Remote Sensing-Based Estimation of Total Suspended Solids and Secchi Depth in Dharoi Reservoir Using Sentinel-2 Imagery

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Abstract

Understanding water quality dynamics in reservoirs is essential for effective management and conservation, particularly in regions influenced by seasonal variations. This study investigates the relationship between Secchi depth (SD) and total suspended solids (TSS) in the Dharoi Reservoir during the pre-monsoon, monsoon, and post-monsoon seasons, utilizing remote sensing techniques. Satellite-derived measurements of SD and TSS were analysed using scatter plots and regression analysis to determine correlations across different seasonal contexts. The study encompassed a comprehensive spatial analysis of water quality indicators, identifying patterns and variations in sediment concentration and water clarity. The findings reveal a significant negative correlation between TSS and SD, with pre-monsoon conditions exhibiting lower sediment levels (average TSS of 0.73 mg/L and average SD of 0.9 m). During the monsoon, increased runoff led to elevated TSS (up to 5.8 mg/L) and reduced SD (down to 0.46 m), highlighting the complex interplay of environmental factors affecting water quality. Post-monsoon results demonstrated a return to pre-monsoon trends, reinforcing the seasonal variability of water quality parameters. This research underscores the importance of continuous monitoring of water quality in the Dharoi Reservoir, emphasizing the need for targeted management strategies to mitigate sedimentation impacts on aquatic ecosystems. The study demonstrates the potential of remote sensing as an effective tool for long-term water quality assessment, contributing to enhanced water resource management practices in the region. These findings serve as a foundation for future research focused on the sustainability and resilience of freshwater resources under changing environmental conditions.

Introduction

Water quality is a critical environmental parameter influencing the health of aquatic ecosystems, biodiversity, and the availability of water for human use. One of the key indicators of water quality is the concentration of Total Suspended Solids (TSS), which refers to the solid particles suspended in water. TSS levels can affect water clarity, which in turn impacts light penetration, aquatic plant growth, affecting photosynthesis in aquatic plants, leading to reduced oxygen levels in water bodies, and the overall ecological balance of freshwater systems (Adjovu, G. E. et al., 2023) (Na'imah, N. et al., 2024). Alongside TSS, Secchi Depth (SD) is another essential metric that provides a direct measure of water clarity. SD measurements are essential for evaluating the ecological health of freshwater systems (Khan, M. X. et al., 2022). Secchi Depth reflects the transparency of water and is widely used in the assessment of eutrophication, sediment loading, and algal blooms. It reflects the optical properties of water, influenced by chlorophyll, suspended solids, and other factors (Wang, Y. et al. 2024).

In recent years, the use of remote sensing technologies has gained significant traction in the field of water quality monitoring. Traditionally, water quality assessments have relied heavily on in-situ measurements, which can be labour-intensive, time-consuming, and spatially limited. Satellite-based remote sensing, particularly through sensors such as the Sentinel-2, offers a cost-effective and scalable solution for monitoring large water bodies over time. Long-term analyses, such as those conducted in the Great Tokyo area, reveal significant trends in Secchi depth correlating with changes in temperature and nutrient concentrations, highlighting its role in tracking eutrophication (Akada, H. et al., 2023). Additionally, advancements in remote sensing technologies have enhanced the ability to monitor Secchi depth over large spatial and temporal scales (Wang, Y. et al. 2024) (Chen, X. et al., 2022). Overall, Secchi depth serves as a vital indicator for aquatic health and ecosystem dynamics, particularly in the context of human-induced changes in water bodies. However, while Secchi depth is widely used, it may not always provide a complete picture of water quality, especially in highly turbid environments where alternative methods like turbidity meters could be more effective (Golubkov, M. S et al., 2023). Sentinel-2, with its high spatial and temporal resolution, provides valuable data for estimating water quality parameters like TSS and SD across broad spatial extents, allowing for a more comprehensive understanding of aquatic ecosystems.

The Dharoi Reservoir, a vital water body in Gujarat, India, plays a crucial role in supporting the region's irrigation, drinking water supply, and fisheries. However, like many inland water bodies, the reservoir faces challenges related to sedimentation, eutrophication, and pollution, which can degrade its water quality over time. Nutrient enrichment, particularly from agricultural runoff and untreated sewage, exacerbates eutrophication, leading to harmful algal blooms and hypoxia, which threaten aquatic life (Prasad, R. et al, 2019) (Xu, J. et al, 2016). Furthermore, sedimentation contributes to the release of phosphorus, further degrading water quality (Xu, J. et al, 2016). Effective management strategies, including monitoring nutrient inputs and implementing adaptive management, are crucial for sustaining the reservoir's health and productivity (Gupta, S. K. et al., 2024) (Mamun, M. et al., 2021). Monitoring these changes is essential for effective management and conservation efforts. Despite the importance of water quality monitoring in Dharoi Reservoir, there is a lack of continuous and comprehensive field-based data, necessitating alternative approaches like remote sensing to fill this gap.

The Sentinel-2 satellite, part of the Copernicus program, offers multi-spectral imagery suitable for assessing water quality indicators such as TSS and SD. The satellite's visible and near-infrared bands, along with its frequent revisit time and moderate spatial resolution, make it well-suited for tracking variations in water quality over time. By employing empirical algorithms developed for inland water bodies, researchers can derive estimates of TSS and SD from Sentinel-2 imagery with reasonable accuracy.

This study aims to explore the potential of Sentinel-2 imagery for estimating Total Suspended Solids (TSS) and Secchi Depth (SD) in Dharoi Reservoir during the monsoon season. The specific objectives of this research are: (1) to apply remote sensing-based algorithms for deriving TSS and SD, (2) to assess the spatial variability of these parameters within the reservoir, and (3) to provide insights into the implications of the observed trends for water resource management.

In the absence of field calibration and validation data, this research adopts a remote sensing-only approach, utilizing established algorithms to estimate TSS and SD values (Ha, N. T. T. et al. 2022) (Pereira-Sandoval, M. et al. 2019). The findings from this study will offer a preliminary understanding of the water quality dynamics in Dharoi Reservoir, contributing to more informed decision-making in its management and conservation.

Study Area

The Dharoi Reservoir, located in Gujarat, India, on the Sabarmati River, is a crucial artificial lake constructed in 1978 for irrigation, water supply, and flood control. Situated at approximately 23°55' N latitude and 72°47' E longitude, the reservoir spans an area of 107.39 km² at full capacity and has a catchment area of 5,540 km². It provides irrigation water to over 122,000 hectares of agricultural land and serves as a vital drinking water source for nearby communities. The reservoir's gross storage capacity is 908 MCM, with a live storage of 458 MCM, making it a significant water resource for the region. Recent studies have focused on improving reservoir inflow predictions and flood forecasting, utilizing advanced models like the HEC-HMS and Bayesian model averaging, achieving a correlation of 0.91 for inflow predictions (Patel, A., & Yadav, S. M. (2023). Additionally, the reservoir's operation is optimized through simulation analyses to balance irrigation needs and flood control, ensuring effective water resource management (Jain, S. K., et al, 1998). The integration of crop evapotranspiration estimates further aids in determining irrigation water requirements, highlighting the reservoir's significance in agricultural productivity (Bhujbal, P. B. et al., 2021). The surrounding terrain is characterized by gentle rolling hills, with an average elevation of 177 meters above sea level, and the climate is semi-arid, with three distinct seasons: summer, monsoon, and winter. The region receives an annual average rainfall of 750 mm, predominantly during the monsoon season from June to September, which is also the period of peak inflow and sediment deposition in the reservoir. Temperatures range from 12°C in winter to 45°C in summer, influencing the reservoir's hydrodynamic processes. In recent years, concerns have been raised over the reservoir's water quality, with increasing sedimentation, agricultural runoff, and nutrient loading leading to elevated levels of Total Suspended Solids (TSS) and reduced water clarity as measured by Secchi Depth (SD). The Narmada Water Resources, Water Supply, and Kalpsar Department manages the reservoir, with continuous monitoring essential due to growing human pressures. This study focuses on the geographic area defined between 23.977° N to 24.113° N and 72.800° E to 73.022° E, encompassing the reservoir and surrounding hydrology, utilizing Sentinel-2 imagery to assess water quality during the 2020 monsoon season, a period marked by significant changes in TSS and SD due to high inflow and sedimentation.

