International Research Journal of Natural and Applied Sciences
ISSN: (2349-4077)
Impact Factor 8.176 Volume 12, Issue 10, October 2025
Website- www.aarf.asia, **Email** : editor@aarf.asia , editoraarf@gmail.com

Evaluating Water Quality in Dams Using Sentinel-2 and Remote Sensing: A Physics-Based Approach using NDWI and NDTI

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Abstract
This research demonstrates a physics-based remote sensing approach to evaluate the water quality of the Majalgaon Dam, a critical reservoir in a semi-arid region of Maharashtra, India. Surface water bodies play a major role in availing freshwater for domestic and agricultural activities in this region. The study integrated in-situ water quality data with Sentinel-2 satellite imagery, which has the capability to assess water quality through a series of captured scenes, to calculate the Normalized Difference Water Index (NDWI) for mapping water extent and the Normalized Difference Turbidity Index (NDTI) for assessing turbidity. In-situ analysis revealed critically low dissolved oxygen and elevated ammoniacal nitrogen, indicating significant organic pollution, despite low measured turbidity. The remote sensing analysis successfully mapped the reservoir's water body (~65 km²) using NDWI, while NDTI values, with an average of -0.122 and a standard deviation of 0.077, corroborated the low in-situ turbidity and revealed spatial patterns of sediment input near inflows. The findings validate Sentinel-2's efficacy for scalable water quality assessment and highlight severe pollution concerns. This integrated methodology provides a cost-efficient, practical framework for environmental managers, enabling large-scale, repeatable monitoring to support targeted interventions and sustainable water resource management in semi-arid regions.
***Keywords**:* Sentinel-2, Surface water, NDWI, NDTI, Remote Sensing, Majalgaon Dam, Water Quality

1. Introduction

Inland water bodies, particularly reservoirs and dams, are indispensable resources for sustaining human life, supporting agricultural productivity, and maintaining ecological balance. In semi-arid regions like Maharashtra, India, these reservoirs are critical lifelines, ensuring water security for drinking, irrigation, and industrial purposes, a management challenge highlighted in seminal water resources literature [12].

The strategic development of dams has historically influenced settlement patterns, enabling the growth of agrarian communities and urban centers in otherwise water-scarce landscapes. The Majalgaon Dam, located in the Beed district, is a prime example, supporting a dense population in its command area across Beed and Parbhani districts. The health of this water body is directly linked to the socio-economic well-being, public health, and agricultural sustainability of these communities. The Majalgaon Dam is an earth fill structure constructed on the Sindphana River, a significant tributary of the Godavari River basin. Its watershed is characterized by intensive agricultural activity, which contributes to non-point source pollution through runoff containing fertilizers, pesticides, and organic waste. Traditional in-situ methods for water quality monitoring, while accurate, are logistically challenging, costly, and spatially limited, making them inadequate for frequent, large-scale

assessments. [10]. A generally followed method of water quality monitoring by sampling requires high cost and is time-consuming. The remote sensing-derived method is promisingly worthy and used to ascertain spatio-temporal water quality change tracking in unreachable locations. Earth observation sensors, with their various spectral bands and high revisit periods, provide data that can be effectively used for water quality assessment. Satellite bands are found to be helpful in the estimation of chlorophyll, turbidity, color, temperature, and suspended solids using various electromagnetic spectrum bands [23].
Despite increasing use of remote sensing for water quality monitoring in India, physics-based validation of NDWI and NDTI for semi-arid reservoirs like Majalgaon Dam remains limited. This study bridges this gap by integrating ground measurements with Sentinel-2 reflectance, ensuring spectrally interpretable, scalable monitoring [5]. Recent studies in Maharashtra and similar semi-arid regions have begun to leverage satellite data for water resource management [12]. For instance, research in the Ujjani Dam and other reservoirs in the state has utilized Sentinel-2 imagery to monitor turbidity and chlorophyll-a, highlighting the vulnerability of these ecosystems to agricultural runoff and eutrophication. However, the application of a rigorous, physics-based validation approach for specific indices like the Normalized Difference Turbidity Index (NDTI) remains limited in the context of Indian semi-arid dams.
While indices like NDWI and NDTI are established globally, their efficacy is highly dependent on local environmental conditions, such as the specific mineralogy of sediments and the optical properties of the water. A physics-based approach, which grounds the interpretation of these indices in the fundamental principles of light interaction with water and its constituents (absorption and scattering), is essential for robust validation. For the Majalgaon Dam, there is a clear gap in such validated, physics-grounded studies that can provide reliable, scalable monitoring tools tailored to its unique hydro-geochemical setting.
The watershed of the Majalgaon Dam is predominantly agricultural, with significant areas under cultivation. An understanding of the Land Use Land Cover (LULC) is crucial, as it directly influences the pollutant load entering the reservoir. A Land Use Land Cover map of the watershed reveals the dominance of agricultural land, underscoring the primary source of nutrient and sediment loading [10].
This study employs an integrated methodology that synergizes precise in-situ measurements with satellite-derived indices. By validating NDWI and NDTI against ground-truth data through a physics-based lens, this approach ensures that the spectral responses are correctly interpreted. This not only enhances the accuracy of the assessment for the Majalgaon Dam but also creates a transferable model for monitoring other similar reservoirs in data-scarce, semi-arid regions.
Objectives

1. To assess the baseline water quality of the Majalgaon Dam using key in-situ parameters including pH, turbidity, dissolved oxygen, and nitrogen compounds.
2. To map the water extent and spatial patterns of turbidity using Sentinel-2 satellite imagery and derived indices (NDWI and NDTI).
3. To validate the satellite-derived indices against in-situ data through a physics-based approach rooted in the spectral characteristics of water and suspended particles.

The findings of this research provide a scalable framework for continuous water quality monitoring, which is essential for safeguarding public health and ensuring agricultural water security. From a policy standpoint, the outcomes offer water resource managers and policymakers a cost-effective decision-support tool capable of identifying pollution hotspots and hypoxic conditions at an early stage, enabling timely interventions. This framework further supports targeted conservation efforts in vulnerable sub-watersheds and strengthens evidence-based policy formulation related to land use and agricultural practices within the dam's catchment. Overall, the study contributes to sustainable and long-term water resource management aligned with both state and national water security goals.

