WATER QUALITY ANALYSIS OF VEMBANAD LAKE SYSTEM: A MULTIDISCIPLINARY APPROACH USING BIOLOGICAL INDICATORS, REMOTE SENSING AND GEOSPATIAL ANALYSIS

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LIST OF ABBREVIATIONS

SL.NO	ABBREVIATION	EXPANSION
1	Ppt	PARTS PER MILLION
2	&	AND
3	°	DEGREE
4	ml	MILLILITRE
5	Rpm	ROTATION PER MINUTE
6	%	PERCENTAGE
7	°c	DEGREE CELCIUS
8	µl	MICROLITRE
9	g	GRAM
10	pH	POTENTIAL OF HYDROGEN
11	mg	MILLIGRAM
12	µmol/L	MICROMOLES PER LITER
13	nm	NANOMETRE
14	µg	MICROGRAM
15	mmol/L	MILLIMOLES PER LITER
16	mg/m^3	MILLIGRAMS PER CUBIC METER
17	PO_4^{3-}	PHOSPHATE ION
18	NO_2^-	NITRITE ION
19	Chl-a	CHLOROPHYLL-A
20	NEDA	N-(1-NAPHTHYL)-ETHYLENE DIAMINE DIHYDROCHLORIDE
21	GIS	GEOGRAPHIC INFORMATION SYSTEM
22	IDW	INVERSE DISTANCE WEIGHTING
23	ESA	EUROPEAN SPACE AGENCY
24	OLCI	OCEAN AND LAND COLOUR INSTRUMENT

25	ARCGIS	AERIAL AND REMOTE COMPUTING GEOGRAPHIC INFORMATION SYSTEM
26	LCI	LAND COVER INDEX
27	SPM	SUSPENDED PARTICULATE MATTER
28	LISA	LOCAL INDICATORS OF SPATIAL ASSOCIATION
29	JPEG	JOINT PHOTOGRAPHIC EXPERTS GROUP
30	CSV	COMMA-SEPARATED VALUES

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ABSTRACT

The Vembanad Lake system, one of the most important water bodies in Kerala, is facing increasing pollution due to human activities such as urbanization, industrial discharge, agricultural runoff and fisheries. This study observed the water quality at four locations Udhayamperoor, Chellanam, Fort Kochi, and Panagad using a multidisciplinary approach that include in-situ sampling, remote sensing, and geospatial analysis. The significant factors analyzed were salinity, pH, chlorophyll-a (Chl-a), phosphate (PO_4^{3-}), nitrite (NO_2^-) and barnacle count, which was used as biological indicators of pollution levels. The results showed significant differences in water quality across the locations. Fort Kochi recorded the highest salinity (30.45 ppt) and barnacle count (234), indicating high marine influence and pollution, while Udhayamperoor had the lowest salinity (24.70 ppt) and barnacle count (54) suggesting lower pollution levels. Panagad had the highest concentration of NO_2^- (2.423 µmol/L) and PO_4^{3-} (9.934 µmol/L), which pointed to excessive nutrient input and a higher risk of eutrophication. Chl-a levels which indicate phytoplankton growth, were also highest at Panagad (4.225 mg/m^3), while Udhayamperoor recorded the lowest Chl-a (0.221 mg/m^3). Using Geospatial interpolation, pollution hotspots were identified at Fort Kochi, Chellanam, and Panagad, where nutrient levels and biological activity were highest. Barnacle counts proved to be a useful indicator of pollution and salinity variations. The present study highlights the importance of regular water quality monitoring to prevent further ecological threats. Implementing monitoring systems with a multidisciplinary approach can help in the timely detection of pollution load and can ensure the sustainability of the Vembanad Lake ecosystem.

Keywords: Vembanadu Lake, Salinity, Barnacle, Geospatial interpolation, Pollution

1. INTRODUCTION

In a biodiversity rich and ecologically significant area like Vembanad Lake system of Kerala India, water quality assessment is an essential part for environmental monitoring. Because of the excessive anthropogenic activities, the Vembanad Lake system is under extreme ecological stress. This water system is an essential resource for local communities for their livelihood. There has been extreme fluctuation in the water parameter values like nutrient concentrations (PO_4^{3-} and NO_2^-), turbidity and DO levels in this region that in turn reflect changing aquatic environment due to urbanization and industrial effluents (Gorde & Jadhav., 2013). This disturbs the normal ecological balance of a system. Eutrophication is the most common phenomenon caused by these changes. This leads to algal bloom and decreases biodiversity (Vidya & Prasad., 2017; Kulk et al., 2021; Theenathayalan et al., 2022; Sundar & Kundapura.,2023). In order to track these changes and to implement effective management strategies, efficient and proper water quality monitoring techniques are needed.

The traditional water quality assessment techniques focus on In-situ sampling and laboratory analysis. This includes the analysis of physicochemical parameters, including pH, turbidity, Chl-a concentration, DO, and nutrient levels (PO_4^{3-} and NO_2^-). Although these in-situ techniques offer accurate and trustworthy measurements, logistical limitations and high costs can restrict the data (Simsek & Gunduz., 2007). These drawbacks of the conventional methods can be eliminated by using an addition method that can help to provide temporal and spatial coverage. One of the advanced methods used is the Remote sensing technologies is a substitute or an addition to conventional monitoring methods. Satellite-based observations provide a more thorough understanding of variations of different water quality parameters in an aquatic ecosystem. This also provides an evaluation of water quality indicators.

Geographic Information Systems (GIS) and statistical modelling are two recent developments in geospatial analysis. Interpolation technique improves the spatial representation, is one of the sophisticated geospatial methods employed in this study. Interpolation techniques like Inverse Distance Weighting (IDW) and Kriging provides more accurate predictions of water quality parameters of unsampled locations or locations that are unreachable by spatial autocorrelation. Large and intricate water systems like the Vembanad Lake system, numerous hydrological and human activities change the water quality parameters. For such complex studies, interpolation is the best method to assess the water quality. It is feasible to create comprehensive spatial interpolation maps of different water quality parameters like DO, turbidity, nutrient distribution and Chl-a concentration by combining with remote sensing data from various sources. This helps identify regions that are most vulnerable to ecological deterioration. Combining these geospatial methods improves the identification of pollution hotspots and offers insightful information for conservation and restoration initiatives (Mantzafleri et al., 2009).

The study of nutrient dynamics, especially the function of PO_4^{3-} and NO_2^- in aquatic ecosystems, is another crucial component of evaluating the quality of water. The process of eutrophication, which is marked by DO depletion, excessive algal growth and thereby decline of water quality, this facilitates excessive concentrations of these nutrients. The main sources of PO_4^{3-} and NO_2^- in the Vembanad Lake system are industrial effluents and untreated sewage discharge. High PO_4^{3-} and NO_2^-concentrations encourage the growth of phytoplankton, which raises Chl-a concentrations and decreases light penetration in the water column. Differing species composition and decreasing biodiversity can upsets the equilibrium of the aquatic ecosystem (Gayathri et al., 2021).

Areas with higher PO_4^{3-} and NO_2^-concentrations tend to show phytoplankton blooms. This has an adverse effect on aquatic life by raising biological stress and lowering DO levels. Developing focused mitigation strategies to lessen eutrophication and preserve ecological stability requires an understanding of the temporal and spatial distribution of these nutrients.

Biological indicators can contribute to water quality analysis apart from the physicochemical parameters. Barnacle populations are one example of a biological indicator that offers important information about the ecological health of aquatic environments. As sessile filter feeders, barnacles are extremely vulnerable to environmental as well as changes in water quality. Salinity levels, DO concentration, and nutrient availability are some of the variables that affect the distribution and abundance of barnacles (Riisgård et al., 2015). This study intends to establish the role of barnacle populations as bioindicators for evaluating eutrophication trends and nutrient pollution in the lake system by examining them in conjunction with physicochemical parameters and the remote sensing data such as (-sentinel 2 and sentinel 3-). Barnacle populations serve as an early warning system for deteriorating water quality, as their settlement, reproductive success, and growth rates are highly dependent on environmental conditions.

Estuarine-dwelling barnacle species are especially vulnerable to changes in quality of water and salinity. Barnacles do best in environments with consistent salinity, but they survive and establish in environments with high salinity. Their density and presence in various Vembanad Lake sections offer important clues about how human activity affects the aquatic ecosystem. Barnacles' physiological reactions, like thickening of their shells can also reveal long-term patterns in the quality of the water. They are useful bioindicators for identifying industrial pollution in aquatic environments because of their capacity to accumulate heavy metals and other pollutants.