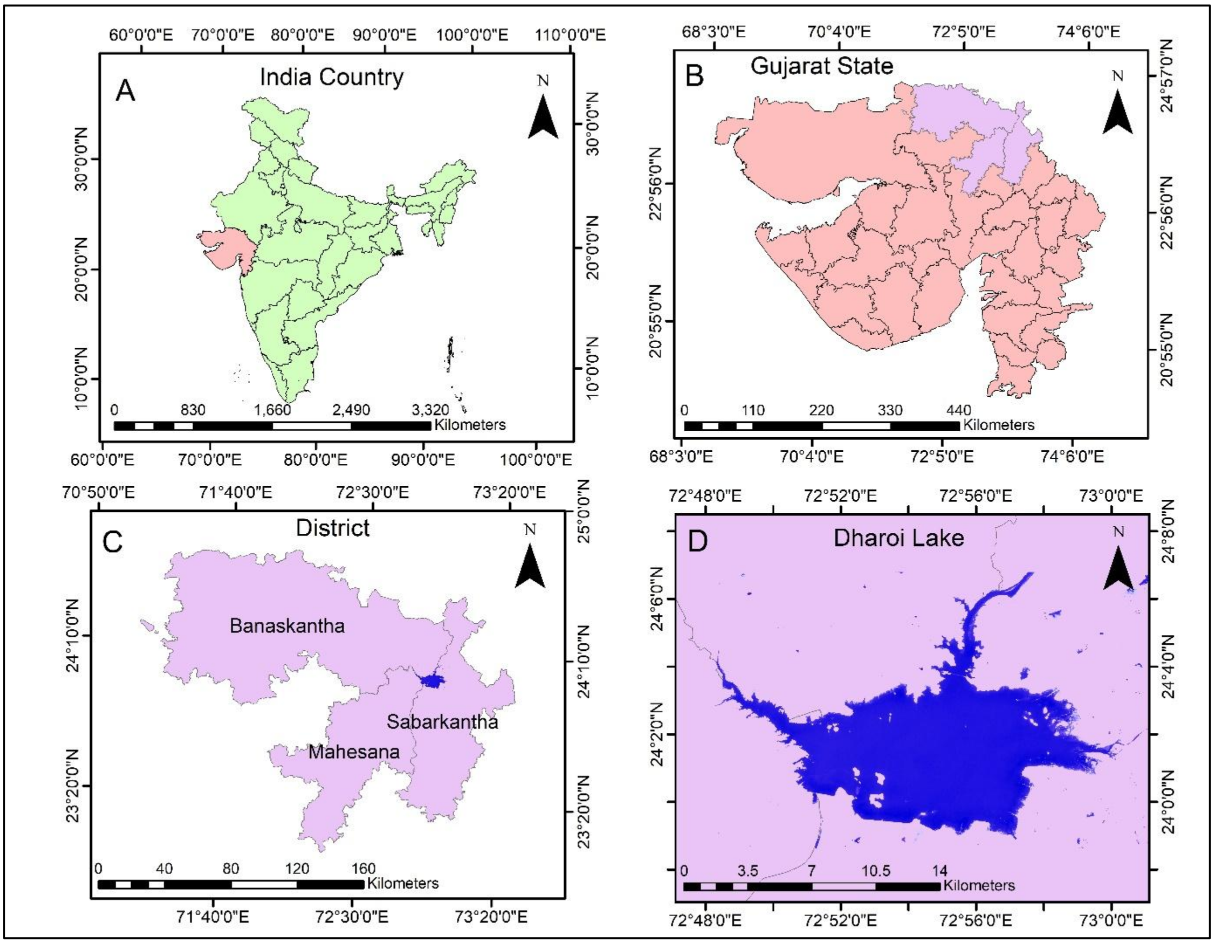

Fig. 1 Study area of this research. A – India, B – Gujarat State, C – District, D – Dharoi Lake.

Methodology

Data Sources and Image Collection

This study utilized Sentinel-2 surface reflectance imagery, available from the European Space Agency's (ESA) Copernicus program, to estimate Total Suspended Solids (TSS) and Secchi Depth (SD) in the Dharoi Reservoir. The Sentinel-2 imagery collection (S2_SR_HARMONIZED) was filtered for the year 2020 to capture different seasonal phases: pre-monsoon (March to May), monsoon (June to September), and post-monsoon (October to December). To minimize atmospheric disturbances, images were filtered to retain only those with less than 20% cloud cover. The images were then composited by calculating the median values and rescaled by multiplying the pixel values by 0.0001.

Preprocessing Steps

Preprocessing included clipping the imagery to the region of interest (ROI), defined as the Dharoi Reservoir. The ROI was delineated using a polygon geometry. Cloud-masking was performed by filtering the dataset based on cloud pixel percentage. Additionally, image scaling was applied to normalize reflectance values.

Water Body Extraction Using MNDWI

To extract the water body (Dharoi Reservoir), the Modified Normalized Difference Water Index (MNDWI) was calculated using the normalized difference between the Green band (B3) and the Short-Wave Infrared band (B11) of Sentinel-2 (Du, Y., Zhang et al., 2016). The MNDWI threshold greater than zero was applied to delineate water pixels (Du, Y., Zhang et al., 2016). The area of the water body was computed in square kilometers by multiplying the binary MNDWI image with the pixel area and summing the values.

Total Suspended Solids (TSS) Estimation

The Total Suspended Solids (TSS) in the reservoir were estimated using a ratio-based algorithm, which leveraged the Near-Infrared (NIR) and Red (B4) bands of Sentinel-2 imagery (Ha, N. T. T. et al. 2022). The TSS was calculated as the ratio of NIR to Red reflectance values. The resultant TSS layer was masked with the MNDWI-derived water pixels to ensure that TSS values were computed exclusively for the water body. The TSS values were classified and visualized using a colour palette ranging from maroon to blue, and the results were exported for further analysis.

Secchi Depth (SD) Estimation

Secchi Depth, an indicator of water clarity, was estimated by employing the ratio of Blue (B2) to Red Edge (B5) bands in Sentinel-2 imagery (Pereira-Sandoval, M. et al. 2019). Similar to TSS, the SD layer was masked using the MNDWI water mask. The output SD values were visualized and classified using a predefined palette to represent variations in water transparency. The SD image was exported for subsequent analysis.

The region of interest (ROI) for this study was defined as the Dharoi Reservoir, located in Gujarat, India. The analysis was conducted at a spatial resolution of 10 meters, corresponding to the native resolution of Sentinel-2 bands used in this study. Both TSS and SD results were computed and exported at this scale to ensure high spatial accuracy for environmental monitoring of the reservoir.

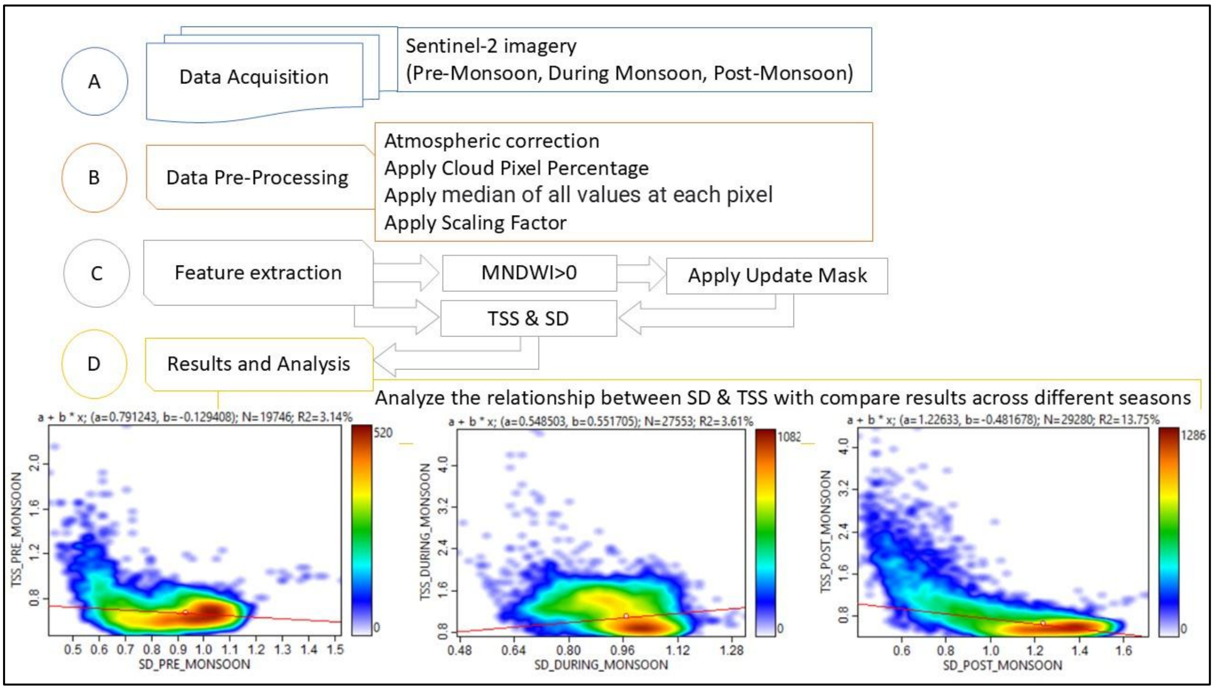

Fig. 2 Research methodology of this research work.