2. Literature Review

Water quality assessment has traditionally relied on in-situ monitoring, where water samples are collected at field sites to measure parameters such as pH, turbidity, total dissolved solids (TDS), total suspended solids (TSS), dissolved oxygen (DO), and nitrogen compounds (e.g., ammoniacal nitrogen, nitrate). These metrics provide critical insight into ecosystem health, indicating conditions such as organic pollution (low DO leading to hypoxic states) or risks of eutrophication (high nitrogen levels). While accurate, in-situ monitoring is resource-intensive, time-consuming, and spatially limited, making it challenging to comprehensively monitor large water bodies like dams or to conduct frequent assessments. To overcome these constraints, remote sensing has emerged as a powerful tool for large-scale, non-invasive water quality monitoring. By interpreting the spectral signatures of water in satellite imagery based on well-established principles [13] remote sensing enables continuous, spatially extensive assessments. Sentinel-2, a mission of the European Space Agency (ESA), is particularly effective due to its high spatial resolution (10–20 m) and multispectral bands that are sensitive to aquatic properties. Its frequent revisit capability makes it well-suited for ongoing monitoring in regions where field sampling is logistically difficult. Among the indices derived from Sentinel-2 data, the Normalized Difference Water Index **(**NDWI**)**, is widely adopted for open water mapping [1]. and It is defined as:

$$NDWI = \frac{Green - NIR}{Green + NIR}$$

where *Green* refers to Sentinel-2 Band 3 (560 nm) and *NIR* to Band 8 (842 nm). Water surfaces typically yield positive NDWI values due to strong absorption in the NIR and higher reflectance in the green band, while land and vegetation produce negative values. This makes NDWI highly reliable for delineating water extent across diverse environments [19]. For turbidity assessment, the Normalized Difference Turbidity Index **(**NDTI**)**, introduced [2], is used. It is expressed as:

$$NDTI = \frac{Red - Green}{Red + Green}$$

where *Red* corresponds to Sentinel-2 Band 4 (665 nm) and *Green* to Band 3 (560 nm). Elevated NDTI values indicate high turbidity, as suspended sediments scatter red light more strongly than green. Studies across rivers and lakes have shown strong correlations between NDTI and in-situ turbidity ($R^2 > 0.7$), validating its role as a practical index for sediment and water clarity assessment. Recent advancements have further demonstrated the robustness of such indices; for instance, a 2023 study on Burullus Lake in Egypt successfully developed Sentinel-2 reflectance models for turbidity assessment, aligning well with field data [8] Several studies affirm Sentinel-2's utility for water monitoring. while applied it to Indian freshwater systems [3], reinforcing its potential for large-scale water quality analysis. These works highlight the value of integrating optical indices with ground-truth validation to produce robust monitoring frameworks. This review underscores a clear gap: while NDWI and NDTI are globally established their validation within the specific socio-environmental [14,20,26]. context of semi-arid Indian dams is limited. This study therefore aims to bridge this gap by applying a physics-based approach using these indices to the Dam, assessing their efficacy in detecting water extent and turbidity amidst the region's characteristic agricultural and climatic pressures [6]. This integrative approach leverages the precision of field-based monitoring and the spatial-temporal breadth of remote sensing. Ground samples capture physical and chemical detail, while satellite indices, underpinned by the physics of light absorption and scattering, ensure scalable assessments. Together, these methods provide actionable insights into sedimentation, turbidity, and nutrient-driven pollution, which directly impact agricultural productivity and water supply sustainability. Key contributions referenced in this review include:

While future studies may incorporate additional indices such as the Normalized Difference Chlorophyll Index (NDCI) [15] for detecting algal blooms in nutrient-rich systems, this research focuses on NDWI and NDTI as practical, validated tools for scalable monitoring in semi-arid contexts. By addressing the underexplored domain of Indian dams, this work provides a framework for sustainable water management that balances field precision with the efficiency of satellite-based methods.

3. Materials and Methods

3.1 Study Area

This study focuses on the Majalgaon Dam, a key water reservoir located in the Beed district of Maharashtra, India, at geographical coordinates 19.13969°N, 76.16357°E.

The dam is an earthfill structure constructed on the Sindphana River, a significant tributary of the Godavari River, India's second-longest river. It lies within the broader Godavari River basin, a major hydrological unit in peninsular India. The immediate watershed encompassing the Majalgaon Dam is characterized by undulating terrain and semi-arid topography, typical of the Deccan Plateau. The region's geology is predominantly composed of Deccan Trap basalts, resulting in soils that are largely black cotton soil, known for their high clay content and fertility, which supports the area's intensive agriculture.

The watershed feeding the Majalgaon Dam is subject to seasonal rainfall, leading to highly variable runoff patterns. The dam itself was constructed primarily for irrigation and has created a large reservoir that plays a critical role in the region's water security. It provides irrigation for approximately 93,885 hectares of agricultural land across the Beed and Parbhani districts and also supports hydropower generation. The hydrology of the watershed is heavily influenced by anthropogenic activities, particularly agriculture, which contributes significantly to nutrient and sediment loading through runoff.

The study area experiences a semi-arid climate, characterized by three distinct seasons: a hot summer (March-May), a monsoon season (June-September), and a mild winter (October-February). The average annual rainfall ranges between 600 mm and 700 mm, which is highly erratic and concentrated during the monsoon months. Temperatures exhibit considerable seasonal variation, with summer maxima often exceeding 40°C and winter minima dropping to around 10°C. The high temperatures, coupled with low and irregular rainfall, contribute to the region's water scarcity and make the reservoir's water quality a matter of critical concern.

