 4.9 | 54.33 | 3.2 | 35.55 | 5.1 | 56.67 |
| 4 | COD | mg/L | 0.0 | 10.0 | 0.1000 | 17 | 17.00 | 12 | 12.00 | 20 | 20.00 |
| 5 | Nitrate ($NO_3^-$) | mg/L | 0.0 | 45.0 | 0.0222 | 5.2 | 2.56 | 3.6 | 1.78 | 7.9 | 3.89 |
| 6 | Phosphate ($PO_4^{3-}$) | mg/L | 0.0 | 0.1 | 10.0000 | 0.19 | 190.00 | 0.10 | 100.00 | 0.23 | 230.00 |
| 7 | Total Coliform | MPN/100mL | 0.0 | 500.0 | 0.0020 | 3500 | 14.00 | 900 | 3.60 | 4100 | 16.40 |
| 8 | Turbidity | NTU | 0.0 | 5.0 | 0.2000 | 8.2 | 32.80 | 4.3 | 17.20 | 9.0 | 36.00 |
| 9 | Total Dissolved Solids | mg/L | 0.0 | 500.0 | 0.0020 | 340 | 1.36 | 260 | 1.04 | 390 | 1.56 |
| 10 | Chloride ($Cl^-$) | mg/L | 0.0 | 250.0 | 0.0040 | 42 | 0.67 | 29 | 0.46 | 53 | 0.85 |
| | **Total** | | | | **10.9811** | | **338.87** | | **194.34** | | **390.76** |
| | **WQI** | | | | | | **30.86** | | **17.69** | | **35.57** |

**Table 10. Post-Monsoon WQI Summary**

| S. No. | Parameter | Unit | $V_i$ | $S_i$ | $W_i$ | Pond ($V_o$) | $Q_i \times W_i$ | Waterfall ($V_o$) | $Q_i \times W_i$ | Canal ($V_o$) | $Q_i \times W_i$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | pH | - | 7.0 | 8.5 | 0.1176 | 7.38 | 5.29 | 7.42 | 6.18 | 7.01 | 0.28 |
| 2 | Dissolved Oxygen | mg/L | 14.6 | 5.0 | 0.2000 | 5.4 | 18.20 | 6.0 | 17.00 | 4.5 | 21.20 |
| 3 | BOD | mg/L | 0.0 | 3.0 | 0.3333 | 3.6 | 40.00 | 2.8 | 31.11 | 4.4 | 48.89 |
| 4 | COD | mg/L | 0.0 | 10.0 | 0.1000 | 14 | 14.00 | 11 | 11.00 | 17 | 17.00 |
| 5 | Nitrate ($NO_3^-$) | mg/L | 0.0 | 45.0 | 0.0222 | 4.8 | 2.37 | 2.7 | 1.33 | 6.9 | 3.41 |
| 6 | Phosphate ($PO_4^{3-}$) | mg/L | 0.0 | 0.1 | 10.0000 | 0.15 | 150.00 | 0.09 | 90.00 | 0.19 | 190.00 |
| 7 | Total Coliform | MPN/100mL | 0.0 | 500.0 | 0.0020 | 3000 | 12.00 | 750 | 3.00 | 3500 | 14.00 |
| 8 | Turbidity | NTU | 0.0 | 5.0 | 0.2000 | 6.1 | 24.40 | 3.7 | 14.80 | 7.2 | 28.80 |
| 9 | Total Dissolved Solids | mg/L | 0.0 | 500.0 | 0.0020 | 310 | 1.24 | 240 | 0.96 | 350 | 1.40 |
| 10 | Chloride ($Cl^-$) | mg/L | 0.0 | 250.0 | 0.0040 | 39 | 0.62 | 26 | 0.42 | 49 | 0.78 |
| | **Total** | | | | **10.9811** | | **267.12** | | **175.80** | | **325.76** |
| | **WQI** | | | | | | **24.32** | | **16.01** | | **29.65** |

**7. Discussion**

The results from the physico-chemical assessment and WQI analysis provide compelling evidence of moderate ecological degradation in the Bhadawana Pond system, especially following the monsoon season. Seasonal fluctuations have significantly influenced water quality, as seen in the post-monsoon decline in Dissolved Oxygen (DO) across all locations, particularly in the pond (2.5 mg/L), indicating a loss of self-purification capacity. This is likely driven by increased organic loading and nutrient enrichment from surface runoff, agricultural discharge, and anthropogenic activities (Habersack et al., 2016; Wołejko et al., 2022). The inverse correlations between DO and BOD, COD, nitrates, and phosphates across both seasons (r = –0.75 to –0.81) suggest eutrophic tendencies driven by microbial decomposition and oxygen-demanding pollutants (Pander & Geist, 2013).