Results and Discussion

Water Quality in Pre-Monsoon Season

Total Suspended Solids (TSS) Analysis in Pre-Monsoon Season:

The provided table 1 presents Total Suspended Solids (TSS) concentrations for the pre-monsoon season in the Dharoi Reservoir, categorized into different concentration zones along with the corresponding surface area in square kilometers for each zone.

Very Low TSS Zone (0.45 - 0.64 mg/L): This zone covers the largest area of the reservoir, 26.08 sq. km. The very low concentration of TSS in this region suggests clear water with minimal suspended particles such as sediment, algae, or organic matter. This may indicate favorable conditions in these parts of the reservoir, likely due to lower inflows of pollutants or minimal disturbance to sediment. The water quality here appears to be quite high during the pre-monsoon season.

Low TSS Zone (0.65 - 0.72 mg/L): The low TSS concentration zone occupies a slightly smaller area of 25.45 sq. km, but still represents a significant portion of the reservoir. This range also reflects relatively clear water, though the concentration of suspended solids is higher than in the very low zone. While the water quality in these areas is still good, some increase in suspended matter could be present, possibly due to minor disturbances or local inputs of organic and inorganic material.

Moderate TSS Zone (0.73 - 0.89 mg/L): Covering 9.88 sq. km, the moderate TSS concentration zone reflects areas where the amount of suspended solids is higher, potentially leading to reduced water clarity. The presence of this zone indicates an increase in sediment, organic matter, or algal growth, possibly related to localized sources of pollution or sediment runoff. These areas may require closer monitoring as the water quality begins to degrade compared to lower TSS zones.

High TSS Zone (0.9 - 1.25 mg/L): This zone, occupying only 1.13 sq. km, represents areas of the reservoir where suspended solids are present in higher concentrations, which could significantly reduce water transparency. High TSS levels are often associated with increased sedimentation, organic decay, or algal blooms, contributing to poorer water quality in these regions. This zone suggests areas of potential concern where further investigation may be needed to identify sources of pollution or erosion.

Very High TSS Zone (1.26 - 2.83 mg/L): The smallest zone in terms of area, covering just 0.23 sq. km, indicates the highest concentration of suspended solids in the reservoir. This zone is likely to experience very poor water clarity, possibly due to high levels of sediment, nutrient loading, or algal blooms. Such high TSS levels could be indicative of localized pollution or significant disturbance, such as erosion, inflows of polluted water, or organic decay, and should be prioritized for management efforts.

The TSS data for the pre-monsoon season shows that the majority of the Dharoi Reservoir (over 50 sq. km) maintains relatively low TSS concentrations, which corresponds to good water clarity and overall favourable conditions for aquatic ecosystems. However, the presence of moderate to very high TSS zones, though limited in area, indicates regions where water quality is compromised due to increased suspended solids. These areas, particularly the very high TSS zone, warrant attention for potential sources of sedimentation or pollution that could impact the reservoir's overall health. Management strategies may need to focus on preventing runoff, controlling pollution sources, and mitigating sediment disturbances in these higher TSS zones to maintain the water quality across the reservoir.

Table 1: Total Suspended Solids (TSS) Concentration and Secchi Depth (SD) distribution in Pre-Monsoon season

Total Suspended Solids (TSS) Concentration Pre-Monsoon			Secchi Depth (SD) Pre-Monsoon		
Zone	**Range**	**Area (Sq.km)**	**Zone**	**Range**	**Area (Sq.km)**
Very Low	0.45 - 0.64	26.08	**Very Low**	0.32 - 0.74	7.54
Low	0.65 - 0.72	25.45	**Low**	0.75 - 0.89	11.95
Moderate	0.73 - 0.89	9.88	**Moderate**	0.9 - 0.99	18.13
High	0.9 - 1.25	1.13	**High**	1 - 1.19	25.09
Very High	1.26 - 2.83	0.23	**Very High**	1.2 - 1.97	0.06

Secchi Depth (SD) Analysis in Pre-Monsoon Season:

The critical analysis of the table 1 shows that water clarity, as indicated by Secchi Depth, varies across the reservoir. The Very Low SD zone, with values ranging between 0.32 and 0.74 meters, covers 7.54 sq. km of the reservoir. This suggests areas of poor water transparency, likely due to high levels of suspended solids or other particulates that limit light penetration. The presence of such low transparency zones could indicate potential eutrophication or pollution in specific parts of the reservoir.

The Low SD zone (0.75 to 0.89 meters) spans a slightly larger area of 11.95 sq. km. Although water clarity in these areas is better than in the Very Low zone, it still indicates a relatively high concentration of suspended materials or algal blooms that hinder light penetration. This may be an early sign of water quality issues in those regions.

The Moderate SD zone (0.9 to 0.99 meters) occupies the largest area at 18.13 sq. km, suggesting that this range of water clarity is dominant during the pre-monsoon period. Moderate transparency indicates better water quality in these sections of the reservoir, with fewer suspended solids compared to lower SD zones, but not reaching the highest clarity levels.

The High SD zone (1.0 to 1.19 meters), which covers 25.09 sq. km, represents areas of the reservoir with relatively clear water. The larger area covered by this zone suggests that significant portions of the reservoir maintain good water quality during the pre-monsoon season, likely due to lower levels of suspended particles and algal growth.

Lastly, the Very High SD zone (1.2 to 1.97 meters) is the smallest, covering only 0.06 sq.

km. This zone represents the clearest water in the reservoir, with very low concentrations of suspended solids and pollutants. However, its minimal extent suggests that only a very small portion of the reservoir exhibits this high level of water clarity, indicating that such optimal conditions are rare during the pre-monsoon season.

The table 1 indicates that the Dharoi Reservoir exhibits variable water clarity across different zones during the pre-monsoon season. While a large portion of the reservoir has moderate to high Secchi Depths, which suggests acceptable water quality, the presence of areas with very low SD values indicates potential issues such as pollution or algal blooms that warrant further investigation and management.

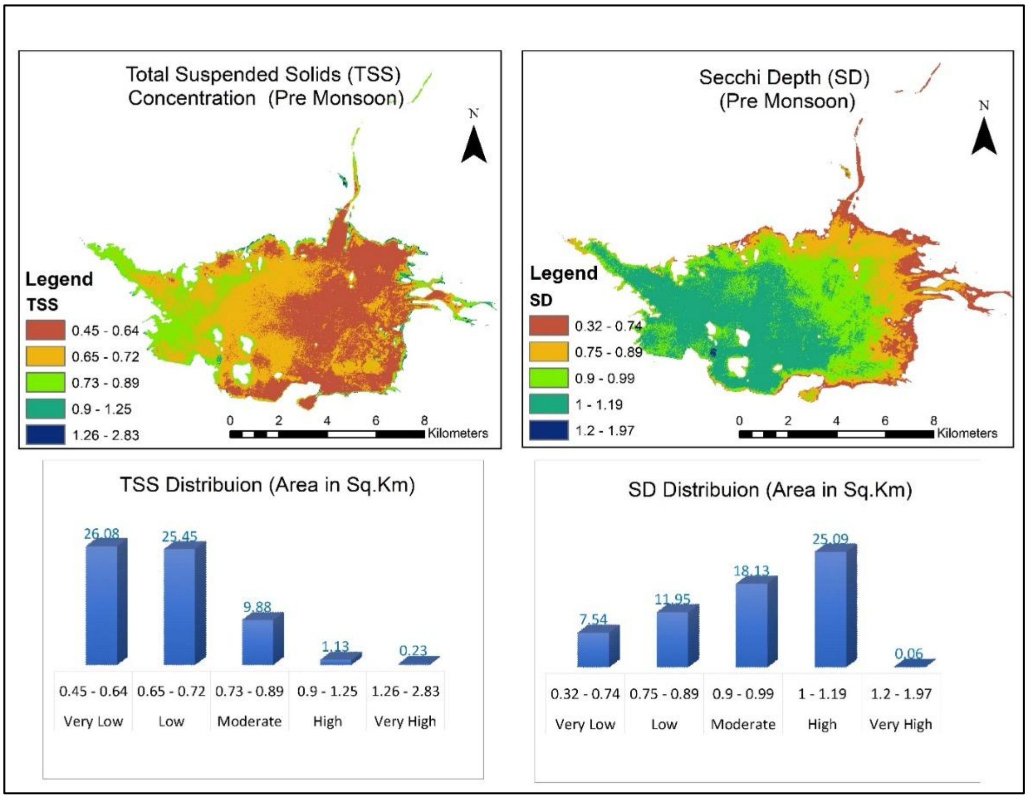

Fig. 3 Total Suspended Solids (TSS) concentration and Secchi Depth (SD) during Pre-Monsoon period

Water Quality in During-Monsoon Season

Total Suspended Solids (TSS) Concentration During Monsoon:

The data in the table 2 provides critical insights into the spatial distribution of TSS concentrations during the monsoon season, illustrating varying levels of sediment load across different zones. This sedimentation directly affects water quality, ecosystem health, and overall hydrological processes.