An approach to water quality assessment that is more comprehensive is provided by the combination of biological indicators and remote sensing techniques (-sentinel 2 and sentinel 3-). While biological indicators offer localized and long-term perspectives on environmental changes, satellite data offers insights at a larger scale. This help to track and forecast changes in water quality by combining these techniques, guaranteeing efficient conservation measures. Real-time monitoring and prediction of the deteriorated zones, marking hotspots can be made possible by GIS-based water quality mapping.

Monitoring Vembanad Lake's water quality also necessitates a deeper comprehension of how land use patterns have changed due to human activity. Increased sedimentation brought on by the growth of urban areas has impacted aquatic habitats and changed nutrient cycles. According to geospatial analysis, areas with high levels of land development have higher sediment loads, which have an adverse effect on aquatic biodiversity and water clarity (Şener et al., 2017).

In order to evaluate the water quality in Vembanad Lake, this study takes a multidisciplinary approach by combining biological indicators, geospatial modelling, and remote sensing data (sentinel 3). The methodology consists of in-situ measurements of physicochemical parameters, laboratory analysis of nutrient concentrations, Chl-a levels, pH, salinity and satellite-based water quality assessments using Sentinel-3 data. Studies of barnacle populations are carried out to assess their efficacy as bioindicators and interpolation is used to improve spatial predictions of water quality parameters. This provides a multidisciplinary face to the study with a reduced cost and spatial and temporal coverage.

The efficiency and accessibility of water quality monitoring have increased due to ongoing developments in remote sensing technology. Predictive modelling is made possible by the combination of satellite data and machine learning algorithms, which enables the creation of different frame works or models to predict changes in the environment. As the anthropogenic activities increase day by day, which distrust the ecological balance, it's important to create a frame work to detect these changes so that proper monitoring and actions can be taken.

2. AIM

The study aims to assess the water quality of Vembanad Lake system, Kerala, India, through a multidisciplinary approach that incorporates biological indicators, remote sensing and geospatial analysis (IDW interpolation).

3. OBJECTIVE

- To assess the water quality parameters like Chl-a, PO_4^{3-}, NO_2^{-}, pH, salinity through in-situ sampling and laboratory analysis.
- To determine the barnacle abundance in each station.
- To obtain Sentinel-3 satellite remote sensing data from European Space Agency's (ESA) Copernicus program.
- To use IDW interpolation for generating spatial distribution map and to overlay barnacle count.
- To combine in-situ data with Sentinel-3 satellite remote sensing data for water quality assessment and hotspot identification.

4. RELEVANCE OF THE STUDY

This study reveals a multidisciplinary approach for the water quality assessment in an aquatic ecosystem, the Vembanad Lake system. An aquatic ecosystem that has a great role in biodiversity and local community maintenance. This study helps to identify water deteriorating causes like eutrophication, algal bloom and other anthropogenic activities by evaluating water quality parameters. To comprehend these changes and lessen possible environmental effects, effective monitoring is crucial. The study focuses on creating a more thorough evaluation of water quality by combining in-situ water quality analysis, biological indicator, combining Sentinel-3 satellite remote sensing and GIS-based spatial interpolation techniques which helps to predict the water quality over a large area from limited samples. The sentinel images provide temporal and special coverage, also provides the environmental data of inaccessible locations. The study aims at identifying hotspots by generating spatial distribution maps that assist in locating changes in DO levels by using IDW interpolation and by incorporating the in-situ values and overlying the barnacle count. The study also emphasizes the barnacle as a potential pollution indicator. This multidisciplinary method improves the precision of water quality evaluation and environment monitoring plans. The study's conclusions can help policymakers create plans for the sustainable management of water resources, protecting the Vembanad Lake system and maintaining its ecological balance.

5. REVIEW OF LITERATURE

Water quality assessments have largely relied on direct field sampling followed by laboratory-based chemical analyses to quantify key parameters such as $NO_2^-$and PO_4^{3-} , DO, turbidity, and Chl-a. While these conventional methods are accurate and widely accepted, they are often time-consuming, labour-intensive, and restricted in terms of spatial and temporal coverage. The growing ecological pressures on aquatic systems particularly from anthropogenic activities, nutrient enrichment, and climate-related changes have highlighted the limitations of these traditional techniques. As a result, there has been a significant shift towards the adoption of advanced, scalable technologies such as satellite remote sensing and geospatial modelling. These tools provide a more efficient, cost-effective, and comprehensive means of monitoring water quality over large and dynamic ecosystems, such as the Vembanad Lake, enabling continuous, real-time observation and improved decision-making for sustainable water resource management (Sivakumar et al., 2022).

5.1. Water Quality Monitoring in Vembanad Lake.

Monitoring water quality is essential for determining the ecological health of an aquatic ecosystem, particularly in the Vembanad Lake system in Kerala, the largest Ramsar site in India. There is an urgent need for an accurate method to evaluate water quality in ecologically significant and biodiverse systems as anthropogenic activities on freshwater ecosystems increase. An extensive large-scale, ongoing, and thorough study of water quality is now possible by incorporating biological markers, satellite remote sensing, and geospatial modelling. Water quality in Vembanad lake system is greatly influenced by the anthropogenic activities, development activities and nutrient enrichment, which pose serious risks to biodiversity and water quality (Kulk et al., 2021; Theenathayalan et al., 2022; Sundar & Kundapura.,2023; Barreto, 2024). Water quality parameters such as turbidity, DO, and Chl-a, on a previously unheard spatial and temporal scale are measured using remote sensing technologies like hyperspectral imagery (Yang et al., 2022). The accuracy of monitoring efforts is greatly enhanced by identifying pollution hotspots and properly estimating water quality indicators, which is achieved by merging machine learning algorithms with remote sensing (Chebud et al., 2012; Ritchie et al., 2003).

Second approach, which provides a more thorough understanding of water quality, is made possible by the combination of remote sensing data with biological indicators such as phytoplankton and aquatic macroinvertebrates. In order to assess Vembanad lake system, where eutrophication is a major hazard, multidisciplinary approach aids in the creation of strong monitoring network (Wang & Yang., 2019). Because for such a large-scale area, multi-dimensional efforts contribute to the result. Results will be more accurate with such multi-dimensional efforts. Information is obtained from satellite photography like sentinel 2 and sentinel 3, biological markers shed light on the ecological effects of pollution and nutrient enrichment. Furthermore, geospatial modelling approaches, such GIS-based water quality mapping, provide important information on the influences of land use changes in the area as well as spatial patterns of water quality (Gholizadeh et al., 2016). These resources aid in locating regions that are most susceptible to contamination and direct focused management initiatives meant to enhance ecosystem health and water quality.

5.2. Nutrient Dynamics and Eutrophication: The Role of Nitrogen and Phosphorus

Nutrient dynamics, particularly the discharge of nitrogen and phosphorus into water bodies, have a significant impact on the overall balance of aquatic ecosystems. Algal bloom and eutophication happens when too many nutrients encourage the growth of aquatic vegetation and algae, which lowers oxygen levels, reduces biodiversity, and degrades water quality (Vezjak et al., 1998; Garnier et al., 2005; Nguyen et al., 2019). Studies have shown that the alarming levels of these nutrients ($NO_2^-$and PO_4^{3-}) in the Vembanad Lake system are due to the growth of dense phytoplankton blooms. These blooms lower water clarity and aid in the depletion of DO. The entire ecosystem is disrupted and aquatic organisms are greatly impacted by this DO depletion, which frequently results in hypoxia (Paimpillil & ThresiammaJoseph, 2006). These extra nutrients are mainly added to Vembanad Lake system in the absorbable nitrogen compounds like nitrate (NO_3) and nitrite (NO_2), which are rapidly absorbed by phytoplankton and encourage their quick growth. They are a form of highly solubilized nitrogen compound (Sujatha et al., 2009; Bhavya et al., 2016). At minimal needed concentration they promote growth. But if they are present in excess they lead to algal bloom and soon to eutrophication (Vidya & Prasad., 2017). The issue is further exacerbated by the fact that phosphorus, usually in the form of PO_4^{3-}, contributes significantly to the eutrophication process. So, the levels of phosphorus and nitrogen are also major parameters that aids in water quality assessment. Thus, elevated turbidity and elevated Chl-a concentrations are frequently seen in the Vembanad Lake system, which are signs of nutrient enrichment and deterioration of the water quality (Gayathri et al., 2021). Addressing eutrophication and guaranteeing the ecosystem's sustainable management require an understanding of the sources, transport processes, and impacts of $NO_2^-$and PO_4^{3-}in the lake system. To restore and preserve Vembanad Lake system, effective management strategies must concentrate on reducing nutrient loading, especially from industrial discharges and untreated sewage.

