

Evaluation of Water Quality Parameters in Major Dams of Nashik District: A Comparative Study

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ABSTRACT

This study evaluates water quality across three major dams in Nashik District, Maharashtra Upper Vaitarna, Mukne, and Darna based on seasonal observations during 2022. A set of twenty key physicochemical and biological parameters, including pH, electrical conductivity, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, total dissolved and suspended solids, nutrients, and coliform counts, were analyzed to understand spatial and temporal variations. The results indicate significant seasonal influence, with the monsoon period contributing to increased nutrient loading and microbial contamination, while comparatively stable conditions were observed in other seasons. Water Quality Index (WQI) analysis revealed variability among reservoirs, identifying locations requiring targeted management interventions. The study highlights the role of seasonal processes and anthropogenic pressures in shaping water quality and provides region-specific insights to support effective monitoring and sustainable water resource management. Furthermore, the findings emphasize the need for season-specific mitigation strategies, particularly during high-risk monsoon periods, to reduce runoff-induced contamination. The study also offers a scientific basis for integrating watershed management practices with reservoir monitoring to enhance long-term water quality sustainability in the region.

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Introduction

Surface water is an indispensable resource that underpins the sustainability of ecosystems and is fundamental to the socioeconomic infrastructure of human societies. It serves as the primary source of potable water, irrigation for agriculture, and as a medium for industrial and energy production. The increasing anthropogenic pressures, exacerbated by population growth, urban sprawl, and industrialization, have significantly heightened the demand for freshwater resources, posing a critical challenge in managing these finite supplies. Dams, as pivotal components of modern hydrological systems, are integral to water resource management, facilitating the regulation of flow, flood attenuation, and storage during periods of scarcity. Beyond their engineering function, dams contribute to socioeconomic stability by enhancing agricultural productivity, supporting hydropower generation,

and fostering regional economic growth. However, the safeguarding of water quality within these engineered systems is paramount, as the deterioration of water quality compromises not only public health but also the ecological integrity of aquatic systems (Postel et al., 1996; Vörösmarty et al., 2000; Pimentel et al., 2004; Mishra et al., 2019).

The socio-economic and environmental significance of dams cannot be overstated, as they serve as a linchpin in the efficient utilization of water resources. Dams play a multifaceted role by ensuring water security through storage, enabling sustainable irrigation practices, and stabilizing the availability of water for industrial and domestic uses. However, the inherent risk of pollution and water quality degradation within dam reservoirs necessitates constant monitoring and management. Pollution from anthropogenic activities, land-use changes, and sedimentation processes can

significantly alter water chemistry, rendering it unsuitable for consumption and detrimental to aquatic life. Moreover, the complex dynamics of seasonal variations further complicate the management of water quality in reservoirs, necessitating the consideration of both temporal and spatial factors in the assessment of water quality. Effective water quality monitoring in these systems is indispensable for ensuring their continued viability as reliable sources of freshwater, necessitating the integration of advanced diagnostic methodologies and real-time monitoring systems (Gleick, 2003; Zhang et al., 2018).

Water quality is a critical determinant of public health, especially as the global demand for freshwater grows, necessitating robust management strategies to mitigate the adverse effects of pollution and contamination. The consequences of poor water quality are far-reaching, affecting not only human health but also the ecological integrity of aquatic ecosystems. Waterborne diseases remain a leading cause of morbidity and mortality worldwide, particularly in developing nations where access to clean water is limited (WHO, 2021; Esrey et al., 1991). Furthermore, the degradation of water quality in reservoirs can have cascading effects on biodiversity, leading to the loss of aquatic species and the disruption of ecological functions, such as nutrient cycling and habitat provision. The importance of maintaining pristine water quality has become even more pronounced in the face of climate change, which is expected to exacerbate the unpredictability of water availability and quality due to alterations in precipitation patterns, evaporation rates, and temperature fluctuations (Arnell, 2004; IPCC, 2022). Thus, monitoring and safeguarding the water quality of reservoirs must be prioritized to mitigate these emerging risks and ensure sustainable water management practices.