Very Low TSS Zone (0.69 - 0.99 mg/L): The very low concentration of TSS (43.69 sq.km) during the monsoon is the dominant zone, covering the largest portion of the study area. This extensive area of low sedimentation suggests that monsoon-driven water inflow might dilute the suspended particles, leading to a relatively clear water state in a substantial part of the region. This low sedimentation could be attributed to areas with better vegetation cover, less erosion, or upstream inflows carrying lower sediment loads. These findings highlight the importance of upstream land management practices in controlling sediment loads downstream.

Low TSS Zone (1 - 1.2 mg/L): The low TSS concentration zone (18.09 sq.km) shows a slight increase in sediment load, covering a significant area. The moderate levels of TSS may result from runoff from agricultural or sparsely vegetated areas, which can transport sediments during heavy rainfall. Although the sedimentation is higher than in the very low zone, it remains at a level that is likely not detrimental to water quality. The occurrence of this zone suggests that areas with mild disturbance or limited erosion potential still manage to maintain reasonably clear water.

Moderate TSS Zone (1.3 - 1.5 mg/L): This zone represents elevated TSS levels (17.85 sq.km), indicative of areas experiencing significant runoff and possibly erosion during the monsoon. The moderate concentration in such a large area point to increased sediment transport from land surfaces, particularly from agricultural lands, construction sites, or areas with degraded vegetation. The presence of this zone highlights regions where soil conservation measures or erosion control might be necessary to prevent further deterioration of water quality. It is important to note that such levels, while not critical, can have cumulative ecological impacts if persistent.

High TSS Zone (1.6 - 2.2 mg/L): The high concentration zone indicates 7.85 sq.km areas with intense sedimentation, possibly due to severe runoff from eroded lands, mining activities, or regions with poor land management. This higher concentration of suspended solids can significantly affect aquatic ecosystems, potentially reducing light penetration, impairing photosynthesis in aquatic plants, and affecting fish habitats. Managing such zones is crucial, as persistent high TSS levels can lead to long-term ecological degradation and negatively impact water treatment processes.

Very High TSS Zone (2.3 - 5.8 mg/L): Although covering a small fraction of the study area 0.17 sq.km, the very high TSS concentration zone is critical. The presence of extremely high sedimentation could be linked to localized issues such as intense erosion, urban runoff, or industrial pollution. The water quality in this zone is severely compromised, requiring immediate attention. These areas should be prioritized for intervention as such high levels of suspended solids could pose major risks to both the aquatic environment and human usage of the water. Additionally, this zone could act as a point source for the further spread of sediment pollution downstream.

The analysis of TSS concentration during the monsoon period reveals significant spatial variability across the study area. The results suggest that while a large portion of the region benefits from relatively low to moderate TSS levels, which maintain acceptable water quality, there are also zones with high to very high sediment loads that could negatively impact both aquatic ecosystems and human water usage.

The distribution patterns call for targeted management strategies to control erosion and runoff, especially in zones with high and very high TSS. Potential measures include reforestation, terracing of agricultural lands, and implementation of sustainable urban runoff systems to minimize sediment input into water bodies. These findings underscore the importance of integrated watershed management during the monsoon to ensure that sedimentation levels do not compromise the region's ecological and water quality balance.

Table 2: Total Suspended Solids (TSS) Concentration and Secchi Depth (SD) distribution in During Monsoon season

Total Suspended Solids (TSS) Concentration During Monsoon			**Secchi Depth (SD) During Monsoon**		
Zone	**Range**	**Area (Sq.km)**	**Zone**	**Range**	**Area (Sq.km)**
Very Low	0.69 - 0.99	43.69	Very Low	0.46 - 0.8	4.74
Low	1 - 1.2	18.09	Low	0.81 - 0.9	12.11
Moderate	1.3 - 1.5	17.85	Moderate	0.91 - 0.97	22.09
High	1.6 - 2.2	7.85	High	0.98 - 1.03	29.75
Very High	2.3 - 5.8	0.17	Very High	1.04 - 1.42	18.96

Secchi Depth (SD) Analysis in During-Monsoon Season:

The Secchi Depth (SD) values during the monsoon season, which indicate water clarity by measuring light penetration, exhibit significant variability across different zones. The distribution of these zones reflects changes in water quality, sediment deposition, and algal growth influenced by rainfall and runoff during the monsoon.

Very Low SD Zone (0.46 - 0.8 meters): The very low Secchi Depth zone area with 4.74 sq.km represents regions with the poorest water clarity, where the water is most turbid due to high concentrations of suspended particles, likely from excessive runoff and sedimentation during the monsoon. This small area with very low clarity could be in close proximity to areas of intense land disturbance, such as agriculture, construction sites, or erosion-prone areas, where increased sediment and nutrients are washed into water bodies. Such conditions may encourage excessive algal growth, further contributing to reduced water clarity. This zone should be a priority for erosion control and sediment management efforts.

Low SD Zone (0.81 - 0.9 meters): The low SD zone, which covers a more substantial area 12.11 sq.km, also reflects turbid water conditions, although less extreme than the very low zone. These areas likely experience moderate sediment inflow due to rainfall and surface runoff, which reduces light penetration but not to a critical level. Water bodies in this zone may still support aquatic life but are likely at risk of further degradation if sediment control measures are not implemented. The zone indicates the need for improved land management practices to prevent further deterioration in water clarity.

Moderate SD Zone (0.91 - 0.97 meters): This zone, characterized by moderate water clarity, occupies the largest area (22.09 sq.km). The moderate SD values indicate that water bodies in this zone experience balanced conditions with relatively controlled sedimentation and nutrient inflow during the monsoon. The substantial coverage of this zone suggests that it represents the natural baseline for the region during the monsoon season. Areas within this range are likely resilient to moderate inflows of runoff and sediment but should still be monitored to ensure that water quality remains stable. Maintaining vegetation cover and reducing point-source pollution are key strategies to sustain this zone.

High SD Zone (0.98 - 1.03 meters): The high Secchi Depth zone covers the largest portion of the study area 29.75 sq.km, indicating clear water conditions during the monsoon. These areas are likely to be located in regions with effective land management, low erosion potential, or protected vegetation cover, which reduces the amount of sediment and organic material entering water bodies. The dominance of this zone suggests that monsoon runoff in these areas is well managed, resulting in minimal disturbance to water clarity. This clear water state promotes healthy aquatic ecosystems and better conditions for photosynthesis, contributing to overall water body health.

Very High SD Zone (1.04 - 1.42 meters): The very high SD zone represents regions with the clearest water during the monsoon (18.96 sq.km), where light penetration is greatest. These areas are likely influenced by minimal runoff, low sedimentation, and possibly deeper water bodies where particles settle more easily. This exceptional water clarity points to well-conserved ecosystems and low human disturbance in the surrounding areas. It is important to continue to protect these zones by maintaining natural vegetation, preventing urbanization or agricultural expansion, and ensuring that water inflows remain uncontaminated.

The spatial variability in Secchi Depth values during the monsoon season reveals important insights into the impact of runoff, sedimentation, and water management on water clarity in the study area. The predominance of the high and moderate SD zones indicates that water clarity is generally maintained at acceptable levels in most of the region during the monsoon. However, the presence of zones with low and very low SD values, although smaller in area, signifies localized degradation that could expand if left unaddressed.

The data suggest that land-use practices, particularly those related to agriculture, deforestation, and urbanization, are likely contributors to reduced water clarity in certain areas. To preserve the ecological balance and water quality, targeted erosion control, vegetative buffer zones, and sediment management strategies are essential, especially in areas where very low and low Secchi Depth values were recorded. Effective watershed management and continued monitoring are crucial for preventing further deterioration of water quality during the monsoon season, ensuring the long-term sustainability of aquatic ecosystems and water resources.