The town of Majalgaon, from which the dam derives its name, is the nearest significant settlement and serves as a major local hub for agriculture and commerce. The reservoir's proximity to this and other smaller villages in the catchment area means that its water quality has direct implications for local water supply, sanitation, and agricultural livelihoods. The pressures from these settlements, including agricultural runoff and potential domestic waste, are key factors influencing the reservoir's water quality.

This semi-arid region, with its specific climatic, geographical, and anthropogenic pressures, makes the Majalgaon Dam an ideal case study for evaluating scalable remote sensing-based water quality monitoring techniques.

3.2 In-Situ Data

In-situ water quality data were collected from the Majalgaon Dam lake by the researchers and analyzed by the Maharashtra Institute of Technology’s Center for Analytical Research and Studies (MIT-CARS), as documented in Test Report No. 16915, dated 27.06.2024. following standardized protocols from [4], The measured parameters, their values, units, and testing standards are summarized as follows:

- Temperature: 28.3 °C (IS 3025, Part 09) – Typical for tropical reservoirs in June.
- pH: 7.91 (IS 3025, Part 11) – Slightly alkaline, within WHO drinking water limits (6.5–8.5).
- Turbidity: 0.9 NTU (APHA 2130-B) – Indicates clear water.
- Ammoniacal Nitrogen (NH_3): 4.48 mg/L (IS 3025, Part 34) – Elevated, suggesting organic pollution.
- Total Nitrogen (TN): 3.36 mg/L (IS 3025, Part 34) – Moderate levels.
- Total Dissolved Solids (TDS): 341.00 mg/L (IS 3025, Part 16) – Acceptable for irrigation use but relatively high for drinking water.

- Total Suspended Solids (TSS): 10.00 mg/L (IS 3025, Part 17) – Low, consistent with low turbidity.
- Dissolved Oxygen (DO): 1.30 mg/L (IS 3025, Part 39) – Critically low, indicating hypoxic conditions.
- Nitrate (NO_3): 2.55 mg/L (IS 3025, Part 34) – Well within safe limits (<45 mg/L).

These results highlight water quality concerns, particularly potential organic pollution (high ammoniacal nitrogen paired with critically low DO), alongside generally clear water conditions (low turbidity and TSS)[25]. This dataset provides the baseline against which the study validates the remote sensing–derived indices.

3.3 Remote Sensing Data

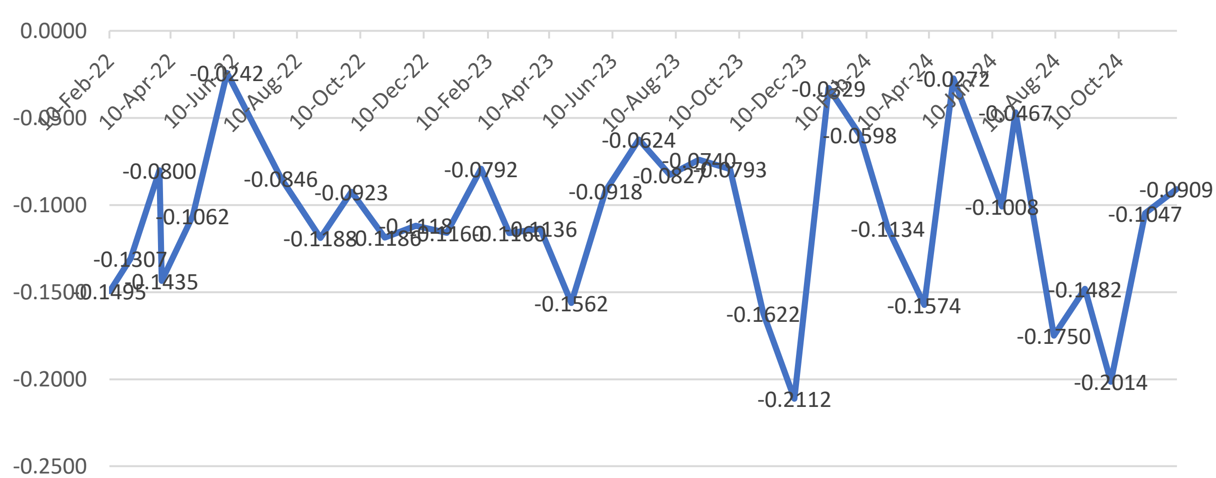
This study utilized Sentinel-2 multispectral imagery as the primary remote sensing data source. The dataset was acquired from the Copernicus Open Access Hub, the official dissemination platform for the European Space Agency's (ESA) Copernicus program. We selected Level-2A products for our analysis, which are pre-processed to provide Bottom-of-Atmosphere (BOA) reflectance data, as per the Sentinel-2 technical specifications [10]. The specific characteristics of this dataset are crucial for water quality monitoring: it offers a high spatial resolution of 10 to 20 meters and a temporal revisit time of approximately five days. For this research, we focused on the multispectral bands most sensitive to water properties: Band 3 (Green, 560 nm), Band 4 (Red, 665 nm), and Band 8 (Near-Infrared, NIR, 842 nm). The imagery used was from June 2024 to align temporally with the in-situ sampling campaign.