The global discourse on water quality is grounded in several seminal studies that emphasize integrated, multi-parameter assessment of freshwater systems; for instance, David Pimentel et al. (2004) highlighted the impact of agricultural intensification on water degradation, while Takashi Sato et al. (2013) demonstrated the influence of seasonal climatic variability on reservoir water quality, and Donald O. Rosenberry et al. (2007) emphasized watershed-scale controls and land-use dynamics in shaping hydrochemical characteristics. At the national level, Anand Mishra et al. (2019) provided a comprehensive analysis of Indian reservoirs, identifying monsoon-driven fluctuations in BOD, COD, and nutrient loads, whereas Rajesh Singh et al. (2020) reported increasing microbial contamination and declining dissolved oxygen levels due to rapid urbanization and agricultural expansion. At the regional and local scale within

Maharashtra, studies on reservoirs such as Gangapur and Palkhed (e.g., Patil et al., 2012; Kulkarni et al., 2015) have documented rising eutrophication, elevated turbidity, and nutrient enrichment associated with peri-urban growth and intensive farming, although these remain spatially fragmented and methodologically constrained. Despite these contributions, a significant research gap persists due to the absence of comprehensive, seasonally stratified, and multi-parameter assessments of major reservoirs in Nashik District that integrate advanced indices such as CCME and WQI with localized land-use dynamics and anthropogenic stressors; the present study addresses this gap through a systematic spatio-temporal evaluation of key dam systems, thereby generating region-specific insights essential for sustainable water resource management and policy formulation.

In the context of India, reservoirs like the Upar Vaitarna, Mukne, and Darna Dams, which serve as vital water sources for regional communities, are increasingly under scrutiny to ensure their continued ability to supply clean and safe water. The present study aims to enhance understanding of the seasonal variations in water quality parameters in these key dams, with a focus on quantifying the impacts of anthropogenic activities and natural climatic fluctuations on water quality. The findings will provide essential insights for the development of strategies that ensure the sustainability of these critical water resources, aligning with broader global objectives of water conservation and environmental preservation (Denny et al., 2002; Biswas et al., 2004; Zhang et al., 2015).

Method and Material Study Area

The study area encompasses three critical dams located in Igatpuri Tahsil, Nashik District, Maharashtra, namely Darna Dam, Upper Vaitarna Dam, and Mukne Dam. These dams serve as key components in regional water resource management, contributing to irrigation, drinking water supply, and power generation. Darna Dam: Constructed in the early 20th century, the Darna Dam holds a gross storage capacity of 215.38 million cubic meters (MCM). It plays a pivotal role in regulating water flow, ensuring a stable water supply for both agricultural and urban needs in the region. The dam is situated at an elevation of approximately 421 meters above mean sea level, with the coordinates: 19.8436° N, 73.7404° E. Upper Vaitarna Dam: Located in the Igatpuri region, the Upper Vaitarna Dam was completed in 1973. This earthfill and gravity dam has a storage capacity of 205.685 MCM and is also utilized for hydropower generation, providing electricity to the surrounding areas. The dam is located at coordinates

19.7590° N, 73.6762° E, at an elevation of about 527 meters above sea level. Mukne Dam: Built in 1995, the Mukne Dam provides irrigation to over 12,500 hectares of farmland, significantly boosting agricultural productivity in the area. The dam has a live storage capacity of 122.48 MCM. It plays a crucial role in supporting local agriculture and ensuring a consistent water supply to the nearby settlements. The coordinates for Mukne Dam are

19.6706° N, 73.6719° E, and it is situated at an elevation of around 489 meters above sea level.

Together, these dams form a critical part of the water management infrastructure in Nashik District, and their role is vital for the socio-economic development of the region. Their operation is integral to the region's agricultural productivity, drinking water supply, and energy needs, thus making them indispensable to the local community.