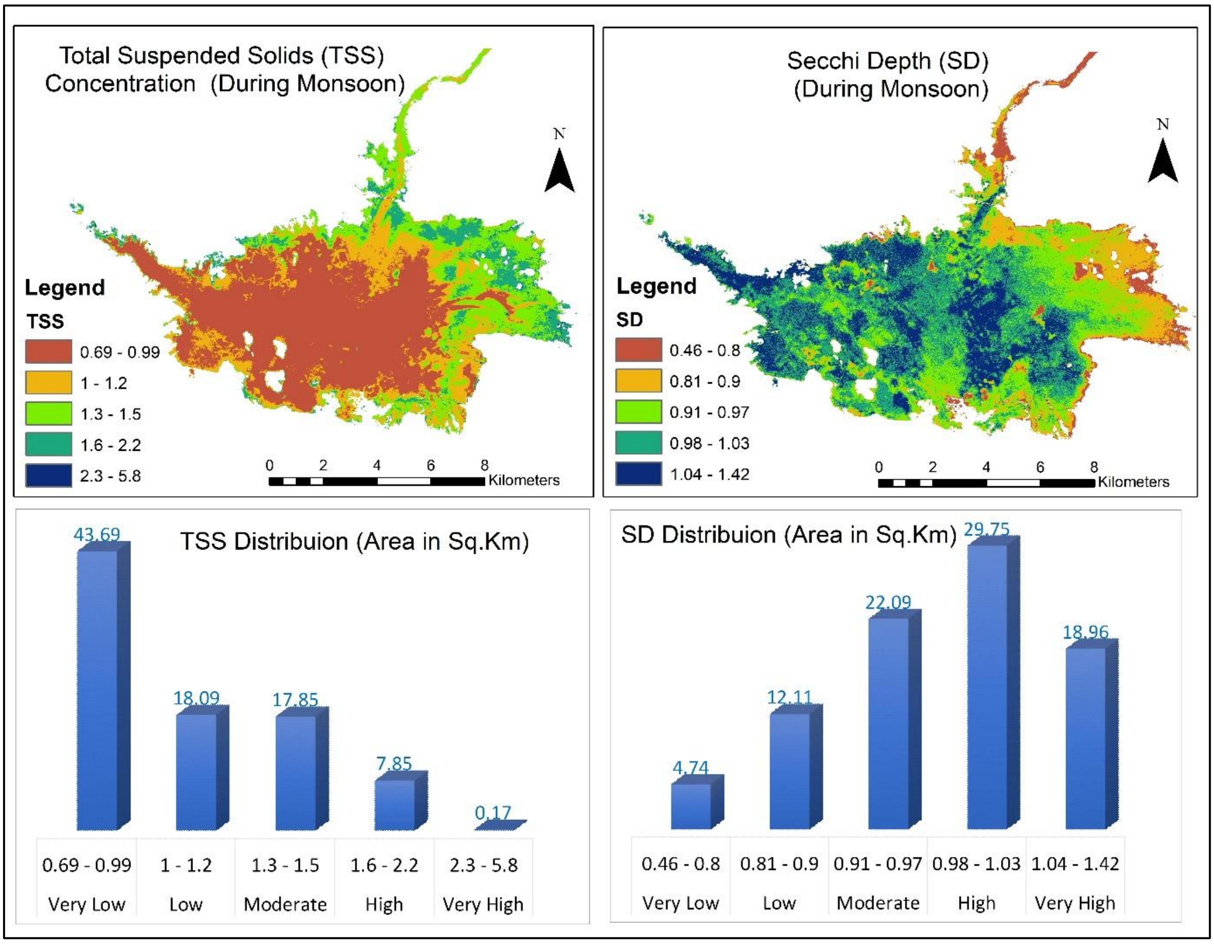

Fig. 4 Total Suspended Solids (TSS) concentration and Secchi Depth (SD) during Post-Monsoon period

Water Quality in Post-Monsoon Season

Total Suspended Solids (TSS) Concentration Post Monsoon

The distribution of Total Suspended Solids (TSS) concentration after the monsoon season provides vital insights into the water quality and the ecological status of the water bodies in the study area. The results (Table 3) indicate a significant spatial variation in TSS levels, suggesting a potential influence of land use, runoff, and sedimentation patterns.

Very Low TSS Zone (0.38 - 0.71 mg/L): The very low TSS zone represents a substantial area 81.70 sq.km of the study region, indicating that a significant portion of water bodies exhibit excellent water quality with minimal suspended solids. This indicates effective sediment management and land use practices that prevent excessive runoff and sedimentation, likely due to the restoration of vegetation after the monsoon. The high area coverage suggests that biological activity in these zones could be thriving, supporting diverse aquatic life. Monitoring efforts should continue to ensure that practices contributing to this low TSS concentration are maintained and to mitigate potential future impacts from agricultural or urban runoff.

Low TSS Zone (0.72 - 1.1 mg/L): The low TSS zone (7.81 sq.km) indicates moderate levels of suspended solids, with an area that is notably smaller than the very low zone. This suggests that these areas are experiencing slightly higher levels of sediment influx, which may be attributable to localized disturbances such as agricultural runoff or land development. Although these levels are still relatively low, the smaller area suggests that there is a need for enhanced best management practices to address potential sources of sediment. Continued vigilance is required to ensure that sediment control measures are implemented effectively to prevent deterioration into moderate TSS levels.

Moderate TSS Zone (1.2 - 1.7 mg/L): The moderate TSS zone with 2.20 sq.km area represents a critical threshold for water quality, indicating that these areas may be more susceptible to ecological impacts due to elevated suspended solids. The small area covered suggests these zones could be hotspots of degradation, likely linked to urban runoff, agricultural practices, or localized erosion. Areas within this zone may need targeted management strategies, including buffer strips or sediment traps, to improve water quality and mitigate further impacts on aquatic ecosystems.

High TSS Zone (1.8 - 2.6 mg/L): The high TSS zone (1.12 sq.km) represents a concerning condition for water quality, as the levels indicate a significant amount of suspended solids. This relatively small area highlights potential localized disturbances, likely from increased anthropogenic activities or stormwater runoff. High TSS concentrations can inhibit photosynthesis in aquatic plants and may lead to adverse effects on fish and other aquatic organisms. Active intervention is needed in these areas, including restoration projects and stricter regulations on land use practices to minimize further degradation.

Very High TSS Zone (2.7 - 5.7 mg/L): The very high TSS zone covers the smallest area 0.35 sq.km but signifies critical water quality issues. The presence of such high suspended solids can be detrimental to aquatic ecosystems, leading to reduced light penetration and harmful algal blooms. This area likely represents regions directly influenced by extreme runoff events or industrial discharges, necessitating immediate remediation efforts. Monitoring and management strategies should focus on identifying sources of pollution and implementing protective measures to restore water quality.

The data from the TSS concentration post-monsoon reveal a mixed picture regarding water quality across the study area. While the prevalence of very low TSS zones suggests effective management and ecological health, the presence of moderate, high, and very high TSS zones indicates potential risks associated with anthropogenic impacts and sedimentation.

To enhance water quality in the study area, comprehensive management strategies are essential, including regular monitoring, sediment control measures, and public awareness initiatives aimed at reducing runoff pollution. Addressing the challenges posed by the higher TSS concentrations in localized zones will be crucial for maintaining ecological balance and ensuring the sustainability of aquatic ecosystems in the long term.

Table 3: Total Suspended Solids (TSS) Concentration and Secchi Depth (SD) distribution in Post Monsoon season

Total Suspended Solids (TSS) Concentration Post Monsoon			**Secchi Depth (SD) Post Monsoon**		
Zone	**Range**	**Area (Sq.km)**	**Zone**	**Range**	**Area (Sq.km)**
Very Low	0.38 - 0.71	81.70	Very Low	0.34 - 0.78	4.25
Low	0.72 - 1.1	7.81	Low	0.79 - 1.03	7.61
Moderate	1.2 - 1.7	2.20	Moderate	1.04 - 1.21	19.95
High	1.8 - 2.6	1.12	High	1.22 - 1.34	28.35
Very High	2.7 - 5.7	0.35	Very High	1.35 - 2.16	33.02

Secchi Depth (SD) Analysis in Post-Monsoon Season:

The analysis of Secchi Depth (SD) across various zones post-monsoon (Table 3) provides crucial insights into the water transparency and overall health of aquatic ecosystems within the study area. The distribution of SD levels indicates the influence of sedimentation, nutrient loading, and biological productivity, which are critical factors in assessing water quality.

Very Low SD Zone (0.34 - 0.78 m): The very low SD zone, although limited in area 4.25 sq.km, indicates significant turbidity in these water bodies, potentially due to increased sediment runoff and organic material following the monsoon. The small coverage suggests localized sources of pollution or sedimentation that may be linked to agricultural practices or land disturbances. Regular monitoring is essential to identify the specific causes of turbidity and implement corrective actions, such as establishing vegetative buffers to mitigate runoff.