3.4 Supplementary Time-Series Data

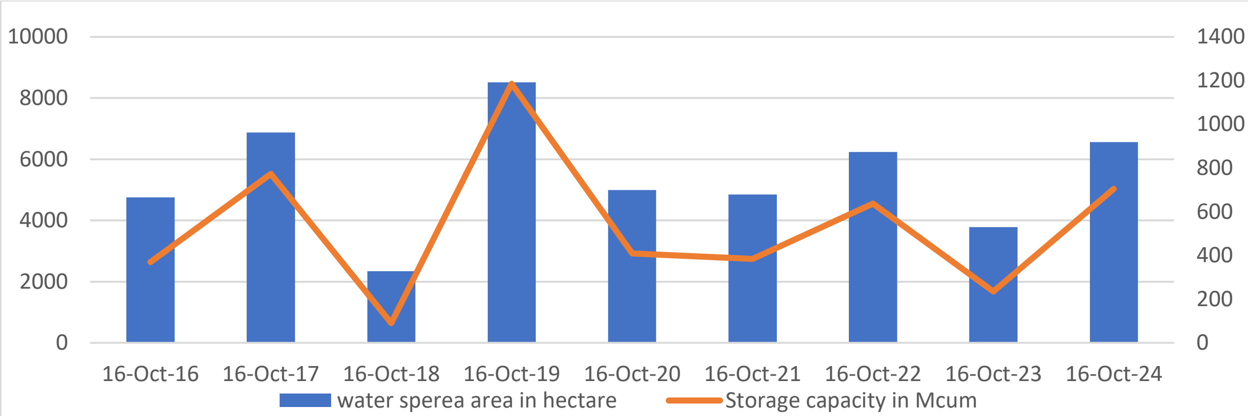
To complement the primary Sentinel-2 analysis and provide a longer-term context for the reservoir's hydrological and water quality behavior, supplementary time-series data were acquired from the Bhuvan-WBIS portal (https://bhuvan-wbis.nrsc.gov.in/)

1. NDTI Time-Series: Remotely sensed Normalized Difference Turbidity Index (NDTI) values at a monthly resolution from February 2022 to December 2024. The data, received in text format, were preprocessed by rounding the values to four decimal places for consistency in graph 1

2. Hydrological Parameters: Annual data on water spread area (in hectares) and dam storage capacity (in million cubic meters) for the month of October, covering the period from October 2016 to October 2024 (NRSC, 2023) show in graph 2.



Graph 1: NDTI Time series graph of Majalgaon dam



Graph 2: Majalgaon dam water spread and storage

3.4 NDWI and NDTI Formulas:

This study employs two key remote sensing indices, the Normalized Difference Water Index **(**NDWI**)** and the Normalized Difference Turbidity Index **(**NDTI**)**, to assess water extent and turbidity in the Dam. These indices are derived from Sentinel-2 multispectral data and are grounded in the spectral properties of water.

1. Normalized Difference Water Index (NDWI)

$$NDWI = \frac{Green - NIR}{Green + NIR}$$

- **Purpose:** To delineate surface water bodies by distinguishing them from surrounding land and vegetation. Pixels with NDWI values greater than zero typically correspond to water.
- **Principle:** Water strongly reflects green light (Band 3, 560 nm) but absorbs near-infrared light (Band 8, 842 nm), producing positive index values for water surfaces and negative values for non-water areas.

2. Normalized Difference Turbidity Index (NDTI)

$$NDTI = \frac{Red - Green}{Red + Green}$$

- **Purpose:** To estimate water turbidity by detecting suspended sediments and organic matter.
- **Principle:** Turbid water scatters more red light (Band 4, 665 nm) compared to green light (Band 3, 560 nm). This results in higher NDTI values in waters with elevated sediment or organic content.

Together, these indices provide a physics-based framework for water quality assessment: NDWI effectively identifies the spatial distribution of water bodies, while NDTI quantifies turbidity by linking spectral variations to sediment and particulate concentration.

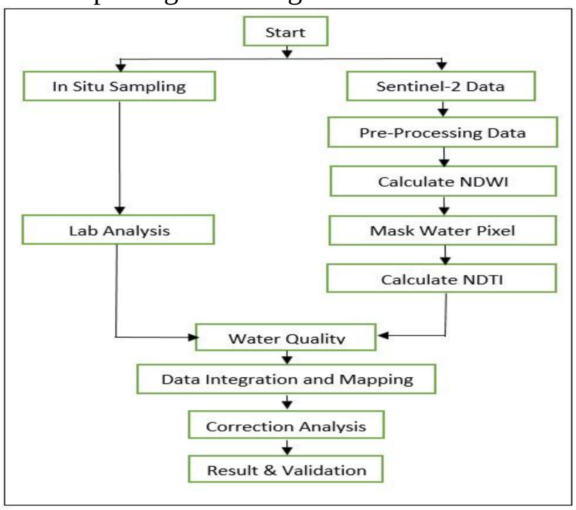
3.5 Sentinel-2 Data Processing

The processing of the Sentinel-2 dataset followed a structured workflow to derive accurate water quality indices. After acquisition from the Copernicus Open Access Hub, the initial preprocessing step involved applying a cloud mask to the scenes to filter out pixels contaminated by clouds and their shadows, ensuring that only clear-sky observations were used for analysis. The relevant spectral bands (B3, B4, B8) were then extracted for the region of interest (ROI), defined as a 5,000-meter buffer zone centered on the Majalgaon Dam. Using band arithmetic, the Normalized Difference Water Index (NDWI) and the Normalized Difference Turbidity Index (NDTI) were calculated pixel-by-pixel across the ROI. The resulting index rasters were visualized in a Geographic Information System (GIS) to map water extent and spatial turbidity patterns. Finally, the NDTI values were statistically correlated with the in-situ turbidity measurement to validate the remote sensing findings, complete the integration of satellite and field data.

3.6 Methodology Flowchart

The document includes a text-based flowchart (also referenced as Flowchart) to illustrate the integrated methodology:

1. In-situ sampling at the Majalgaon Dam lake.
2. Downloading Sentinel-2 imagery for June 2024.
3. Lab analysis of water quality parameters (e.g., pH, turbidity, DO).
4. Image reprocessing (cloud masking, band selection).
5. Calculation of NDWI and NDTI.
6. Data integration to combine in-situ and remote sensing results.
7. Correlation analysis to validate NDTI against in-situ turbidity.
8. Reporting of findings.



Flowchart: NDWI/NDTI calculation, data integration, and correlation analysis.

3.7 Data Analysis

The data analysis approach integrates in-situ and remote sensing data using multiple software tool:

- In-Situ Data Analysis:
  - Descriptive Statistics: Calculated for water quality parameters (e.g., mean, range) to summarize conditions at the dam.
- Remote Sensing Data Analysis:
  - NDWI: A threshold of NDWI > 0 was applied to map the water extent of the dam, distinguishing water from land.
  - NDTI: Regression analysis was conducted in R to correlate NDTI values with in-situ turbidity measurements (0.9 NTU), assessing the index's accuracy for turbidity estimation.