5.3. $NO_2^-$and PO_4^{3-}Estimation Techniques

In water bodies like Vembanad Lake, the laboratory-based estimates of nutrient concentrations provide a potent tool for identifying regions with elevated nutrient levels when combined with satellite remote sensing data like sentinel 2 and sentinel 3 images. This helps to monitor the threats like eutrophication and learn important information about its ecological effects, such as oxygen depletion, toxic algal blooms. This also led to species composition changes. This approach helps in the early identification of environmental stressors by constantly monitoring nutritional status of the aquatic environment. This allows for more effective management strategies to mitigate the effects of eutrophication and safeguard the health of Vembanad Lake system and similar ecosystems (Nasir, 2010).

Assessing nutrient dynamics in aquatic environments requires the use of in-lab methods for measuring $NO_2^-$and PO_4^{3-} levels (Kaisary et al., 2012). The ascorbic acid approach, which involves the formation of a blue complex with PO_4^{3-} ions that can be measured spectrophotometrically at a wavelength of 880 nm, is one commonly used technique for determining PO_4^{3-} concentrations. This method has proven to be highly accurate and sensitive, which makes it perfect for identifying low PO_4^{3-} concentrations and supplying trustworthy information for nutrient assessments.

Water Quality Measurements Protocol for COMAPS Programme was followed for the estimation of NO_2^- rates in samples. The NO_2^- rates were determined using the Griess reaction. This process creates a diazonium salt from nitrite and sulphanilamide, which subsequently reacts with N-(1-naphthyl)-ethylene diamine dihydrochloride to yield a purple compound. A dependable method for NO_2^- quantification is to measure the absorbance of this purple compound at 540 nm, which yields the concentration of NO_2^-.

5.4. Quantification of Chl-a Using Acetone Extraction Method

$PO_4^{3}$and NO_2^-, Chl-a estimation plays a crucial role in evaluating the overall health of aquatic ecosystems. Chl-a concentrations, often used as an indicator of phytoplankton biomass, provide valuable insight into the productivity of water bodies. Typically, Chl-a is estimated using a spectrophotometric method where the extract from filtered water samples is measured at a specific wavelength, typically around 665 nm, following solvent extraction with acetone (Strickland & Parsons, 1972). This provides a reliable index of the algae concentration, which is often directly related to nutrient availability and eutrophication. By integrating Chl-a data with other water quality parameters like DO, a more comprehensive understanding of the trophic status of aquatic ecosystems like Vembanad Lake can be obtained, aiding in the prediction of algal blooms and the associated ecological impacts (Iriarte et al., 2007).

5.5. Salinity and water pH

The laboratory findings of Thiyagarajan et al. (2003) showed that attachment success is much better at higher salinities, with maximum attachment rates (>80%) at 31ppt and drastically lower attachment rates (<33%) at salinities below 24ppt. Salinity plays a crucial role in barnacle population and its proliferation. Studies by Nardone et al. (2018) showed that acidic environment may be created due to the anthropogenic activities, larger barnacles with greater shell mass and base plate area were produced at slightly acidic pH.

5.6. Satellite Remote Sensing for Water Quality Monitoring

A powerful and effective remedy for the difficulties encountered by traditional in-situ techniques of water quality assessment is satellite remote sensing. Satellite imagery (sentinel 2 and sentinel 3) helps to cover up the drawbacks of conventional monitoring techniques because it allows evaluations at enormous spatial scales and temporal frequencies. A key component of the European Space Agency's (ESA) Copernicus program, the Sentinel-3 mission has been effective in providing high-quality data on aquatic ecosystems. Sentinel-3, outfitted with the Ocean and Land Colour Instrument (OLCI), is capable of monitoring important water quality parameters like suspended particulate matter (SPM), turbidity, and Chl-a. (Griffith, 2002; Alparslan et al., 2007). Assessing these factors are important because these factors contribute to the water quality. By evaluating these factors, the quality of water may be evaluated.

In aquatic environments, Chl- a concentration is a crucial indicator of nutrient concentration and algae blooms and is commonly used as a primary productivity indicator. A major drop in water quality and toxic algal blooms can result from eutrophication, which is caused by an overabundance of nutrients like $NO_2^-$and PO_4^{3-}(Topp et al., 2020; Sun et al., 2022). Chl-a concentrations can be tracked over wide geographic areas using Sentinel-3 remote sensing data, which gives them vital information about the temporal and spatial fluctuations in algal growth.

The Vembanad Lake system, has an alarming increase of $NO_2^-$and PO_4^{3-} concentration due to urbanization and agricultural runoff is a growing concern. Remote sensing provides a proactive method of controlling water quality and stopping additional ecological deterioration by identifying early indicators of eutrophication (Purandara et al., 2018; Sajeev et al., 2020).

Sentinel-3's OLCI provides information on suspended particulate matter and turbidity in addition to Chl-a, both of which are essential for assessing the physical well-being of aquatic environments. By decreasing penetration of light in the water column, elevated turbidity levels often brought on by sediment disturbance or agricultural runoff can degrade water quality, affecting plant growth and upsetting aquatic ecosystems. By reducing photosynthetic efficiency and changing organism habitats, high turbidity levels can also negatively impact the aquatic food web (Karunakaran et al., 2019). Sentinel-3 remote sensing data is essential for locating pollution hotspots, detecting elevated turbidity levels, and directing management tactics. The littoral zones of lakes can be evaluated by the Sentinel-2 satellite which compliments Sentinel-3, which offers a more thorough analysis of water quality at the local level with improved spatial resolution of 10 to 20 meters (Prasad et al., 2024). Sentinel-2 is a vital tool for thorough water quality management in systems like Vembanad Lake because of its high resolution, which makes it possible to identify more subtle pollution sources like urban runoff, sediment accumulation, and localized agricultural practices (Parthasarathy, 2023). When combined, these satellite images provide a thorough method for managing the quality of the water in freshwater ecosystems.

5.7. Geospatial Analysis and Kriging for Predicting Water Quality

In large aquatic ecosystems like Vembanad Lake system, geospatial analysis is essential for providing accurate spatial forecasts of water quality parameters when paired with methods like IDW. New interpolation techniques like IDW and Kriging are geostatistical interpolation technique, produces more accurate spatial estimates by forecasting values at unsampled locations using the spatial autocorrelation among observed data points (Simsek & Gunduz., 2007). In situations where in-situ sampling would be expensive or logistically difficult, this technique enables researchers to forecast water quality parameters like turbidity, Chl-a, and nutrient concentrations over wide areas.

By employing IDW interpolation for the spatial arrangement between data points, resulting in a more credible insight of water quality across the entire water body (Şener et al., 2017). Large-scale studies, like those carried out in Vembanad Lake, where water quality indicators can be mapped with more spatial precision, benefit greatly from the use of Kriging. The usefulness of Kriging for ecological studies also emphasizes its function in forecasting water quality in vast and isolated aquatic environments.

IDW greatly improves the temporal coverage and spatial resolution of water quality evaluations when combined with remote sensing data, which helps in monitoring changes in water bodies continuously and widely using satellite data, like that from the Sentinel-3 and Sentinel-2 missions. This allows us to monitor over time. Interpolation in conjunction with remote sensing data can produce detailed surface maps of turbidity levels, nutrient distribution, and Chl-a concentrations, among other water quality parameters. Mapping regions with high nutrient levels that might be more susceptible to dangerous algal blooms and identifying eutrophication hazards are two applications where this integration is especially helpful and thereby offering thorough insights into water quality over wide areas. Acknowledging the ecological health of water bodies requires the combination of remote sensing and geostatistical techniques like interpolation, which are the crucial resources for early intervention and mitigation plans (Mantzafleri et al., 2009).

To deepen the studies, spatial autocorrelation techniques like buffer evaluation and Local Indicators of Spatial Association (LISA) are used, which evaluate more about how land use and human activities affect water quality. This helps to determine important nutrient sources and forecast their long-term effects on water quality by examining the spatial distribution of urban and agricultural areas surrounding the Lake system (Brezonik et al., 2002). Areas most susceptible to nutrient loading, such as those close to urban wastewater discharges or agricultural runoff, can be identified using buffer analysis. This aids in determining how human activity affects water quality and makes it easier to create focused management plans. More accurate monitoring and decision-making for the future are made possible by the combination of buffer analysis and spatial autocorrelation, which also helps identify possible nutrient pollution hotspots (Hacısalihoğlu et al., 2016).

Additionally, geospatial analysis based on Kriging has demonstrated its application in forecasting algae blooms and supporting aquatic systems nutrient management. The ecological balance of aquatic ecosystems is threatened by eutrophication, which is frequently brought on by excessive nutrient inputs from human sources like wastewater. Early detection of eutrophic conditions is made possible by the continuous monitoring of water quality and nutrient levels over wide areas made possible by the integration of interpolation with remote sensing data (Subramaniam et al., 2023). Kriging-based spatial predictions can help locate eutrophication hotspots in Vembanad Lake system and track their evolution over time.