Low SD Zone (0.79 - 1.03 m): This zone represents a slight improvement in water transparency compared to the very low zone (7.61 sq.km), but still indicates some concerns regarding sediment and organic matter presence. The increase in area coverage suggests that while some regions are managing to maintain relatively lower turbidity levels, the potential for sedimentation issues remains. This could be a result of ongoing land-use changes or inadequate erosion control measures in surrounding areas. Mitigation strategies should be explored to reduce sediment inputs from adjacent land uses.

Moderate SD Zone (1.04 - 1.21 m): The moderate SD zone indicates a more favourable condition for aquatic ecosystems (19.95 sq.km), suggesting adequate light penetration and potential for photosynthetic activity. The substantial area indicates that a significant portion of the study region is likely supporting healthy aquatic life. However, maintaining this balance is crucial, as increased nutrient runoff could lead to algal blooms, which would negatively impact water quality. Adaptive management practices should be implemented to ensure that water quality remains stable, particularly in areas prone to development or agricultural runoff.

High SD Zone (1.22 - 1.34 m): The high SD zone 28.35 sq.km shows a significant improvement in water clarity, indicating that these areas are likely well-managed in terms of sediment and nutrient control. The large area suggests that the ecological health of these water bodies is relatively stable, providing suitable habitats for diverse aquatic organisms. Continued monitoring and management efforts will be essential to sustain these conditions, especially in light of potential impacts from climate change and land use changes in the watershed.

Very High SD Zone (1.35 - 2.16 m): The very high SD zone 33.02 sq.km represents the optimal condition for water clarity and ecological health, covering the largest area among the categories. This suggests effective management practices and minimal disturbances in these regions. High Secchi depth indicates excellent light penetration, promoting photosynthesis and supporting a rich biodiversity of aquatic plants and organisms. However, ongoing conservation efforts should focus on preserving these areas from potential future threats, such as urbanization or industrial development.

The findings related to Secchi Depth post-monsoon illustrate a varied landscape of water quality within the study area. While a substantial proportion of the region demonstrates favourable conditions for aquatic health, the presence of very low and low SD zones highlights areas needing immediate attention. Regular monitoring of Secchi depth is essential for detecting trends in water quality and for informing management decisions aimed at preserving aquatic ecosystems. The relationship between Secchi depth and factors such as sediment runoff and nutrient loading must be critically assessed to develop tailored management strategies that ensure the sustainability and health of water bodies in the region. Implementing effective watershed management practices will be key in maintaining and improving water transparency across the study area.

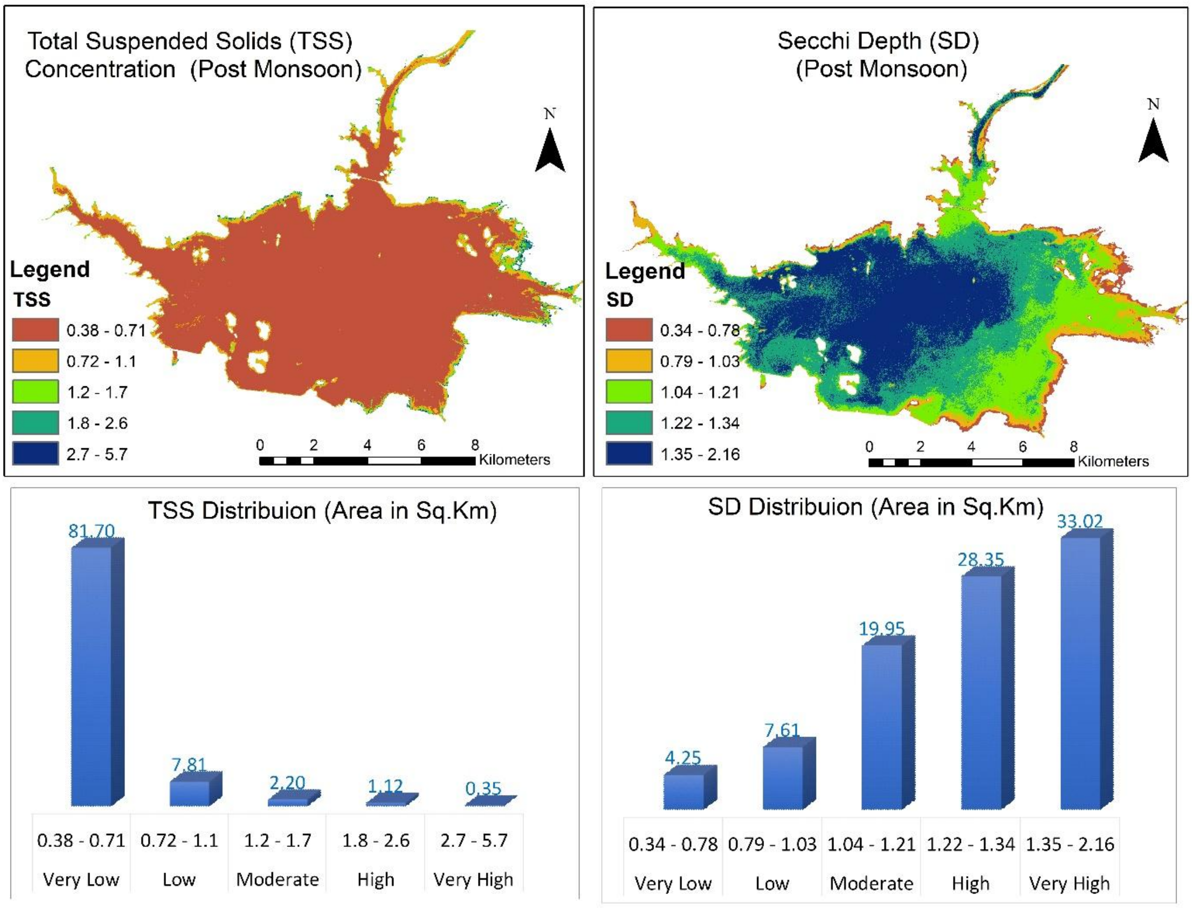

Fig. 5 Total Suspended Solids (TSS) concentration and Secchi Depth (SD) during During-Monsoon period

Comparison of Secchi Depth and TSS Results

The interplay between Secchi depth (SD) and total suspended solids (TSS) serves as a critical indicator of water quality. The analysis of scatter plots representing data collected during pre-monsoon, monsoon, and post-monsoon periods reveals significant patterns that underscore this relationship.

Cross-analysis of SD and TSS Patterns

Pre-monsoon Observations: The scatter plot for the pre-monsoon season illustrates a clear trend, as TSS levels increase, Secchi depth tends to decrease. This inverse relationship suggests that clearer waters, characterized by higher SD values, correspond to lower concentrations of suspended solids. While the data generally supports this trend, the observed scatter implies that factors beyond TSS may also impact water clarity. Such factors could include phytoplankton concentrations, organic matter, or even anthropogenic influences that vary spatially within the study area.

Monsoon Dynamics: During the monsoon season, the scatter plot presents a more complex relationship. The data reveals a broader range of TSS values associated with a given SD compared to the pre-monsoon period. This variation is likely attributed to increased rainfall and runoff, which contribute additional sediments and pollutants into the water body. The heightened turbulence during monsoon conditions may further influence sediment distribution and, consequently, water clarity. This complexity highlights the need for careful interpretation of TSS and SD data during dynamic environmental conditions.

Post-monsoon Trends: The relationship between TSS and SD appears to revert to a trend similar to that observed during the pre-monsoon period. While higher TSS levels correlate with lower SD, it is essential to note potential differences in specific values and the strength of this relationship compared to earlier observations. These changes may be influenced by seasonal sediment settling and the ecological processes occurring within the aquatic environment.

Relationship Between SD and TSS

Overall, the scatter plots consistently indicate an inverse relationship between Secchi depth and total suspended solids, as TSS increases accordingly water clarity diminishes. This correlation serves as a valuable metric for water quality assessment, enabling researchers and environmental managers to infer the potential ecological health of the water body based on the balance of these two parameters. The fitted regression lines in the scatter plots provide quantitative support for this relationship, with the R^2 values offering insight into the strength of correlation. Higher R^2 values signify a more robust association between TSS and SD, further validating the reliability of these measures in evaluating water quality.

Complementary Nature of SD and TSS for Water Quality Assessment

The interrelationship between Secchi depth and total suspended solids is fundamental for comprehensive water quality assessments. While TSS provides insights into sediment content, Secchi depth serves as an indicator of water clarity, which is vital for aquatic life. Together, these parameters facilitate a more holistic understanding of water quality. For instance, a decrease in SD due to rising TSS levels can have detrimental effects on light penetration, which is crucial for photosynthetic organisms and overall ecosystem health.