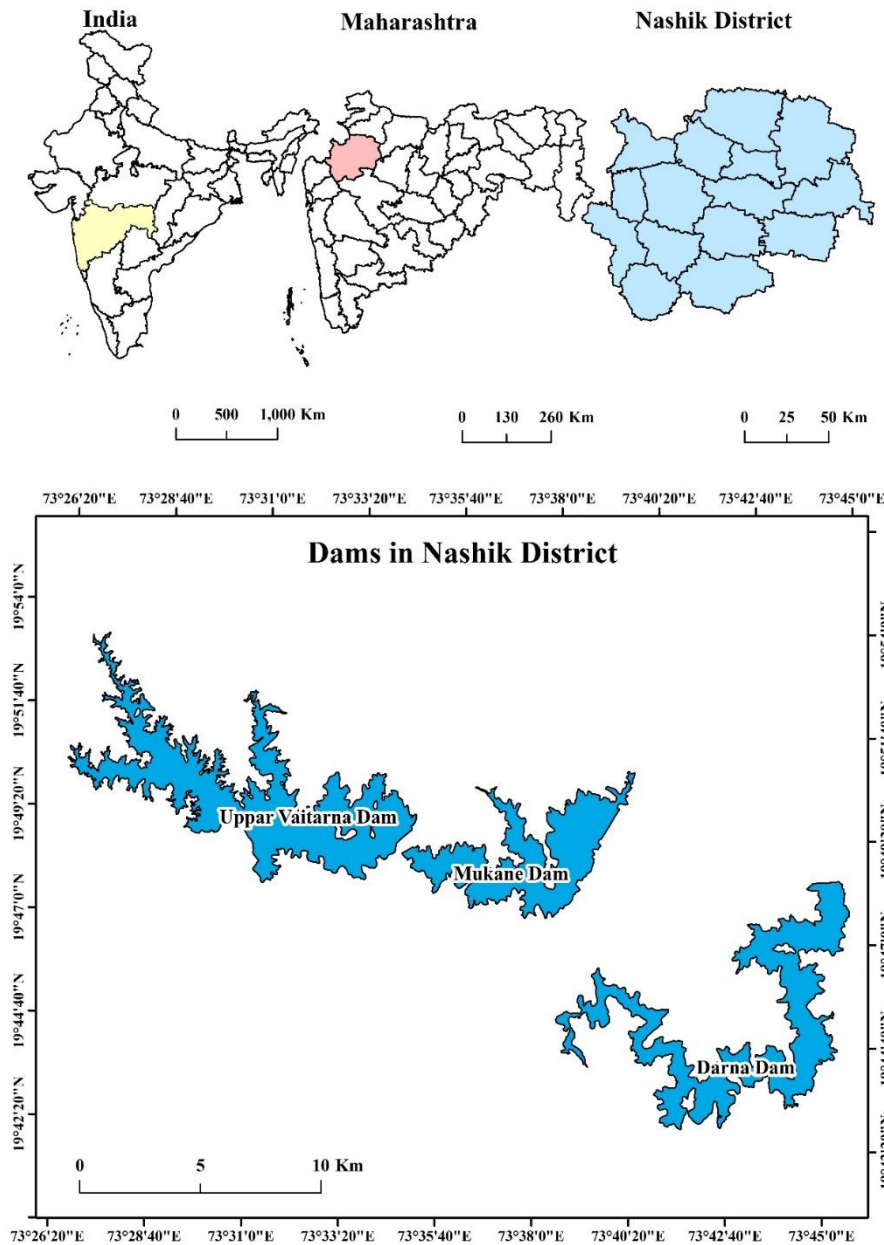


Figure 1: Location Map of the Study Area

Data Collection and Analysis

The data collection process for this study involved systematic sampling of water quality parameters from three significant dams in Igatpuri Tahsil, Nashik District—Darna Dam, Upper Vaitarna Dam, and Mukne Dam—over three distinct seasons: pre-monsoon, monsoon, and post-

monsoon of 2022. Water samples were collected from multiple points within the reservoirs, including surface, middle, and bottom layers, ensuring comprehensive spatial coverage. On-site testing was conducted using a YSI Pro handheld meter to measure real-time parameters such as pH, dissolved oxygen (DO), electrical conductivity (EC),

turbidity, and temperature. These parameters were immediately recorded to provide instant data on the water’s physical and chemical status. In addition, key chemical and nutrient parameters, including BOD, COD, TDS, nitrate, and phosphate concentrations, were analyzed in the laboratory using advanced instruments like AAS and ICP-MS for heavy metals.

Water Quality Index (WQI)

The Water Quality Index (WQI) is a tool that simplifies complex water quality data into a single, easily interpretable value, making it

accessible to a wide audience. For this study, WQI calculations will be based on two widely recognized methods: CCME WQI and WAM WQI, chosen for their simplicity and effectiveness in assessing water quality globally. The WQI will be calculated using WHO standards for drinking and irrigation quality (Table 1), which serve as benchmarks for the water from Darna, Upper Vaitarna, and Mukne Dams. These indices provide a comprehensive overview of water quality, offering critical insights for sustainable water resource management and public health.

Table 1: Standard Values For Water Quality (WHO)

Parameter	Standard Value
Physical Parameters	
Temperature (°C)	25-30°C (ideal range for aquatic life)
Turbidity (NTU)	<5 NTU (for clean water)
Total Suspended Solids (TSS)	<30 mg/L (for clean water)
Chemical Parameters	
pH	6.5-8.5 (WHO recommended range for drinking water)
Electrical Conductivity (EC)	<1500 µS/cm (indicates dissolved ions)
Total Dissolved Solids (TDS)	<500 mg/L (recommended for drinking water)
Dissolved Oxygen (DO)	>5 mg/L (essential for aquatic life)
Biochemical Oxygen Demand (BOD)	<5 mg/L (lower BOD is better)
Chemical Oxygen Demand (COD)	<20 mg/L (lower COD indicates lower organic pollution)
Alkalinity	20-200 mg/L (buffering capacity of water)
Hardness (Calcium and Magnesium)	100-300 mg/L (indicates water hardness)
Nitrate (NO ₃ ⁻)	<50 mg/L (WHO standard for drinking water)
Phosphate (PO ₄ ³⁻)	<0.5 mg/L (low levels prevent eutrophication)
Chlorides	<250 mg/L (WHO standard for drinking water)
Nutrient and Pollutant Load	
Ammonia (NH ₃)	<0.5 mg/L (high levels can be toxic)
Heavy Metals	
Arsenic	<0.01 mg/L (WHO standard for drinking water)
Lead	<0.01 mg/L (toxic, especially to children)
Cadmium	<0.003 mg/L (high levels are toxic)
Biological Parameters	
Coliform Count (Fecal Coliform)	<10 CFU/100 mL (indicates safe drinking water)