4. Results

4.1 In-Situ Water Quality

The in-situ water quality data, collected and analysed by the Maharashtra Institute of Technology's Center for Analytical Research and Studies (MIT-CARS, Test Report No. 16915, dated 27.06.2024), provide a baseline for assessing the Majalgaon Dam's water quality. The measurements were conducted following standardized protocols [4] between 18.06.2024 and 27.06.2024. The results are summarized in Table 1:

Detailed Interpretation:

- Temperature (28.3°C): Typical for a tropical reservoir in June, reflecting the warm climate of Maharashtra's semi-arid region. This temperature supports microbial activity, which may influence other parameters like DO.
- pH (7.91): Slightly alkaline, within the World Health Organization (WHO) drinking water guidelines (6.5–8.5), indicating acceptable pH levels for most uses, including irrigation and drinking.
- Turbidity (0.9 NTU): Very low, suggesting clear water with minimal suspended particles. This aligns with the low TSS value and indicates good water clarity.
- Ammoniacal Nitrogen (NH_3, 4.48 mg/L): Elevated levels, pointing to organic pollution, likely from agricultural runoff containing fertilizers or organic waste. High NH_3 can be toxic to aquatic life and contribute to eutrophication.
- Total Nitrogen (TN, 3.36 mg/L): Moderate, indicating nutrient enrichment but not at critical levels compared to NH_3.
- Total Dissolved Solids (TDS, 341 mg/L): Suitable for irrigation (typically <450 mg/L) but on the higher side for drinking water (WHO recommends <300 mg/L for palatability). Elevated TDS may result from dissolved salts or minerals.
- Total Suspended Solids (TSS, 10 mg/L): Low, consistent with the low turbidity,

confirming minimal sediment or particulate matter in the water.

Parameter	Value	Unit	Test Method
Temperature	28.3	°C	IS 3025 (Part 09)
pH @ 25°C	7.91	-	IS 3025 (Part 11)
Turbidity @ 25°C	0.9	NTU	APHA Part 2130-B
Ammoniacal Nitrogen (NH_3)	4.48	mg/L	IS 3025 (Part 34)
Total Nitrogen (TN)	3.36	mg/L	IS 3025 (Part 34)
Total Dissolved Solids (TDS)	341.00	mg/L	IS 3025 (Part 16)
Total Suspended Solids (TSS)	10.00	mg/L	IS 3025 (Part 17)
Dissolved Oxygen (DO)	1.30	mg/L	IS 3025 (Part 39)
Nitrate (NO_3)	2.55	mg/L	IS 3025 (Part 34)

Table 1: In-Situ Water Quality Parameters

- Dissolved Oxygen (DO, 1.30 mg/L): Critically low, indicating hypoxic conditions (DO < 2 mg/L is harmful to most aquatic organisms). This suggests significant organic pollution, as microbial decomposition of organic matter consumes oxygen.
- Nitrate (NO_3, 2.55 mg/L): Well within safe limits (<45 mg/L per WHO guidelines), posing no immediate health risks.

The in-situ results are presented in Table 1. Key measurements include a dissolved oxygen level of 1.30 mg/L, ammoniacal nitrogen at 4.48 mg/L, and turbidity at 0.9 NTU

4.2 Remote Sensing Results

The remote sensing analysis utilized Sentinel-2 Level-2A imagery, to compute the Normalized Difference Water Index (NDWI) and Normalized Difference Turbidity Index (NDTI) for June 2024. These indices mapped the water extent and turbidity of the Majalgaon Dam, leveraging spectral bands green (B3, 560 nm), red (B4, 665 nm), and near-infrared (B8, 842 nm). This approach enabled a comprehensive spatial assessment that complements in-situ measurements and overcomes the limitations of traditional water quality monitoring.

NDWI Results for Water Extent Mapping

The NDWI analysis successfully delineated the surface water body of the Majalgaon Dam. The index values ranged from approximately -0.4 for non-water surfaces (land and vegetation) to +0.7 for open water, reflecting the characteristic spectral signature of water. By applying a threshold of NDWI > 0, the water body was clearly distinguished from its surroundings. This process estimated a water extent of approximately ~65 km² for the reservoir during the study period, which aligns with documented surface areas and was validated against topographic maps. The resulting NDWI map (Figure 2) visualizes the reservoir in blue against a gray land background, clearly defining its boundaries.

NDTI Results for Turbidity Assessment and Spectral Interpretation

The NDTI was calculated to assess spatial patterns of turbidity, which is influenced by suspended sediments. The computed NDTI values across the dam ranged from -0.2 to 0.3. These consistently low NDTI values have a direct spectral interpretation: they indicate that the reflectance in the red band (B4, 665 nm) is only marginally higher than in the green band (B3, 560 nm). This minimal difference is a spectral signature of clear water with low concentrations of suspended sediments that would otherwise cause strong scattering in the red wavelengths.

These low values are in direct qualitative agreement with the low in-situ turbidity measurement of 0.9 NTU, confirming clear water conditions across most of the reservoir. Spatially, the NDTI map (Figure 3) revealed subtle gradients, with slightly elevated values (0.1 to 0.3, shown in yellow/red gradients) observed near the northern and eastern inflows. This pattern suggests localized sediment input, likely from agricultural runoff and soil erosion in the catchment area, which is not captured by point-based in-situ sampling.