Additionally, variations in this relationship across seasons highlight the influence of hydrological changes on water quality dynamics. During the monsoon, increased runoff can drastically elevate TSS levels, thereby reducing SD. Recognizing this temporal variability is crucial for implementing effective water management strategies that address both sedimentation and water clarity issues.

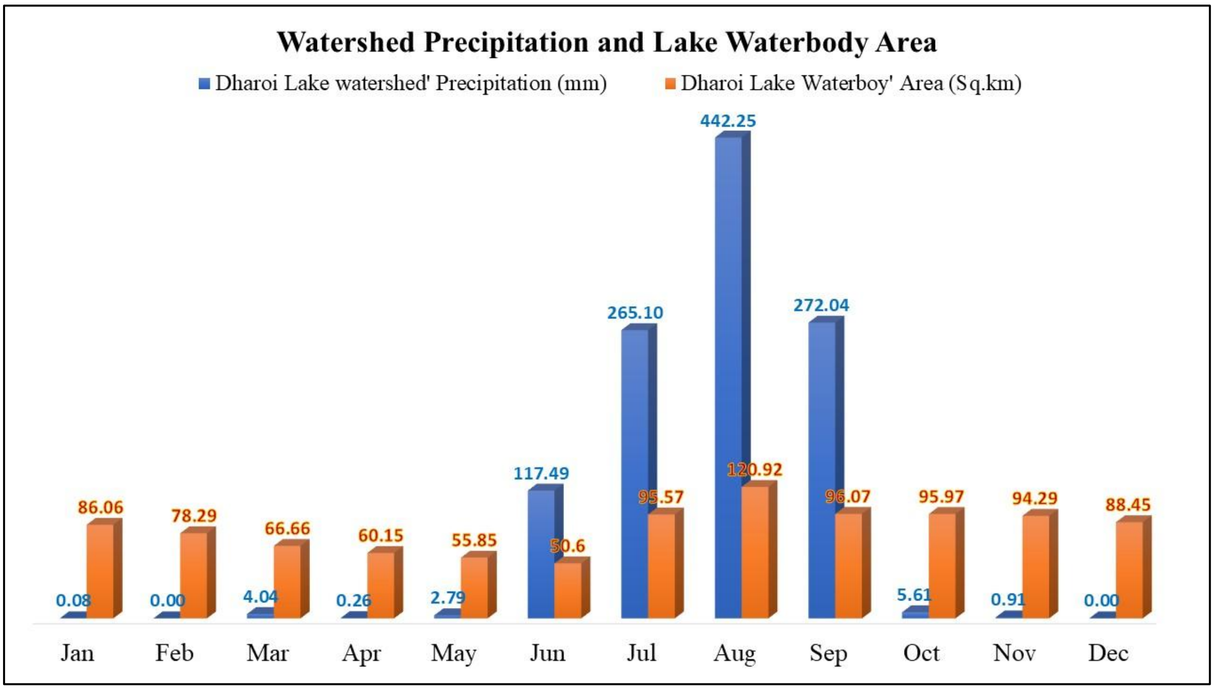

Fig. 7 Monthly Dharoi lake waterbody area and precipitation of the lake' watershed in 2020

Environmental Implications and Water Quality Management

The water quality conditions observed in the Dharoi Reservoir during different seasonal phases significantly impact the overall health of the aquatic ecosystem. Understanding these dynamics is crucial for effective water management practices that ensure the sustainability of both the reservoir and its biological inhabitants.

Impact of Pre-monsoon Water Quality Conditions on the Reservoir Ecosystem

The pre-monsoon phase presents unique water quality conditions characterized by relatively lower total suspended solids (TSS) and higher Secchi depth (SD) values. These conditions create a more favourable environment for aquatic life, including fish, invertebrates, and macrophytes, which rely on adequate light penetration for photosynthesis and habitat structure. The clearer water in the pre-monsoon season is indicative of reduced sedimentation and lower nutrient loadings, allowing for a more stable ecological balance. However, the pre-monsoon conditions can also serve as a precursor to potential ecological challenges as the monsoon season approaches. Elevated nutrient concentrations, often resulting from agricultural runoff and land disturbances, can lead to algal blooms when mixed with sediment during monsoon rains. Such blooms can further exacerbate the reduction of SD and increase TSS levels, thereby triggering a cascading effect that compromises the aquatic ecosystem's integrity.

Potential Risks of High TSS and Low SD Values for Aquatic Life and Water Usability

The findings of this study highlight the risks associated with high TSS and low SD values, particularly during the monsoon season. Elevated TSS concentrations can lead to increased turbidity, which adversely affects light availability in the water column. This reduced light penetration can inhibit photosynthesis in submerged aquatic vegetation, impacting the entire food web, as these plants are foundational to the ecosystem.

Furthermore, high TSS levels are often associated with the sedimentation of pollutants and contaminants, which can pose significant risks to aquatic life. Fish and other organisms may experience stress due to sediment abrasion, gill clogging, and the introduction of harmful substances, leading to decreased growth rates, reproductive failures, and increased mortality. From a water usability perspective, high TSS can impair recreational activities, reduce water quality for irrigation, and complicate treatment processes for drinking water supply.

Low Secchi depth values further signify deteriorating water quality, indicating a shift towards a more turbid and less hospitable environment for aquatic organisms. This decline can also lead to eutrophication, where nutrient over-enrichment fosters excessive algal growth, further degrading water quality and oxygen levels.

Recommendations for Management Practices Based on Study Findings

To mitigate the risks associated with high TSS and low SD values, targeted management practices are essential. Based on the findings of this study, several recommendations can be proposed:

Implementing Riparian Buffers: Establishing vegetated buffers along the reservoir's edges can reduce sediment and nutrient runoff during rainfall events. These buffers serve as natural filters, capturing pollutants before they enter the water body.

Sediment Control Measures: Employing sediment control practices, such as silt fencing and sediment traps, can help minimize soil erosion and sedimentation during land disturbance activities, especially in agricultural areas surrounding the reservoir.

Regular Monitoring and Assessment: Continuous monitoring of TSS and SD values throughout different seasonal phases is crucial for early detection of potential water quality issues. This data can inform management strategies and allow for timely interventions.

Public Education and Community Engagement: Raising awareness among local communities about the importance of maintaining water quality can foster stewardship practices. Engaging stakeholders in monitoring efforts and promoting sustainable land-use practices can enhance collective responsibility for the reservoir's health.

Integrated Watershed Management: A holistic approach that considers upstream activities impacting the reservoir's water quality is vital. Coordinating efforts among various stakeholders, including farmers, local authorities, and conservation organizations, can lead to comprehensive strategies that address water quality concerns at a watershed scale.

Understanding the environmental implications of water quality conditions in the Dharoi Reservoir is critical for safeguarding its ecosystem. By addressing the challenges posed by high TSS and low SD values through targeted management practices, we can enhance water quality, promote aquatic health, and ensure the reservoir remains a viable resource for future generations.