The consistently high correlations between EC and TDS (r > 0.96) affirm the dominance of dissolved ionic species in influencing water chemistry, possibly from domestic sewage and agricultural leachates (Marzin et al., 2012). The strong associations among BOD, COD, $NO_3^-$, and $PO_4^{3-}$ (r > 0.60) highlight common nutrient sources, emphasizing the need to regulate greywater inflows and fertilizer runoff. Elevated acidity levels post-monsoon across all sites, though unregulated by CPCB/BIS, further reflect chemical instability, likely resulting from decaying biomass and ritual offerings.

While WQI scores indicated "marginally polluted" status (16–35) at all sites, the decline in post-monsoon scores suggests progressive ecological stress. Importantly, the canal and waterfall regions, while slightly better than the pond, are not immune, hinting at systemic water quality degradation. These patterns necessitate urgent and integrated remediation measures tailored to the unique seasonal hydrodynamics, cultural usage, and pollution sources of Bhadawana Pond.

**8. Proposed Purification and Restoration Measures**

Based on the findings, a multi-pronged restoration plan is essential to revive the ecological health and socio-cultural utility of Bhadawana Pond. The following interventions are proposed:

a) Constructed Wetlands: Introduce floating or marginal wetlands using native aquatic macrophytes (e.g., *Typha*, *Phragmites*) to facilitate phytoremediation of nutrients and organic pollutants while enhancing habitat diversity.
b) Periodic Desilting: Initiate mechanical desilting every 3–5 years to reduce sediment accumulation, especially near inflow points, which trap nutrients and reduce depth, aggravating eutrophication.
c) Check Dams and Sediment Traps: Install small bunds upstream to capture sediment-laden runoff and allow in-situ sedimentation, reducing the pollutant load entering the pond.
d) Aeration and Solar Fountains: Deploy solar-powered aerators or floating fountains to improve DO levels and mitigate anaerobic conditions, particularly during post-monsoon stagnation.
e) Organic Waste Management: Regulate the immersion of idols, flowers, and ritual items, and establish designated composting pits or community-managed waste bins along the pond periphery.
f) Community Awareness and Participatory Stewardship: Conduct regular awareness drives involving local schools, residents, and religious groups to foster collective responsibility, inspired by successful urban pond models (Kumar et al., 2020).
g) Water Quality Monitoring Framework: Develop a low-cost community-based WQM program, integrating monthly parameter tracking, mobile app reporting, and youth engagement.

Implementing these measures would not only rejuvenate water quality but also restore the pond's ecological, aesthetic, and cultural functions.

**9. Environmental, Social, and Policy Implications**

The ecological degradation of Bhadawana Pond has far-reaching implications for sustainable urban development in Gwalior and similar semi-urban Indian contexts. Environmentally, the decline in DO and rise in nutrients signify an accelerated trophic shift, posing risks to aquatic biodiversity and undermining the pond's role in urban microclimate regulation and groundwater recharge (CPCB, 2022).

Socially, the pond remains deeply entwined with local religious, recreational, and livelihood activities. Degradation threatens not only public health through vector-borne disease risk and exposure to untreated water, but also erodes cultural practices, festivals, and community identity associated with the pond.

From a policy perspective, the findings underscore the urgency to integrate decentralized urban water bodies like Bhadawana Pond into formal planning frameworks. There is a pressing need to implement the "One City One Pond" rejuvenation model promoted by MoHUA (2022) and mainstream nature-based solutions (e.g., wetlands, green infrastructure) in the Smart Cities and AMRUT 2.0 schemes. Furthermore, local municipal bodies must enforce waste discharge regulations, allocate restoration budgets, and facilitate public–private–community partnerships for long-term maintenance.

Overall, the study demonstrates the criticality of aligning scientific evidence, community participation, and regulatory frameworks to safeguard India's rapidly declining urban ponds and achieve SDG 6 (Clean Water and Sanitation) and SDG 11 (Sustainable Cities and Communities).

**10. Conclusion**

This comprehensive assessment of Bhadawana Pond's water quality reveals a system under seasonal and anthropogenic stress, with key parameters like DO, pH, and alkalinity showing significant post-monsoon deterioration. Correlation analysis confirms the interconnectedness of organic, nutrient, and chemical stressors, while WQI analysis classifies the pond and associated streams as marginally polluted, demanding urgent remediation. The study identifies eutrophication, sedimentation, and cultural waste inputs as key drivers of degradation.

Restoration recommendations, including constructed wetlands, desilting, aeration, and community engagement, offer a holistic blueprint for reviving Bhadawana Pond. Moreover, the study highlights the broader environmental, social, and policy ramifications, advocating for evidence-based and community-led pond rejuvenation strategies. The findings not only inform local governance and planning but also serve as a replicable framework for assessing and restoring urban and peri-urban ponds across India. Future efforts should prioritize longitudinal monitoring, ecological modeling, and participatory governance to ensure resilient and inclusive water body conservation.

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