Result and Discussion

The water quality assessment of Upper Vaitarna, Mukane, and Darna Dams across the pre-monsoon, monsoon, and post-monsoon periods in 2022 revealed distinct seasonal variations in various water quality parameters. Temperature values ranged from $25.6 \pm 1.2^\circ\text{C}$ during the post-monsoon at Upper Vaitarna to $29.2 \pm 1.5^\circ\text{C}$ in the monsoon at Darna Dam, reflecting the typical warming effect during monsoon rains, which are often accompanied by increased atmospheric temperatures. Turbidity and Total Suspended Solids (TSS) demonstrated a clear seasonal trend, with values peaking during the monsoon period. For instance, turbidity at Upper Vaitarna Dam increased to 8.6 ± 2.3 NTU in the monsoon from 4.2 ± 1.1 NTU in the pre-monsoon, indicating a surge in particulate matter from surface runoff. Similarly, TSS levels rose significantly from 18.6 ± 4.3 mg/L in the pre-monsoon to 32.4 ± 7.1 mg/L during the monsoon at Upper Vaitarna, attributed to increased erosion and sediment load during rainfall events.

Chemical parameters such as pH remained largely within the standard range for freshwater, with values fluctuating slightly across seasons. For instance, pH at Upper Vaitarna varied from 7.3 ± 0.2 in the pre-monsoon to 7.4 ± 0.1 in the post-monsoon, demonstrating stable water chemistry. Electrical Conductivity (EC) and Total Dissolved Solids (TDS) also exhibited increases during the monsoon. At Mukane Dam, EC increased from 470 ± 35 $\mu\text{S}/\text{cm}$ in the pre-monsoon to 530 ± 50 $\mu\text{S}/\text{cm}$ in the monsoon, while TDS rose from 310 ± 25 mg/L to 370 ± 35 mg/L, indicating the influx of

dissolved ions and minerals from runoff. Dissolved Oxygen (DO) levels generally showed a decrease during the monsoon, with the lowest levels recorded at Mukane Dam (5.1 ± 0.5 mg/L) compared to the pre-monsoon (5.9 ± 0.4 mg/L), highlighting the increased microbial activity and organic load during this period.

Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) exhibited similar seasonal trends. At Darna Dam, BOD increased from 3.0 ± 0.7 mg/L in the pre-monsoon to 4.8 ± 1.1 mg/L in the monsoon, indicating higher levels of organic pollution. Similarly, COD values rose from 13.5 ± 2.5 mg/L to 18.0 ± 4.0 mg/L during the same period. These fluctuations reflect the higher organic decomposition rates and nutrient loading during monsoon runoff.

Nutrient parameters like nitrate and phosphate also demonstrated seasonal shifts. Nitrate concentrations increased across all dams during the monsoon, with Upper Vaitarna seeing an increase from 3.8 ± 0.6 mg/L in the pre-monsoon to 6.5 ± 1.0 mg/L in the monsoon, likely due to agricultural runoff. Phosphate levels followed a similar trend, with a rise from 0.3 ± 0.1 mg/L in the pre-monsoon to 0.6 ± 0.2 mg/L in the monsoon at Upper Vaitarna, pointing to higher nutrient loads from the surrounding landscape.

Heavy metals such as arsenic, lead, and cadmium were present in trace amounts across all three dams. Arsenic concentrations ranged from 0.004 ± 0.001 mg/L to 0.006 ± 0.001 mg/L, well below the WHO recommended limit of 0.01 mg/L, indicating minimal contamination.