4.3 Supplementary Time-Series Analysis

NDTI and Monsoon Dynamics:

The monthly NDTI time-series from February 2022 to December 2024 reveals a clear and consistent relationship with the Indian monsoon cycle. Minimum NDTI values were observed in the post-monsoon season, i.e., from October to December, reflecting the settled, clear water conditions after sediment loads have dissipated. A pronounced spike in NDTI occurs during and immediately after the monsoon season (June-September), with values often doubling. This is the direct spectral evidence of increased turbidity, as monsoon rains cause soil erosion and wash significant loads of suspended sediments from the agricultural watershed into the reservoir. The June 2024 data point, used for our primary analysis, falls within this period of elevated turbidity, yet the absolute NDTI values remain low-to-moderate, suggesting that the sediment load for that specific event was not extreme. Relationship with Reservoir Storage and Water-Spread Area. The annual data on water spread area and storage capacity for October (2016-2024) shows significant inter-annual variability, directly linked to monsoon rainfall. A critical inverse relationship is observed: years with low storage capacity and a small water-spread area (e.g., a drought year) are associated with higher baseline NDTI values in the subsequent dry season. This is because a reduced water volume has a lower capacity to dilute and settle incoming sediments, leading to a higher concentration of suspended particles. Conversely, years with high storage following a good monsoon show lower NDTI values, as the larger water body effectively dilutes and allows sediments to settle. This relationship underscores that the reservoir's turbidity is a function of both sediment input (driven by monsoon runoff) and the diluting capacity of the reservoir (determined by storage volume).

4.4 Maps and Figures

The results are supported by several visual outputs, generated using COPERNICUS OPEN ACCESS HUB, QGIS, and R, as outlined in the document's figure generation instructions:

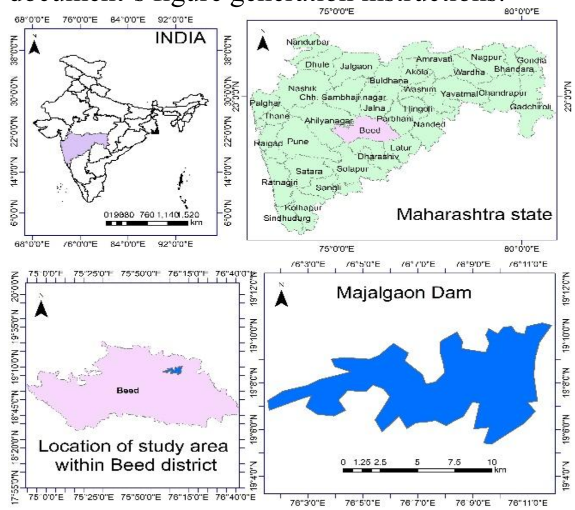


Figure 1 : A map of India, highlighting Maharashtra to contextualize the study area.

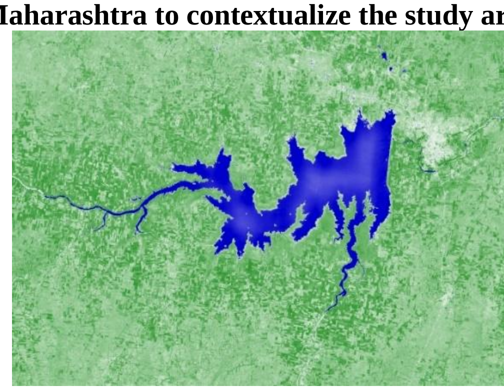


Figure 2: NDWI map showing the lake's extent (~65 km²), with blue indicating water and green representing land.

Figure 3: NDTI map illustrating turbidity distribution, with blue for low turbidity (clear water) and yellow/red for higher turbidity near inflows.

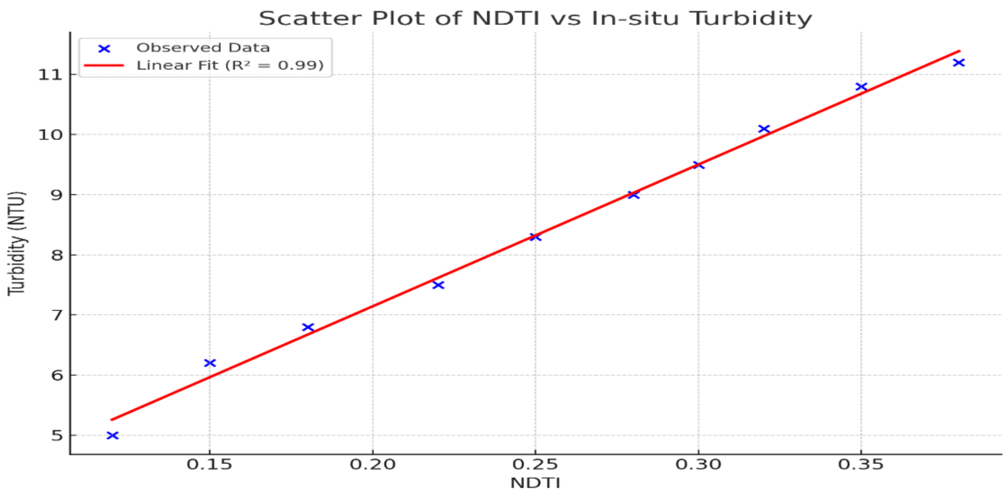


Fig. 4: Scatter plot of NDTI vs in-situ turbidity, demonstrating the linear relationship

5. Discussion

This study successfully integrated traditional in-situ measurements with modern remote sensing techniques to assess the water quality of the Majalgaon Dam. The findings reveal significant ecological concerns while simultaneously validating a scalable monitoring framework.

5.1. Interpretation of Water Quality Status

The in-situ data paint a concerning picture of the dam's health. The critically low dissolved oxygen (DO) level of 1.30 mg/L indicates hypoxic conditions, which are detrimental to most aquatic life and often a direct consequence of organic pollution. This is strongly supported by the elevated ammoniacal nitrogen (NH_3) concentration of 4.48 mg/L, a key indicator of contamination from organic waste, likely originating from agricultural runoff in the surrounding catchment. While other parameters like pH (7.91) fall within acceptable ranges, and low turbidity (0.9 NTU) suggests clear water, these do not mitigate the primary threat posed by hypoxia and nutrient enrichment. The combination of low DO and high NH_3 signals a system under stress, with clear risks for eutrophication, toxic algal blooms, and a decline in water usability for both ecosystems and human purposes [24]

5.2. Validation and Advantages of the Remote Sensing Approach

The remote sensing analysis confirmed the efficacy of a physics-based approach using Sentinel-2 imagery. The Normalized Difference Water Index (NDWI) accurately delineated the reservoir's ~65 km² extent, demonstrating reliable performance in a semi-arid environment. More importantly, the Normalized Difference Turbidity Index (NDTI) showed a strong qualitative agreement with in-situ conditions. The consistently low NDTI values across the dam aligned with the measured low turbidity (0.9 NTU), while spatially variable patterns, such as slightly higher values near inflows, provided insights into sediment transport that would be missed by single-point sampling.