5.8. Biological Indicators and the Role of Species Assemblages

Certain organisms reflect and react to the changes in the environment. Their survival and changes greatly depend on the surrounding environment in which they live. These biological indicators contribute to the water quality assessment and offer a deeper understanding of ecosystem health. One such organism that serves as excellent bioindicators is the Barnacle (Vaezzadeh et al., 2021), they are sensitive to changes in water quality. They are filter feeders and their population is directly correlated with food source availability, which is influenced by water quality parameters like turbidity, DO and Chl-a (Riisgård et al., 2015). Barnacle population is highly subjected to nutrient fluctuations that cause the chemical changes in the water (Lozano Bilbao et al., 2021). They have highlighted that barnacle populations also offer crucial insights into the early stages of eutrophication.

Barnacle responds to the changes like DO and nutrient concentration. Barnacle populations typically flourish in environments with moderate nutrient concentrations like NO_2^- and PO_4^{3-}, while excessive nutrient enrichment can cause a decline in their population. Because excessive nutrients result in hypoxia and algal blooms, which reduce barnacle abundance (Crisp, 1960). Other parameters which design the distribution of barnacles are salinity, temperature and pH. Changes in the distribution and abundance of barnacles are early signs of ecological shifts (Zanette et al., 2015). Additionally, Alcázar Treviño et al., (2021) shows how the study of distribution and abundance of barnacles helps to anticipate the urban environment, particularly how nutrient-enriched runoff affects water quality and the life of organisms.

Barnacle populations in Vembanad Lake reflect the effects of nutrient enrichment (NO_2^- and PO_4^{3-}) and eutrophication. Evaluating barnacle growth and densities help to address events like nutrient stacking on the food web and ultimately effect the ecosystem consistency (Anagha et al., 2022). The extent of eutrophication can be interpreted by growth rates, reproductive success and the biomass of barnacle populations. Further, they can be used to evaluate the effects of pesticides, endocrine disruptors and heavy metals on aquatic environments (Powell & White., 1990). Incorporation of biological markers can aid in directly evaluating the quality of water.

6. MATERIALS AND METHODS

6.1. Selection of the study area

The present study was conducted in the Vembanad lake, Kerala, southwest coast of India. Four stations were selected for the study that include: Udhayamperoor (Latitude 9.9104° N, Longitude 76.3579° E), Chellanam (Latitude 9.85798° N, Longitude 76.28015° E) centrally located point, Fort Kochi (Latitude 9.96831° N, Longitude 76.24203° E) and Panagad (Latitude 9.88274° N, Longitude 76.32985° E).

Apart from the geographic attributes of the location this is an area with high flora and fauna diversity. Most people in and around this region rely heavily on the local ecosystem. However, human interference has significantly impacted this environment, leading to water quality degradation and future threats such as eutrophication. The water quality in this area is largely influenced by river inflow, tidal exchanges and precipitation. This ecosystem experiences tidal fluctuations, with saltwater intrusion from the Arabian sea occurring along with changes in freshwater supply during the monsoon season. These factors contribute to the dynamic nature of the ecosystem. The sampling was done in May, 2024 as early rain affects parameters like turbidity, nutrient levels, and DO (Sathyendranath et al., 2018).

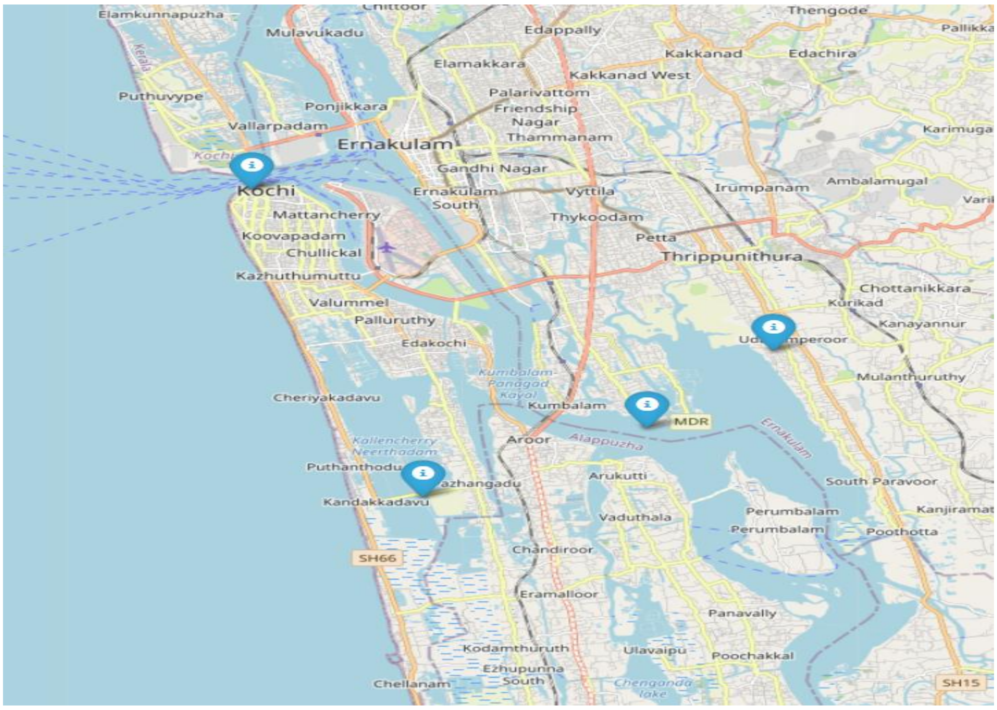

Fig.1: Area of study (a).

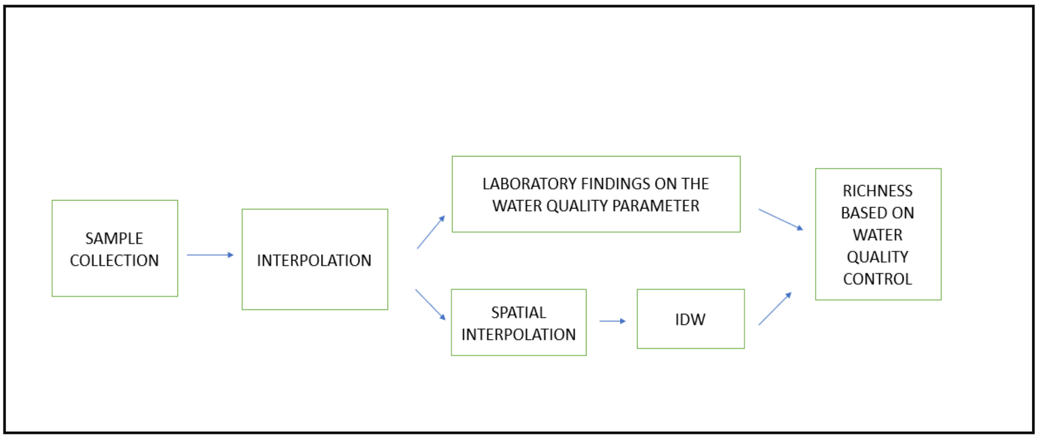

Fig.2: Outline of the work.

Water samples were collected from all the stations for further analysis in a tarson (500 ml) bottle. For the chlorophyll analysis amber tarson (500 ml) bottles were used. Salinity and temperature were measured using a multi parameter probe. Quadrat sampling was the technique adopted for the counting of the barnacles. This method was used to count the barnacles from all four sample sites (Murray, 2002).

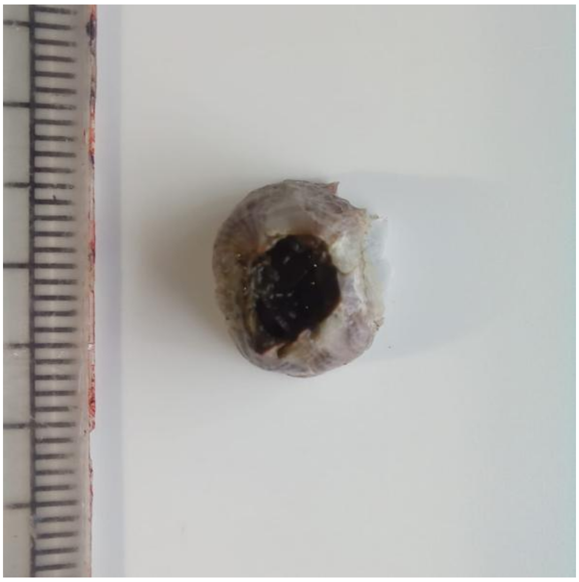

Fig.3: Biological indicator-Barnacle.