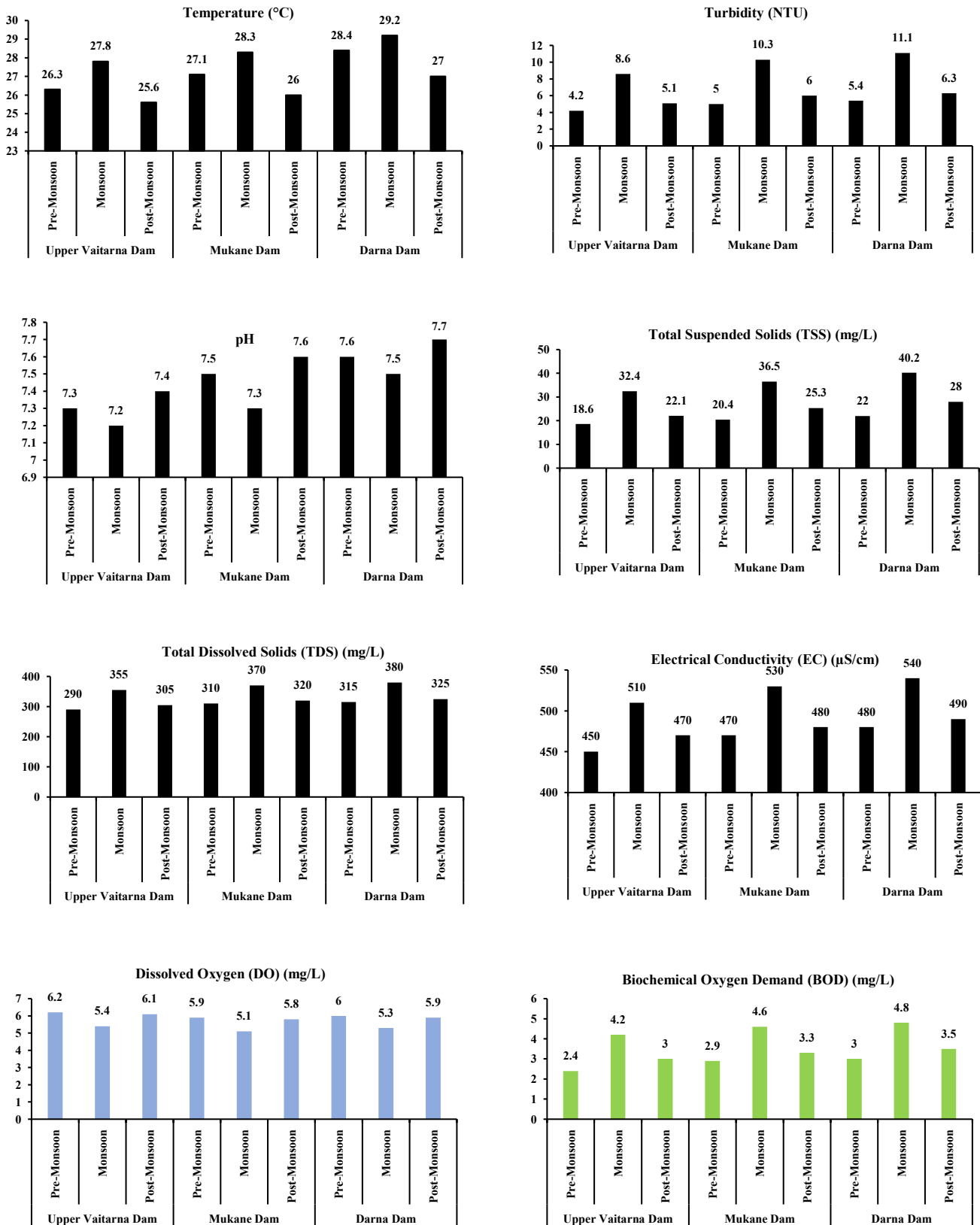


Figure 2: Spatio-temporal Trend of physicochemical Parameters-I

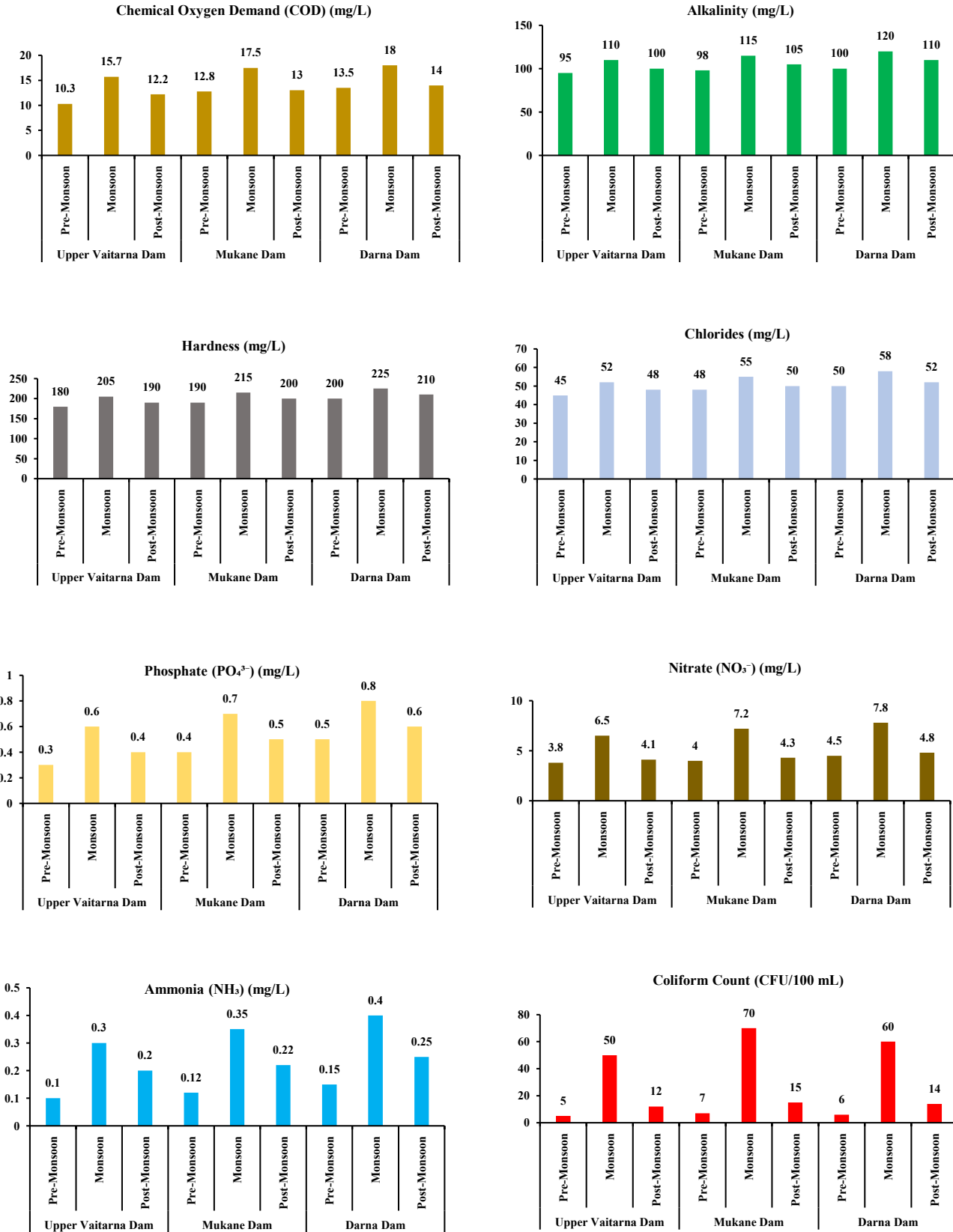


Figure 3: Spatio-temporal Trend of physicochemical Parameters-II

Table 2: Physicochemical Analysis of Dams-2022

Parameter	Upper Vaitarna Dam			Mukane Dam			Darna Dam		
	Pre-Mon	Monsoon	Post-Mon	Pre-Mon	Monsoon	Post-Mon	Pre-Mon	Monsoon	Post-Mon
Temperature (°C)	26.3 ± 1.5	27.8 ± 2.0	25.6 ± 1.2	27.1 ± 1.7	28.3 ± 1.9	26.0 ± 1.4	28.4 ± 1.6	29.2 ± 1.5	27.0 ± 1.3
Turbidity (NTU)	4.2 ± 1.1	8.6 ± 2.3	5.1 ± 1.4	5.0 ± 1.2	10.3 ± 2.6	6.0 ± 1.5	5.4 ± 1.3	11.1 ± 2.8	6.3 ± 1.7
TSS (mg/L)	18.6 ± 4.3	32.4 ± 7.1	22.1 ± 5.0	20.4 ± 5.3	36.5 ± 9.2	25.3 ± 6.1	22.0 ± 5.6	40.2 ± 10.1	28.0 ± 7.3
pH	7.3 ± 0.2	7.2 ± 0.3	7.4 ± 0.1	7.5 ± 0.2	7.3 ± 0.3	7.6 ± 0.1	7.6 ± 0.2	7.5 ± 0.3	7.7 ± 0.2
EC (µS/cm)	450 ± 30	510 ± 45	470 ± 35	470 ± 35	530 ± 50	480 ± 40	480 ± 40	540 ± 55	490 ± 45
TDS (mg/L)	290 ± 25	355 ± 40	305 ± 30	310 ± 25	370 ± 35	320 ± 30	315 ± 30	380 ± 40	325 ± 32
DO (mg/L)	6.2 ± 0.5	5.4 ± 0.6	6.1 ± 0.4	5.9 ± 0.4	5.1 ± 0.5	5.8 ± 0.3	6.0 ± 0.5	5.3 ± 0.5	5.9 ± 0.4
BOD (mg/L)	2.4 ± 0.8	4.2 ± 1.2	3.0 ± 1.0	2.9 ± 0.6	4.6 ± 1.0	3.3 ± 0.9	3.0 ± 0.7	4.8 ± 1.1	3.5 ± 1.1
COD (COD) (mg/L)	10.3 ± 2.1	15.7 ± 3.6	12.2 ± 3.0	12.8 ± 2.4	17.5 ± 3.4	13.0 ± 3.1	13.5 ± 2.5	18.0 ± 4.0	14.0 ± 3.2
Alkalinity (mg/L)	95 ± 15	110 ± 18	100 ± 14	98 ± 15	115 ± 18	105 ± 12	100 ± 18	120 ± 20	110 ± 16
Hardness (mg/L)	180 ± 20	205 ± 25	190 ± 18	190 ± 20	215 ± 22	200 ± 20	200 ± 22	225 ± 30	210 ± 25