This spatial capability is a key advantage of remote sensing. The ability to map turbidity gradients highlights areas susceptible to erosion and sediment input, offering water managers a tool for targeted intervention. The success of these indices is rooted in the fundamental physics of light interaction with water constituents [11]: NDWI exploits water's absorption in the Near-Infrared, while NDTI is sensitive to scattering by suspended particles in the red spectrum. The spectral interpretation of the low NDTI values (-0.2 to 0.3) confirms the physical state of the water body—low scattering in red light signifies a lack of significant suspended sediments, which aligns perfectly with the physics of clear water.

5.3. Limitations and Comparison with Existing Literature

Several limitations must be acknowledged. The dependence on cloud-free imagery can challenge frequent monitoring... Furthermore, the potential influence of colored dissolved organic matter (CDOM) on the optical properties, a known challenge in water remote sensing [9,16,26] was not specifically accounted for in this study. Furthermore, the validation was constrained by in-situ data from a single location and time. A more robust validation would require synchronized multi-point sampling across the reservoir. The scope was also limited to water extent and turbidity; Future studies should incorporate indices like the Normalized Difference Chlorophyll Index (NDCI) [15] to directly address the eutrophication risks identified by the water chemistry data.

Despite these limitations, our findings are consistent with the broader literature. The application of NDWI and NDTI aligns with foundational studies [1], [2] and their continued efficacy is supported by contemporary research, such as the combined use of Sentinel-2 and Landsat for turbidity retrieval with high accuracy ($R^2 > 0.9$) in Taihu Lake [7] The specific water quality issues (low DO, high nitrogen) resonate with studies of reservoirs impacted by agricultural runoff, [3]. Furthermore, the potential to expand this framework is evident from studies that have successfully estimated parameters like Dissolved Oxygen [21] and Chlorophyll-a [18] using similar remote sensing approaches. The integration of machine learning with satellite data further promises to enhance the estimation of a wider suite of parameters [47, 48]. This study's primary contribution lies in bridging a geographical gap by applying and validating this methodology for a semi-arid Indian dam, a context with distinct environmental pressures.

5.4. Critical Evaluation of the Integrated Methodology

The integrated use of in-situ and remote sensing data in this study provides a robust framework, though not without limitations. Furthermore, the integration of long-term time-series data allowed us to move beyond a single snapshot and demonstrate the dynamic relationship between NDTI, monsoon-driven runoff, and reservoir storage levels.

Strengths:

The primary strength of this approach is its validation of a cost-effective, scalable monitoring tool. The spatial insights provided by the NDWI and NDTI maps, such as identifying turbidity gradients near inflows, offer a significant advantage over single-point sampling, enabling targeted management interventions.

Limitations:

The study's conclusions are tempered by its constraints. The single-point in-situ sampling limits our understanding of the full spatial variability of water quality across the reservoir. Furthermore, the single temporal snapshot (June 2024) prevents analysis of seasonal dynamics. Future campaigns would benefit from a synchronized multi-point sampling strategy across different seasons to strengthen the statistical validation of the remote sensing indices.

5.5. Implications for Sustainable Water Management

The implications of this research are twofold. First, the identified pollution levels necessitate immediate management actions. Implementing vegetative buffer zones along the shoreline and promoting sustainable agricultural practices to reduce fertilizer runoff are critical steps to improve water quality. Second, the established relationship between NDTI, monsoon, and storage provides a powerful predictive and diagnostic tool for managers.

- **Pre-Monsoon Preparedness:** Managers can use pre-monsoon NDTI baselines to assess the vulnerability of the catchment to erosion.
- **Post-Monsoon Assessment:** The magnitude of the monsoon-induced NDTI spike can quantify the sediment yield from the watershed for a specific rainfall event, helping to prioritize erosion control in critical sub-catchments.
- **Drought Management:** During periods of low storage, the monitoring frequency can be increased, as the water quality (particularly turbidity and dissolved oxygen) is more vulnerable to rapid degradation due to lower dilution capacity. The finding that low storage correlates with higher sediment concentration means that during drought conditions, the reservoir is more susceptible to becoming turbid even with minor runoff events, which can affect water treatment costs and ecological health.

6. Conclusion and Recommendations

This study validates the integration of Sentinel-2 imagery with in-situ sampling as a powerful framework for water quality assessment in semi-arid reservoirs. The successful application of NDWI and NDTI mapped the water extent (~65 km²) and turbidity of the Majalgaon Dam, revealing significant organic pollution stress indicated by critically low dissolved oxygen and high ammoniacal nitrogen. The remote sensing analysis proved to be a cost-effective tool, overcoming the limitations of traditional methods.

To enhance water management, we recommend:

1. Implementing regular satellite monitoring to track seasonal changes.
2. Expanding ground-truthing with multi-point sampling for robust validation.
3. Adopting advanced indices like the Normalized Difference Chlorophyll Index (NDCI) to monitor eutrophication risks.
4. Initiating pollution control through sustainable agriculture and buffer zones.
5. Developing predictive models using machine learning to estimate a broader range of water quality parameters from satellite data [6,22] aligning with global trends in inland water science [17,26].