6.2. Determination of Chlorophyll

Chl-a is a common and abundant pigment in all photosynthetic organisms. For the chlorophyll estimation water samples were collected from all four stations in an amber tarson bottle (500 ml). Collected sample (500 ml) were filtered through a filter 0.4µm pore size filter paper (Whatman glass micro fibre filter). The pigments was extracted using 90% acetone and kept overnight at 4°C followed by centrifugation. The contents of the tubes were centrifuged at room temperature for 10 minutes at 3000 rpm. The supernatant was subjected to spectrophotometer analysis at the wavelengths 750, 664, 647 and 630nm. Correction for each extinction of small turbidity blank is done by subtracting at 750nm from 664, 647 and 630nm absorption (Strickland & Parsons, 1972).

$$Chl\text{-}a = 11.85E_{664} - 1.54E_{647} - 0.08E_{630}$$

- E_{664} = Absorbance at 664 nm
- E_{647} = Absorbance at 647 nm
- E_{630} = Absorbance at 630 nm

6.3. Determination of Phosphate (PO_4^{3-})

The PO_4^{3-}concertation was determined for samples collected from all the four station. Mixed reagent was prepared by addition of 125 mL of the ammonium molybdate solution (Dissolve 12.5 g of ammonium molybdate tetrahydrate in 125 mL of water and store it in a clean container) to 350 mL of 9 N sulfuric acid (250 mL of concentrated Sulfuric acid (H_2SO_4) to 750 mL of water in a 1-liter volumetric flask), then add 20 mL of the potassium antimony tartrate solution (Dissolve 0.5 g of potassium antimony tartrate in 20 mL of water and store in a glass bottle), mix well, and store in an amber glass bottle.

About 10 g of ascorbic acid was dissolved in 50 mL of water followed by addition of 50 mL of 9 N Sulfuric acid to prepare the ascorbic acid solution, and stored in an amber bottle in a refrigerator. For the standard stock solution, weigh 0.1361 g of potassium dihydrogen phosphate (KH_2PO_4) was weighed and 1 mL of 9 N H_2SO_4 was added to make up the volume to 100 mL with water in a standard flask.

The working standard solution was prepared by transferring1 mL of the stock solution to a 100 mL volumetric flask and diluting it to the mark with distilled water, with a concentration of 100 µmol PO_4^{3-}/L. Transfer 1 mL of 100 µmol solution into another 100 mL volumetric flask and diluted to the mark with water.

For calibration, 25 mL each of water was measured as a blank and working standard solutions in clean stopper glass tubes, in triplicate. About 0.5 mL of Ascorbic acid solution was added to each tube followed by addition of 0.5 mL of mixed reagent. As the blue colour appeared the sample was measured at 880 nm in a spectrophotometer using distilled water as the reference. The PO_4^{3-}concentration in the sample is determined based on these absorbance measurements (Kaisary et al., 2012).

$$PO_4^{3-}(\mu mol/L) = F\times(A_s - A_b)$$

Where:

- F = Factor value, calculated as:

$$F=\frac{\text{Concentration of standard solution}}{A_{st}-A_b}$$

- A_b = Absorbance of the blank
- A_st = Absorbance of the standard
- A_s = Absorbance of the sample

  Measured at: 880 nm

6.4. Determination of Nitrite – Nitrogen (NO_2^{-} – N)

The water Quality Measurements Protocol for COMAPS Programme were followed for the estimation of NO_2^{-} in samples. For the estimation, nitrite stock solution was initially prepared by adding 0.069 g Anhydrous sodium nitrite ($NaNO_2$) and then dissolved in 100 mL of water in a standard 100 mL flask. This stock solution contains 10 mmol/L NO_2-N. Then dissolve 1 g of sulphanilamide in 10 mL of concentrated HCl, followed by the dilution at 100 mL using distilled water and then transfer to an amber glass bottle. For the preparation of N-(1-naphthyl)-ethylene diamine dihydrochloride (NEDA) of 0.1 g in 100 mL of water and stored it in an amber glass bottle.

For the working standard solutions, 1 mL of the nitrite stock solution was added into a 100 mL volumetric flask and diluted with distilled water, thus obtaining a solution containing 100 µmol NO_2-N/L. About 1 mL of this solution was transferred into another 100 mL flask and diluted to the mark with distilled water, with concentration of 1 µmol NO_2-N/L. By repeating the same procedure standards 2, 3, 4, and 5 was prepared. For blank about 25 mL each of distilled water and working standard solutions was measured in triplicate, and transferred into a clean stopper glass tube. Followed by the addition of 0.5 mL of sulphanilamide to each tube. To this add 0.5 mL of NEDA solution, allow the reaction to proceed for 15 minutes. The absorbance was measured at 540 nm using a spectrophotometer with water as the reference.

$$NO_2^- (\mu mol/L) = F \times (A_s - A_b)$$

Where:

- F = Factor value, calculated
- F= Concentration of standard solution

  Ast−Ab
- A_b = Absorbance of the blank
- A_st = Absorbance of the standard
- A_s = Absorbance of the sample

  Measured at: 540 nm

6.5. Satellite Remote Sensing data for Water Quality Monitoring

A powerful and effective remedy for the difficulties encountered by traditional in-situ techniques of water quality assessment is satellite remote sensing. A key component of the European Space Agency's (ESA) Copernicus program, the Sentinel-3 mission has been effective in providing high-quality data on aquatic ecosystems. Sentinel-3, outfitted with the Ocean and Land Colour Instrument (OLCI), is capable of monitoring important water quality parameters like Chl-a, DO, suspended particulate matter (SPM) and turbidity (Griffith. ,2002; Alparslan et al., 2007). Assessing these factors was important because these factors contribute to the water quality. By evaluating these factors, the quality of water may be evaluated.

6.6. IDW: Interpretation of observed in-situ and satellite remote sensing

The study employed the collection of data from specific points therefore IDW interpolation method was applied to form a continuous DO distribution map. The IDW formula used in ArcGIS is:

$$Z(x) = \frac{\sum_{i=1}^{N} \frac{Z_i}{d_i^p}}{\sum_{i=1}^{N} \frac{1}{d_i^p}}$$

where;

- Z(x) = estimated value at location xxx
- Z_i = known value at point iii
- d_i = distance from known point iii to location xxx
- p = power parameter
- N = total number of known points used for interpolation

For the process of interpolation, import the data to the ArcGIS. Click 'add data' and add Sentinel-3 DO raster image. Also add the the CSV file containing NO_2^-, PO_4^{3-} , pH, Salinity, Chl-a, and Barnacle Count. This step ensures the conversion of csv to a point feature layer using 'display XY data', setting Latitude (Y) and Longitude (X) as coordinates.

For Creating a Shapefile for the Study Area, open 'Arc Toolbox', select 'Minimum Bounding Geometry' from 'Data Management Tools' and import point layer (CSV point). Click 'Run' to generates a polygon shapefile. Mask the Study Area for Limited Interpolation. To limit the interpolation to the demarcated region, Open 'Arc Toolbox' select 'Spatial Analyst Tools' click on 'Extraction' and 'Mask'. Select Sentinel- DO raster. Select and import the Study Area Shapefile. Click 'Run'.

Because field measurements are point-based and Sentinel-3 DO data is in raster format, DO values need to be extracted for every sample point. To allocate DO values to every sample location, use the 'Extract Values to Points' tool found under 'Spatial Analyst Tools'.

For Applying IDW (Inverse Distance Weighting), Open 'Arc Toolbox' select 'Spatial Analyst Tools Interpolation' and then select 'IDW'. Input the already generated file with DO at specific points and select the Z-Value field as DO. Click 'Run' option to create an IDW-based DO distribution map. IDW assigns more weight to closer points. Right-click on the IDW raster layer and click on 'Properties'. Select 'Symbology' and the 'Colour Ramp'. Adjust the transparency to (30-50%). Adjust Legend, Scale Bar, and North Arrow. Click ‘Layout View’ and ‘Export Map’ and Save as JPEG .

The next step involves adding Sampling Points with Barnacle Count Graduation. Import Sample Points with DO to the ArcGIS map. Select ‘Symbology’, ’Graduated Colours based on Barnacle Count. Set the boundary for the study area. Click ‘Add Data’ and import the study area shapefile. Adjust the boundary, colour, layer order. Save the final map. Open ‘Layout View’ in ArcGIS for addition of Legend, Scale Bar, North Arrow. After the final modification save as JPEG.

7. RESULT

Different water quality parameters were analysed from four different stations: Fort Kochi, Chellanam, Panagad, and Udhayamperoor. Barnacle count in an area is greatly affected by salinity, pH, NO_2^-, PO_4^{3-} and Chl-a concentrations and Kriging interpolation of DO was used to further support the data from these experiments.