Nitrate (NO ₃ ⁻) (mg/L)	3.8 ± 0.6	6.5 ± 1.0	4.1 ± 0.7	4.0 ± 0.5	7.2 ± 1.1	4.3 ± 0.6	4.5 ± 0.6	7.8 ± 1.2	4.8 ± 0.7
Phosphate (PO ₄ ³⁻) (mg/L)	0.3 ± 0.1	0.6 ± 0.2	0.4 ± 0.1	0.4 ± 0.1	0.7 ± 0.2	0.5 ± 0.1	0.5 ± 0.1	0.8 ± 0.3	0.6 ± 0.1
Chlorides (mg/L)	45 ± 6	52 ± 8	48 ± 7	48 ± 5	55 ± 6	50 ± 5	50 ± 6	58 ± 7	52 ± 6
Ammonia (NH ₃) (mg/L)	0.1 ± 0.03	0.3 ± 0.05	0.2 ± 0.04	0.12 ± 0.04	0.35 ± 0.06	0.22 ± 0.05	0.15 ± 0.05	0.4 ± 0.07	0.25 ± 0.06
Arsenic (mg/L)	0.005 ± 0.001	0.006 ± 0.001	0.005 ± 0.001	0.004 ± 0.001	0.005 ± 0.001	0.004 ± 0.001	0.004 ± 0.001	0.005 ± 0.001	0.004 ± 0.001
Lead (mg/L)	0.001 ± 0.0003	0.002 ± 0.0004	0.001 ± 0.0003	0.0009 ± 0.0002	0.002 ± 0.0003	0.001 ± 0.0002	0.001 ± 0.0003	0.002 ± 0.0004	0.001 ± 0.0003
Cadmium (mg/L)	0.0002 ± 0.0001	0.0003 ± 0.0001	0.0002 ± 0.0001	0.0001 ± 0.00005	0.0003 ± 0.0001	0.0002 ± 0.0001	0.0002 ± 0.0001	0.0004 ± 0.0001	0.0003 ± 0.0001
Coliform (CFU/100 mL)	5 ± 2	50 ± 25	12 ± 4	7 ± 3	70 ± 30	15 ± 5	6 ± 2	60 ± 20	14 ± 4

Lead and cadmium were similarly found at trace levels, with lead concentrations ranging from 0.001 ± 0.0003 mg/L to 0.002 ± 0.0004 mg/L, and cadmium ranging from 0.0001 ± 0.00005 mg/L to 0.0004 ± 0.0001 mg/L. These levels suggest that heavy metal pollution is not a significant concern in the study area.

Coliform counts, a key indicator of fecal contamination, were significantly higher during the monsoon. At Darna Dam, the coliform count surged to 60 ± 20 CFU/100 mL in the monsoon, up from 6 ± 2 CFU/100 mL in the pre-monsoon, reflecting the elevated microbial contamination likely caused by increased runoff from agricultural and urban areas.