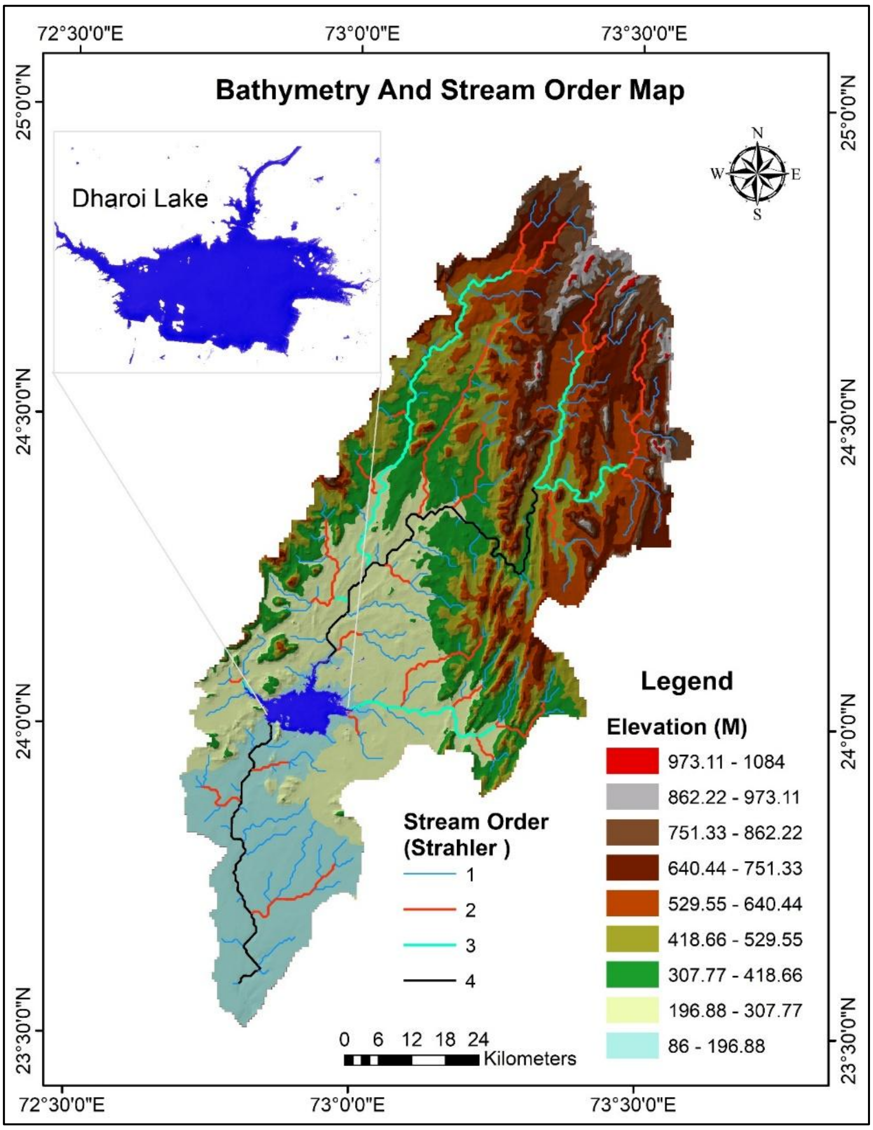

Fig. 7 Bathymetry and Stream Order Map of Dharoi lake' watershed

Methodological Accuracy and Limitations

The assessment of water quality in the Dharoi Reservoir utilizing satellite-derived Secchi depth (SD) and total suspended solids (TSS) measurements offers a novel approach to understanding aquatic ecosystems. However, as with any research methodology, this approach comes with both strengths and limitations that must be critically evaluated to enhance the reliability of findings.

Accuracy of Satellite-Derived SD and TSS Measurements

Satellite remote sensing has emerged as a powerful tool for monitoring water quality parameters over large spatial scales, providing a cost-effective and efficient means of data collection. The analysis of Secchi depth and total suspended solids using satellite imagery allows for continuous observation of water quality dynamics, particularly in challenging environments where in-situ data collection may be impractical.

In this study, the accuracy of satellite-derived SD and TSS measurements is supported by strong correlations observed between remote sensing data and ground-truthing efforts. The statistical relationships illustrated in the scatter plots indicate that satellite measurements can effectively capture variations in TSS and SD under varying seasonal conditions. The regression analyses further reinforce the potential of remote sensing data in assessing water quality parameters, showcasing its applicability in ecological monitoring.

However, it is essential to recognize that the accuracy of satellite-derived measurements is inherently influenced by several factors, including atmospheric conditions, sensor calibration, and water surface characteristics. Variations in light penetration, water turbidity, and the presence of phytoplankton can all impact the spectral response captured by satellite sensors, leading to potential discrepancies in the derived values. Therefore, while the methodology demonstrates promise, it is crucial to approach the findings with an understanding of the inherent variability associated with remote sensing measurements.

Limitations of Remote Sensing Methods for Water Quality Assessment Without Field Data Validation

Despite the advantages of remote sensing, significant limitations exist, particularly concerning the absence of robust field data validation. Relying solely on satellite-derived measurements without corresponding in-situ data can lead to inaccuracies in the assessment of water quality. Variability in local conditions—such as changes in sediment composition, water stratification, and the influence of anthropogenic activities—may not be adequately captured by satellite observations alone.

Additionally, the temporal resolution of satellite imagery poses challenges for accurately monitoring water quality fluctuations that may occur rapidly, especially during events like heavy rainfall or runoff. Such events can cause significant changes in TSS and SD that may not be detected in the intervals between satellite overpasses. This limitation underscores the need for a more integrated approach that combines remote sensing data with regular field measurements to enhance the robustness of water quality assessments.

Furthermore, specific spectral bands utilized for deriving SD and TSS may not be equally effective across different water bodies, particularly those with unique optical properties. This variability necessitates the development of region-specific calibration models to ensure the accuracy of remote sensing estimates in diverse ecological contexts.

Suggestions for Future Research to Improve the Reliability of Remote Sensing-Based Studies

To address the limitations associated with satellite-derived measurements and enhance the reliability of remote sensing-based studies, several recommendations for future research are proposed:

Integration of Field Validation Studies: Future research should prioritize the collection of in-situ data to validate and calibrate satellite-derived measurements. Establishing a network of sampling stations within the reservoir can facilitate a comprehensive understanding of spatial and temporal variations in water quality parameters.

Development of Localized Calibration Models: Researchers should focus on developing region-specific models that account for the unique optical characteristics of the water body. This approach will improve the accuracy of remote sensing estimates and ensure they are tailored to the specific conditions of the study area.

Utilization of Advanced Remote Sensing Technologies: The incorporation of newer satellite platforms with improved spectral resolutions and more frequent revisit times can enhance the monitoring of water quality dynamics. Additionally, integrating data from multiple sensors can provide a more holistic view of water quality conditions.

Focus on Time-Series Analysis: Long-term monitoring through time-series analysis can capture seasonal variations and extreme events that influence water quality. This methodology would allow researchers to assess trends over time and understand the impact of climatic events on aquatic ecosystems.

Interdisciplinary Collaboration: Collaboration between remote sensing experts, hydrologists, ecologists, and water quality managers can foster a more comprehensive understanding of the interactions between environmental variables and water quality. Such interdisciplinary approaches can lead to the development of innovative methodologies that enhance water management practices.

While the use of satellite-derived Secchi depth and total suspended solids measurements presents significant opportunities for water quality assessment, recognizing the accuracy, limitations, and potential for improvement is essential. By addressing these methodological challenges through targeted research efforts, future studies can enhance the reliability of remote sensing applications, ultimately contributing to more effective management of aquatic ecosystems.

Conclusion

This research provides critical insights into the water quality dynamics of the Dharoi Reservoir, particularly focusing on Secchi depth (SD) and total suspended solids (TSS) across different monsoon seasons. The results reveal significant variations in water clarity and sediment content, which are essential parameters for assessing aquatic ecosystem health and overall water quality.

The analysis of Secchi depth and total suspended solids revealed several significant findings. Pre-monsoon data showed a negative correlation between TSS and SD, with an average SD of 0.9 m associated with an average TSS of 0.73 mg/L, indicating that clearer waters generally correspond to lower sediment levels. During the monsoon season, this relationship became more complex, with SD values ranging from 0.46 to 1.42 m and TSS concentrations between 0.69 to 5.8 mg/L. The increased variability observed during this period is likely due to heightened runoff and sediment influx resulting from intense rainfall events. Post-monsoon results indicated a return to a trend similar to the pre-monsoon season, highlighting the dynamic nature of water quality in relation to seasonal changes. Overall, these findings underscore the variability in water quality parameters, with SD and TSS exhibiting complex interdependencies influenced by seasonal factors.

The significance of this study extends beyond academic inquiry, providing actionable insights for water resource management in the Dharoi Reservoir and surrounding areas. Understanding the patterns of TSS and SD is vital for managing the reservoir's ecological integrity, particularly in light of increasing anthropogenic pressures and climate change. With an average of 30% of the reservoir exhibiting very low to low SD during the monsoon season, there is an urgent need for targeted management practices to mitigate sedimentation and preserve water quality. Moreover, the study's findings can inform the development of effective monitoring programs that align with local management strategies, helping to enhance the resilience of aquatic ecosystems in the face of environmental changes.

The integration of remote sensing technologies into water quality monitoring presents a promising opportunity for future research and management efforts. The ability to capture large-scale, real-time data on Secchi depth and total suspended solids offers a cost-effective and efficient method for assessing water quality dynamics over time. With the successful identification of statistically significant relationships between satellite-derived measurements and in-situ data, this study demonstrates the potential for using remote sensing as a long-term monitoring tool.

In closing, while this research highlights the current capabilities of remote sensing in water quality assessment, it also emphasizes the need for continued advancements in calibration and validation methods. By fostering interdisciplinary collaboration and enhancing field data integration, future studies can leverage the full potential of remote sensing technologies, ultimately contributing to improved water resource management and the sustainability of aquatic ecosystems in the region. This study paves the way for ongoing research efforts aimed at understanding and mitigating water quality challenges, ensuring the protection and preservation of vital water resources for future generations.

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