7.1 Barnacle Count

In this present study, the barnacle showed variation in distribution among stations. The highest abundance was observed at Fort Kochi (234 individuals), followed by Chellanam (167 individuals), Panagad (153 individuals), Udhayamperoor (54 individuals) (Table.1 and Fig.4).

Table 1: Abundance of barnacle at four stations.

Stations	Count of Barnacles
UDAYAMPEROOR	54
CHELLANAM	167
FORT KOCHI	234
PANAGAD	153

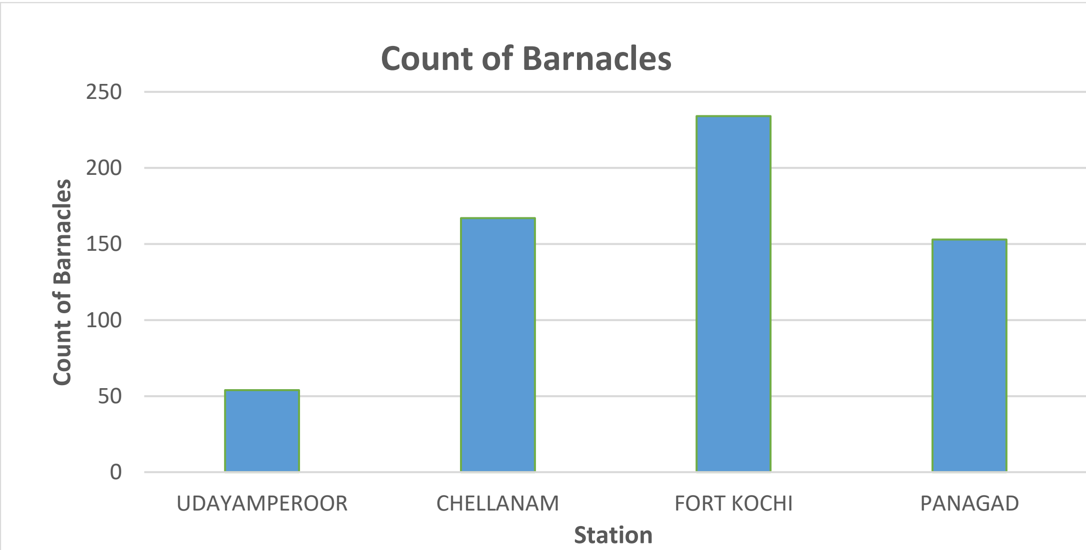

Fig.4: Abundance of barnacle in each stations.

7.2. Salinity

The salinity in each station varied with the highest observed at Fort Kochi (30.45 ppt), followed by Chellanam (26.61 ppt). The lowest salinity levels were measured at Udhayamperoor and Panagad with 24.70 ppt with 24.27 ppt respectively (Table.2 and Fig.5).

Table 2: Variation of Salinity levels at four stations

Stations	Salinity(ppt)
UDAYAMPEROOR	24.70
CHELLANAM	26.61
FORT KOCHI	30.45
PANAGAD	24.27

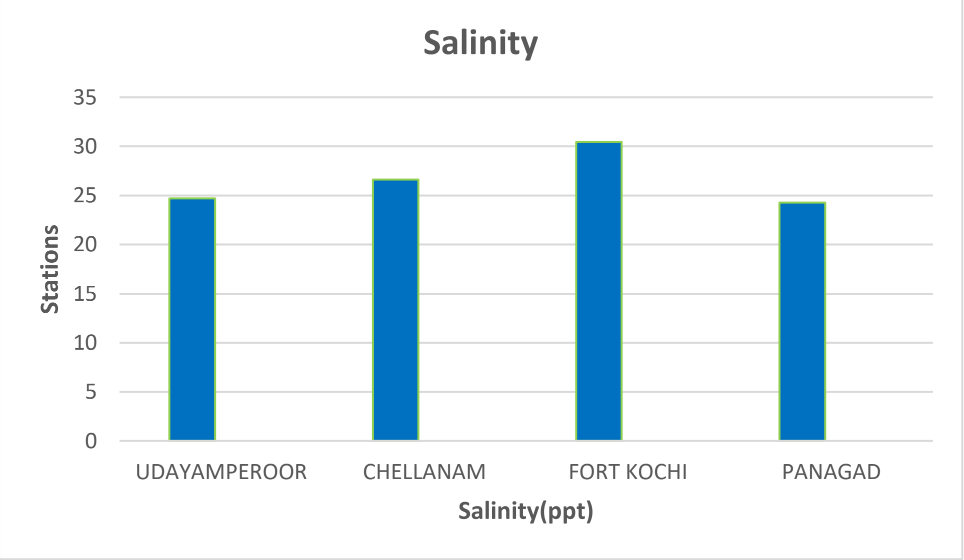

Fig.5: Variation of Salinity levels in each stations

7.3 pH

The pH of the water samples also varied among the stations ranging from 6.21 to 7.22. The lowest pH was observed at Fort Kochi (6.21), followed by Chellanam (6.83) .The pH level observed at Panagad was 7.11, while Udhayamperoor recorded pH value of 7.22 (Table.3 and Fig.6).

Table 3: Variation of pH at four stations

Stations	pH
UDAYAMPEROOR	7.22
CHELLANAM	6.83
FORT KOCHI	6.21
PANAGAD	7.11

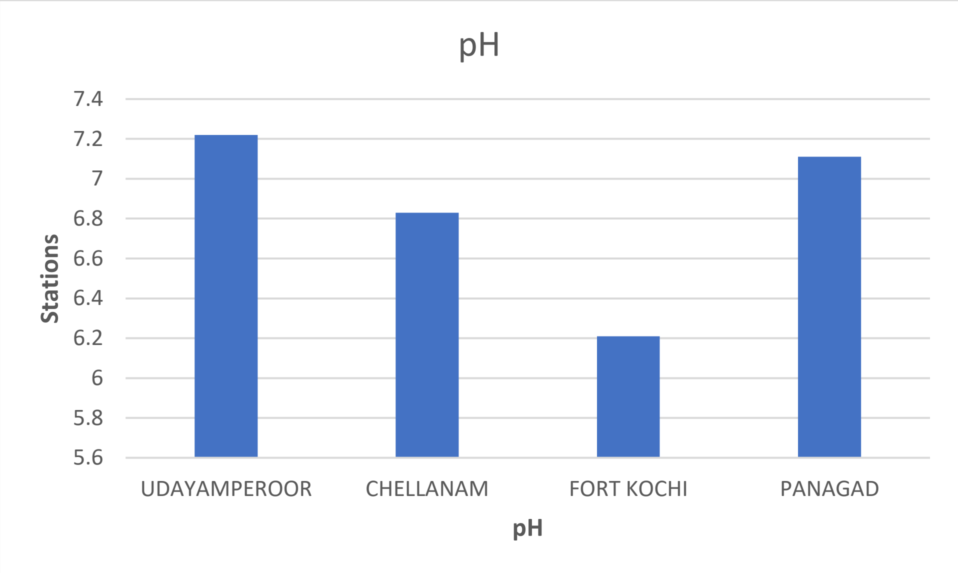

Fig.6: Variation of pH at four station.

7.4. <u>Chlorophyll-a (Chl-a)</u>

Chl-a concentrations, which indicate phytoplankton biomass, were measured across the four stations. Panagad recorded the highest chl-a concentration at 4.225 mg/m^3, followed by Fort Kochi (3.732 mg/m^3), Chellanam (3.009 mg/m^3), and the lowest recorded at Udhayamperoor with a concentration of 0.221 mg/m^3 (Table.4 and Fig.7).

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Table 4: Variation in Chl-a levels at four stations.

Stations	chlorophyll a(mg/m^3)
UDAYAMPEROOR	0.221
CHELLANAM	3.009
FORT KOCHI	3.732
PANAGAD	4.225

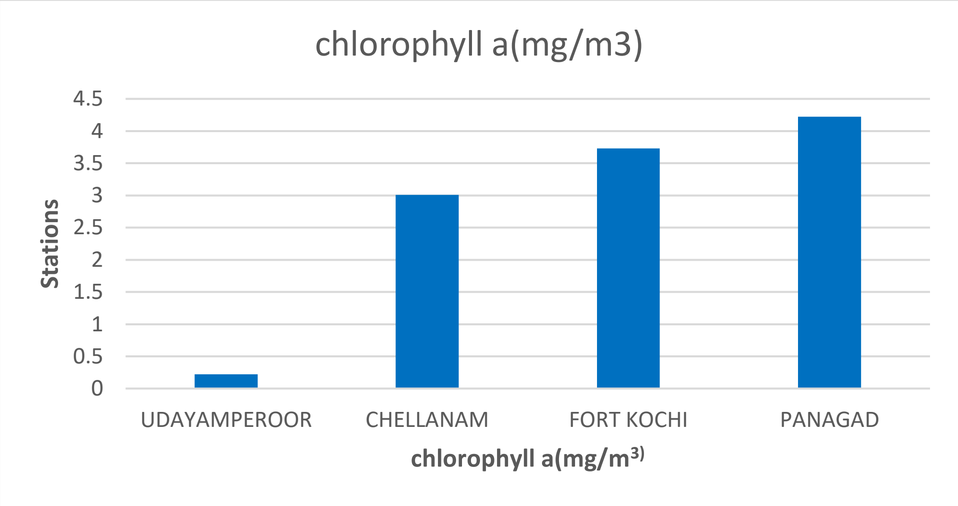

Fig.7: Variation in Chl-a levels at each stations.