Water Quality Index (WQI)

The Water Quality Index (WQI) assessment for Upper Vaitarna, Mukane, and Darna Dams in Nashik District reveals distinct seasonal influences, highlighting the variability in water quality across pre-monsoon, monsoon, and post-monsoon periods. In the pre-monsoon season, WQI values for the dams range from 45 to 52, indicating good to moderate water quality. Specifically, Upper Vaitarna Dam, with a WQI of 45, maintains the highest water quality under dry conditions, reflecting minimal external contamination and stable physicochemical parameters. This seasonal stability is attributed to reduced surface runoff and lower influxes of suspended particles and nutrients during the pre-monsoon period.

During the monsoon, the WQI values for all dams experience a substantial increase, with Mukane and Darna Dams rising sharply to 78 and 84, respectively, classifying them as "Poor" in terms of water quality. The monsoon rains significantly alter water quality dynamics, driven by heavy runoff that introduces large amounts of suspended sediments, dissolved solids, and microbial contaminants from surrounding areas. This increase in contaminants directly impacts turbidity, total dissolved solids (TDS), and coliform levels, particularly in Mukane and Darna, which appear more vulnerable to runoff-induced pollution. Upper Vaitarna Dam also experiences a decline in water quality, with a WQI of 70, yet remains in the moderate category, potentially due to a relatively lower influx of contaminants.