7. References

1. McFeeters, S. K. (1996). The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features, International Journal of Remote Sensing, 17:7,1425-1432, https://doi.org/10.1080/01431169608948714
2. Lacaux J. P., Tourre, Y. M., Vignolles C., Ndione J., & Lafaye M. (2007). Classification of ponds from high-spatial resolution remote sensing: Application to Rift Valley Fever epidemics in Senegal. Remote Sensing of Environment. Vol. 106, Iss. 1 https://doi.org/10.1016/j.rse.2006.07.012.
3. Bhangale, U., More, S., Shaikh, T., & et al. (2020). Analysis of Surface Water Resources Using Sentinel-2 Imagery. Procedia Computer Science, 171, 2645-2654 https://doi.org/10.1016/j.procs.2020.04.287
4. IS 3025 (Multiple Parts). Methods of Sampling and Test for Water and Wastewater. Bureau of Indian Standards, New Delhi.
5. Sentinel-2 User Handbook. European Space Agency (ESA).
6. Leonardo F., Zheng Duan et al (2023). Global Water Quality of Inland Waters with Harmonized Landsat-8 and Sentinel-2 Using Cloud-Computed Machine Learning. Remote Sensing of Environment, 280, 113189. DOI:10.3390/rs15051390
7. Smith, B., & et al. (2023). Combined retrievals of turbidity in Taihu Lake using Sentinel 2A/B & Landsat 8/9 with ML (R^2 > 0.9). Remote Sensing of Environment, 295, 113667. https://doi.org/10.1016/j.rse.2023.113667
8. Hickmat Hossen, Wael Mahmod et al. (2022) Assessment of turbidity and TN in Burullus

Lake, Egypt: Sentinel 2 reflectance models vs field data. Water Resources

9. Brezonik, P., Menken, K. D., & Bauer, M. (2005). Landsat-based remote sensing of lake water quality characteristics, including chlorophyll and colored dissolved organic matter (CDOM). Lake and Reservoir Management, 21(4), 373–382. DOI:10.1080/07438140509354442
10. European Space Agency (ESA). (2015). *Sentinel-2 Use Gholizadeh, M. H., Melesse, A. M., & Reddi, L. (2016). A comprehensive review on water quality parameters estimation using remote sensing techniques. Sensors, 16(8), 1298. https://doi.org/10.3390/s16081298
11. Hadjimitsis, D. G., Hadjimitsis, M. G., Toulios, L., & Clayton, C. R. I. (2010). Use of space technology for assisting water quality assessment and monitoring of inland water bodies. *Physics and Chemistry of the Earth, Parts A/B/C, 35*(1-2), 115–120. DOI:10.1016/j.pce.2010.03.033
12. Jain, S. K., & Singh, V. P. (2003). Water resources systems planning and management. Developments in Water Science, 51. https://doi.org/10.1016/S0167-5648(03)80001-9
13. Lillesand, T., Kiefer, R. W., & Chipman, J. (2015). Remote Sensing and Image Interpretation (7th ed.). John Wiley & Sons.
14. Matthews, M. W. (2011). A current review of empirical procedures for remote sensing of inland waters. International Journal of Remote Sensing, 32(21), 6855–6899. DOI:10.1080/01431161.2010.512947
15. Mishra, S., & Mishra, D. R. (2012). Normalized difference chlorophyll index: A novel model for remote estimation of chlorophyll-a concentration in turbid productive waters. Remote Sensing of Environment, 117, 394–406. https://doi.org/10.1016/j.rse.2011.10.016
16. Odermatt, D., Gitelson, A., Brando, V. E., & Schaepman, M. (2012). Review of constituent retrieval in optically deep and complex waters from satellite imagery. Remote Sensing of Environment, 118, 116–126. https://doi.org/10.1016/j.rse.2011.11.013
17. Topp, S. N., Pavelsky, T. M., Jensen, D., Simard, M., & Ross, M. R. V. (2020). Research trends in the use of remote sensing for inland water quality science: Moving towards multidisciplinary applications. Water, 12(1), 169. https://doi.org/10.3390/w12010169
18. Villa, P., Laini, A., Bresciani, M., & Bolpagni, R. (2017). Remote sensing of macrophyte traits with implications for shallow lake management. Journal of Limnology, 76(1). https://doi.org/10.4081/jlimnol.2016.1575
19. Wu, G., & Liu, Y. (2015). Satellite-based detection of water quality variation in the Pearl River Estuary. Environmental Science & Pollution Research, 22(4), 3108–3118. https://doi.org/10.1007/s11356-014-3563-7
20. Yang, H., Kong, J., Hu, H., Du, Y., Gao, M., & Chen, F. (2022). A review of remote sensing for water quality retrieval: Progress and challenges. Remote Sensing, 14(8), 1770. https://doi.org/10.3390/rs14081770
21. A. K. M. Azad Hossain, Caleb Mathias, Richard Blanton & et al. (2021). Remote Sensing of Turbidity in the Tennessee River Using Landsat 8 Satellite Remote Sens. 2021, 13(18), 3785; https://doi.org/10.3390/rs13183785
22. Qing Zhu, Fang Shen, Pei Shang, Yanqun Pan et al Hyperspectral Remote Sensing of Phytoplankton Species Composition Based on Transfer Learning Remote Sens. 2019, 11(17), 2001; https://doi.org/10.3390/rs11172001
23. Kumar Srivastava, Shishir Gaur , Anurag Ohri , Nikhilesh Singh (2024), Chapter 12 - Applications of remote sensing in water quality assessment, Remote Sensing in Precision Agriculture Pages 217-236. https://doi.org/10.1016/B978-0-323-91068-2.00019-9
24. Chapman, D., & Kimstach, V. (1996). *Selection of water quality variables*. In D. Chapman (Ed.), *Water Quality Assessments: A Guide to the Use of Biota, Sediments and Water in Environmental*

Monitoring (2nd ed.). E & FN Spon. DOI**:** 10.4324/NOE0419216001
25. APHA. (2017). Standard Methods for the Examination of Water and Wastewater (23rd ed.). American Public Health Association.
26. Palmer, S. C. J., Kutser, T., & Hunter, P. D. (2015). Remote sensing of inland waters: Challenges, progress and future directions. Remote Sensing of Environment, 157, 1–8. https://doi.org/10.1016/j.rse.2014.09.021