7.5 Phosphate (PO_4^{3-}-P)

Nutrient levels also varied among four stations, with the highest value for PO_4^{3-}observed at Panagad (9.9340 µmol/L). Fort Kochi measured a PO_4^{3-} concentration of 4.2752 µmol/L, while Chellanam measured a concentration of 3.9079 µmol/L and Udhayamperoor with a concentration of 3.1410 µmol/L (Table.5 and Fig.8).

Table 5: Variation of PO_4^{3-} levels at four stations.

Stations	Phosphate (µ mol/l)
UDAYAMPEROOR	3.141
CHELLANAM	3.9079
FORT KOCHI	4.2752
PANAGAD	9.934

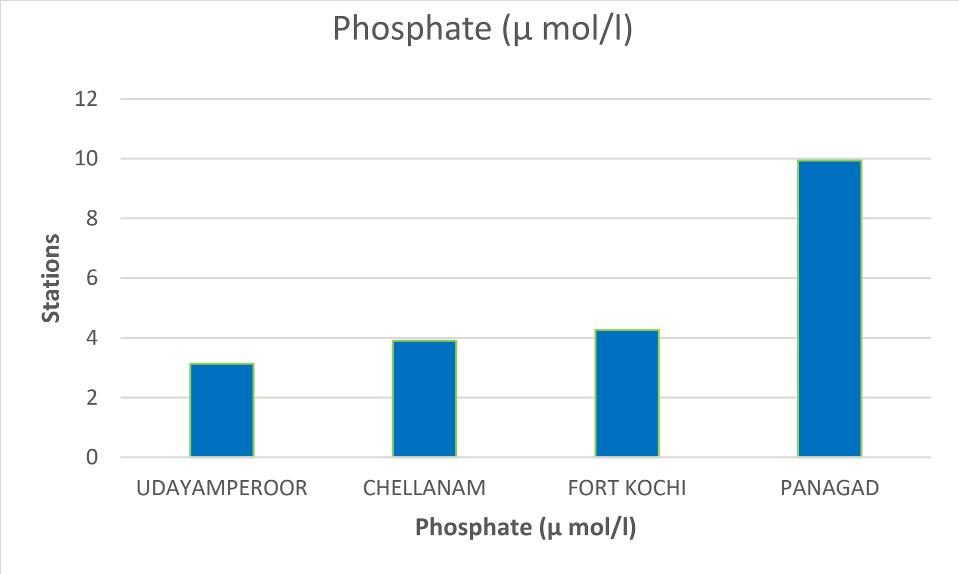

Fig.8: Variation in PO_4^{3-} concentrations in each stations.

7.6 Nitrate (NO_2-N)

NO_2^- concentrations also varied significantly across the four stations. The highest NO_2^- concentration was recorded at Panagad (2.423 μmol/L) followed by Fort Kochi (0.739 μmol/L), Chellanam (0.627 μmol/L), and the least at Udhayamperoor with a concentration of 0.314 μmol/L (Table.6 and Fig.9).

Table 6: Variation in NO_2^- concentration among four stations.

Stations	Nitrite (μ mol/l)
UDAYAMPEROOR	0.314
CHELLANAM	0.627
FORT KOCHI	0.739
PANAGAD	2.423

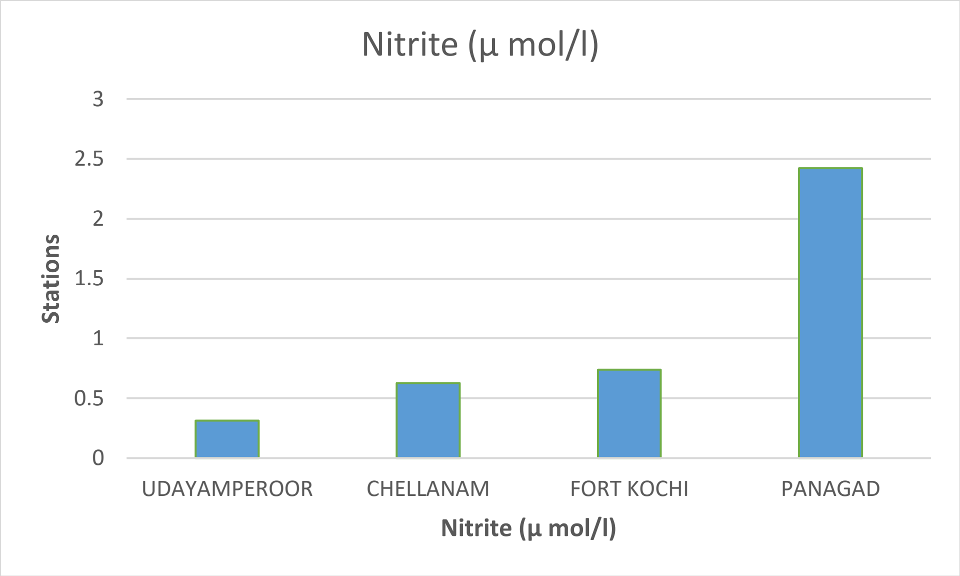

Fig.9: Variation in distribution of NO_2^- concentration at four stations.

7.7 Sentinel-3 Data Extraction

Access Sentinel-3 data through the Copernicus Open Access Hub. Focus on Sentinel-3 OLCI (Ocean and Land Colour Instrument) products which provide chl-a concentration data, serving as an indirect indicator of DO, SST and CDOM. Sentinel-3 products can be downloaded in NetCDF or HDF5 formats, and analyse these datasets (Fig.10).

Data from CDM, Algal pigmentation concentration and total suspended matter. But for the interpolation DO data were used.