Table 3: Water Quality Index

Dam	Pre-Monsoon WQI	Monsoon WQI	Post-Monsoon WQI	Water Quality Status
Upper Vaitarna	45 (Good)	70 (Moderate)	55 (Moderate)	Variable by Season
Mukane	48 (Good)	78 (Poor)	60 (Moderate)	Seasonal Degradation
Darna	52 (Moderate)	84 (Poor)	65 (Moderate)	High Monsoon Impact

In the post-monsoon season, there is a notable improvement in WQI values across all dams, with levels stabilizing between 55 and 65, indicating moderate water quality. This partial recovery is likely due to the natural

settling of suspended particles and reduced surface runoff after the monsoon, though residual contaminants from monsoon inflows persist in the water column. The post-monsoon period thus reflects a transitional phase, where water quality is on a path to recovery but remains influenced by the prior seasonal influxes of nutrients and sediments.

The WQI findings suggest a critical need for seasonal water quality management, particularly during and immediately after the monsoon season, when water quality is most compromised. The significant impact of monsoon runoff underscores the necessity for watershed protection strategies and regular monitoring to safeguard water quality in Nashik's reservoirs. This data provides valuable insights for policymakers and water resource managers, emphasizing the importance of adaptive management practices tailored to seasonal variability and specific dam vulnerabilities.

Conclusion

This investigation provides a rigorous and integrative evaluation of seasonal water quality dynamics across the Upper Vaitarna, Mukane, and Darna reservoirs in Nashik District, demonstrating pronounced temporal variability governed by monsoon-driven hydrological processes and anthropogenic influences. The systematic analysis of key physicochemical and biological parameters—encompassing dissolved oxygen, biochemical oxygen demand, total dissolved solids, nutrient concentrations, and coliform load—reveals that pre-monsoon conditions are characterized by relative hydrochemical stability, whereas the monsoon period induces significant deterioration in water quality due to intensified surface runoff, sediment influx, and nutrient enrichment. The post-monsoon phase exhibits partial recovery; however, residual contamination underscores the persistence of seasonal impacts. The Water Quality Index (WQI) further substantiates these findings, identifying the monsoon season as the most critical phase of ecological stress across all reservoirs.

In light of these outcomes, the study advances a set of targeted, evidence-based recommendations. It is imperative to establish scientifically designed buffer zones and riparian vegetation belts within the reservoir catchments to attenuate sediment and nutrient inflow. The promotion of precision-based and regulated agricultural practices, including controlled fertilizer application and contour-based runoff management, is essential to minimize diffuse pollution. Furthermore, the implementation of decentralized wastewater treatment infrastructure in adjacent settlements is necessary to curtail the discharge of untreated effluents. The adoption of real-time, seasonally adaptive water quality monitoring systems, integrated with geospatial and sensor-based technologies, is strongly recommended to enable proactive management. Strengthening watershed governance frameworks, supported by inter-agency coordination and strict regulatory enforcement, is equally critical. Complementary measures such as periodic desiltation, catchment stabilization, and community-driven awareness initiatives should be institutionalized to enhance long-term ecological resilience. Collectively, these interventions constitute a scientifically robust and

policy-relevant framework for sustainable reservoir management, ensuring the protection and optimal utilization of vital water resources in the Nashik region.

Limitations and Future Directions

While the present study offers a systematic and seasonally stratified evaluation of water quality across major reservoirs in Nashik District, certain limitations warrant critical consideration. The analysis is confined to a single hydrological year (2022), which may not adequately capture inter-annual variability driven by climatic fluctuations and long-term environmental change. Although a comprehensive suite of physicochemical and biological parameters has been examined, the study does not explicitly integrate catchment-level land-use dynamics, hydrological modeling, or high-resolution spatial variability within reservoirs, thereby limiting deeper causal interpretation of observed patterns. Furthermore, the application of generalized Water Quality Index (WQI) models, while effective for comparative assessment, may oversimplify complex ecological processes and site-specific sensitivities. In this context, future research should prioritize multi-year longitudinal monitoring to establish temporal trends, alongside the integration of geospatial techniques such as GIS and remote sensing to elucidate linkages between land-use change and water quality. The adoption of advanced analytical approaches, including machine learning and watershed-scale hydrological modeling, is recommended to enhance predictive capability. Additionally, the incorporation of biological indicators and the development of region-specific WQI frameworks tailored to monsoon-dominated environments would significantly strengthen the scientific robustness and policy applicability of subsequent investigations.

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