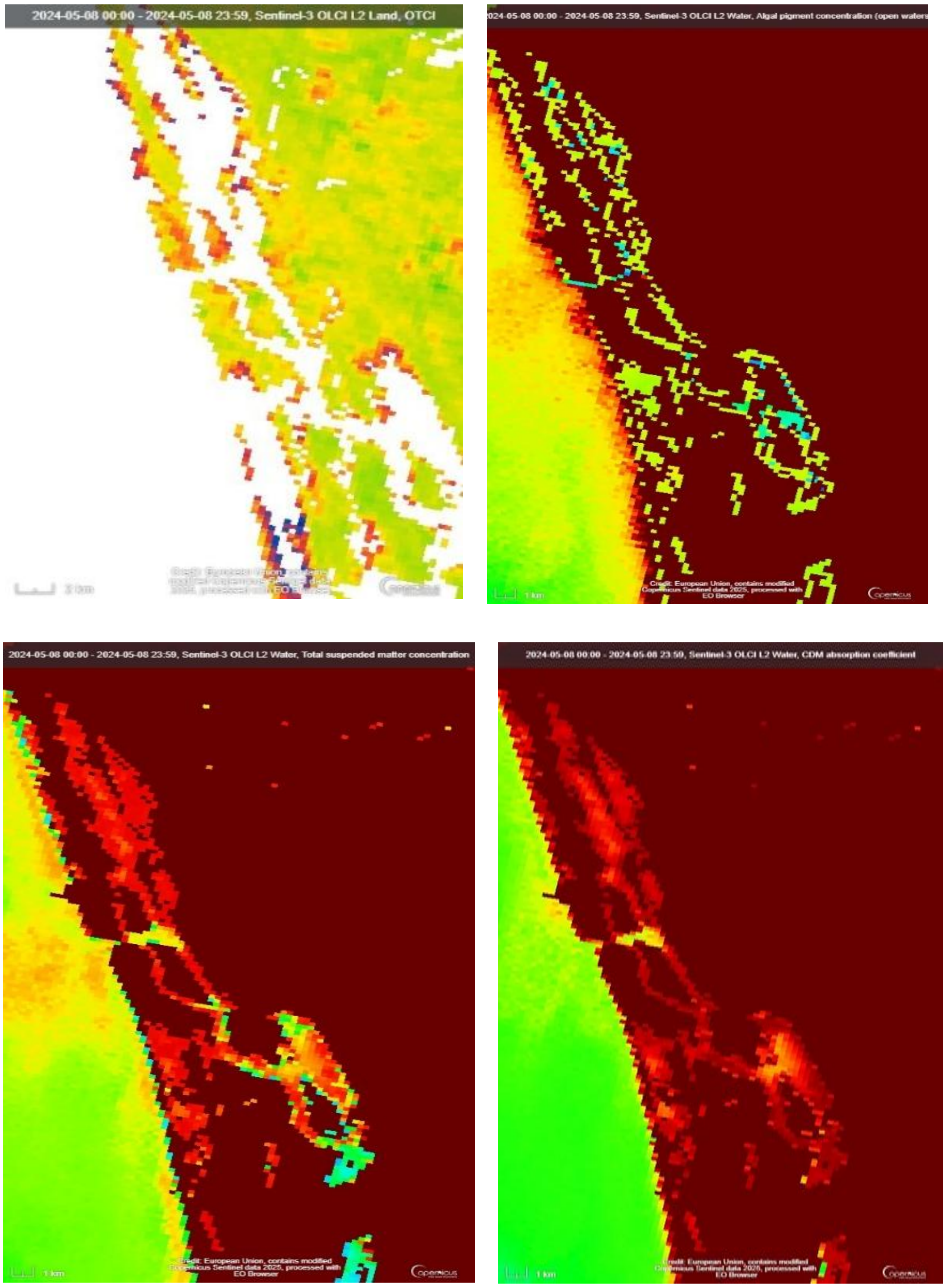

Fig.10: Sentinel-3 products

7.8 IDW Interpolation of DO

DO map product of the interpolation was overlaid with barnacle distribution data, this enabled visual comparison of barnacle abundance and oxygen levels (Fig.11). After interpolation the results indicate Fort Kochi, Chellanam and Panagad as three hotspots.

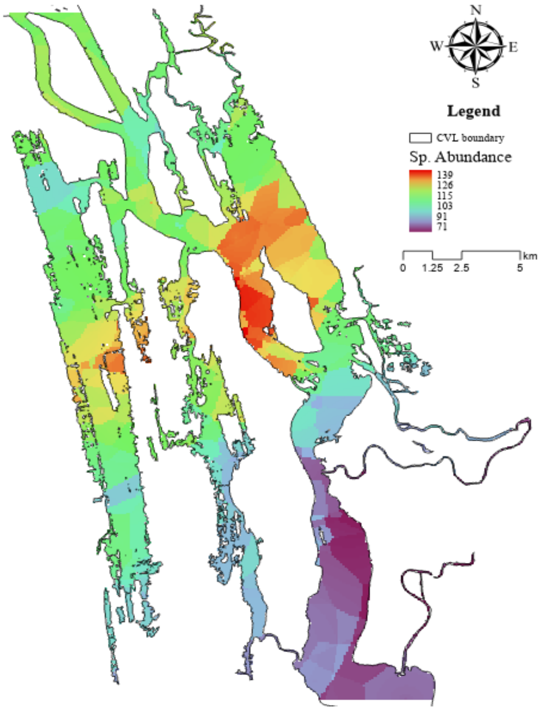

Fig.11: Water quality analysis map.

8. DISCUSSION

A combination of geographic and environmental factors led to the selection of Fort Kochi, Chellanam, Panagad, and Udhayamperoor as study locations. The four stations selected displays a variation in the environmental conditions. The hydrological conditions greatly affect different parameters like nutrient concentration ($NO_2^-$and PO_4^{3-}) and pH. Fort Kochi is a station with marine influence, costal station. Thus, marking a station with high saline conditions. Chellanam is situated along the coast but receives influences from both seawater and estuarine water thus creating a dynamic and an intermediate environment. Panagad is situated in an estuarine system, which has a varying salinity system due to tidal exchange and freshwater inflows. Udhayamperoor, is primarily influenced by freshwater and represents a low-saline environment and reduced marine influence indicating inland stations.

The analysis of in-situ data along with interpolation revealed three hotspots- Chellanam, Fort Kochi, and Panagad. Barnacle count was the main determinant of hotspot status, with Fort Kochi having the highest count, followed by Chellanam, Panagad and Udhayamperoor having the least count. Varying water quality parameters and environmental conditions also led to this conclusion. Nutrient levels ($NO_2^-$and PO_4^{3-}), Salinity, Chl-a concentration and pH are some of the variables that affect barnacle populations. Higher salinity and adequate nutrient availability are the favourable conditions that promotes barnacle growth. Udhayamperoor had low salinity levels, while Fort Kochi had the highest.

Fort Kochi and Chellanam had high levels of $NO_2^-$and PO_4^{3-}, while Panagad had the highest levels. Udhayamperoor, on the other hand, had the lowest levels of $NO_2^-$and PO_4^{3-}, which resulted in lower phytoplankton growth, as evidenced by its low concentration of Chl-a. The low nutrient levels at Udhayamperoor contributed to the lower barnacle count. Udhayamperoor had lower levels of Chl-a and nutrient concentrations, indicating that it receives less nutrient pollution, which restricts barnacle growth. This station also has freshwater influence that reduce pollution levels.

The laboratory findings of Thiyagarajan et al., (2003) directly supports the observations of declining barnacle populations from Fort Kochi to Panagad. Although barnacles may survive at a variety of salinity levels, research showed that attachment success is much better at higher salinities, with maximum attachment rates (>80%) at 31ppt and drastically lower attachment rates (<33%) at salinities below 24 ppt. This explains the gradient of declining barnacle abundance from Fort Kochi to Panagad.

Fort Kochi had the lowest pH and the highest barnacle count; this aligns with the conclusion that barnacles can survive in slightly acidic environments. The acidic environment maybe created due to anthropogenic activities. Larger barnacles with greater shell mass and base plate area were produced at slightly acidic (Nardone et al., 2018).

The distribution of barnacles in a region depends on the PO_4^{3-}concentration. PO_4^{3-} concentrations were highest in Panagad, followed by Fort Kochi and Chellanam. Panagad maintained fewer barnacles than Fort Kochi and Chellanam, even though it had the greatest PO_4^{3-} levels. The excessive PO_4^{3-} concentrations may prevent barnacle population growth, while moderate levels may promote barnacle settlement. The high PO_4^{3-} levels found at Panagad suggest possible nutrient pollution and eutrophication, which results in phytoplankton blooms and hypoxic condition that reduce barnacle survival (Vidya & Prasad., 2017).

The NO_2^- concentrations in Panagad, Fort Kochi and Chellanam were a replica of PO_4^{3-} level. Fort Kochi and Chellanam had high NO_2^- levels that contributes to the abundance of the barnacle. The NO_2^- levels in turn contribute to phytoplankton growth (Sajeev et al., 2020). Panagad maintained fewer barnacles than Fort Kochi and Chellanam, even though it had the greatest NO_2^- levels. This suggests that high NO_2^- concentrations crossing a certain threshold will cause the decline in the barnacle population (Nasir, 2010).

Chellanam and Fort Kochi had moderate levels of Chl-a. Observed results aligns with the satellite derived water quality observation by Kulk et al. (2021). Panagad had the highest Chl-a value. This might be due to the estuarine condition influenced by the tidal exchange and the freshwater movement. Also, highest $NO_2^-$and PO_4^{3-} level supports the phytoplankton growth. Fort Kochi and Chellanam marked moderate levels of Chl-a. Fort kochi stations experience strong tidal mixing which helps in nutrient distribution. This in turn helps in nutrient proliferation. Chellanam is situated along the coast but receives influences from both seawater and estuarine water thus extracting the advantages of both freshwater and marine water. Also, these stations exhibited moderate nutrient level that supports the phytoplankton growth.

However, Fort Kochi has high barnacle count due to strong tidal influence, urban inputs and hard substrate. Barnacles are filter feeders and they depend on organic detritus, bacteria and smaller suspended particles even though phytoplankton biomass is low (Riisgård et al., 2015).

Fort Kochi exhibited the highest barnacle abundance, which coincided with high salinity and slightly acidic conditions. The site recorded high PO_4^{3-} and NO_2^- levels, moderate Chl-a concentration suggesting that barnacle proliferation may be influenced by nutrient availability and salinity. The high salinity indicates a strong marine influence, which may provide optimal conditions for barnacle attachment and growth. Given that Fort Kochi had the lowest pH and the highest barnacle count. It may be because of the fact that the acidic environment created due to the anthropogenic activites sustain their survival.

Chellanam has the second-highest barnacle count, indicating environment with High Barnacle abundance and productivity. The result indicates moderate salinity and slightly acidic pH. This station also has moderate Chl-a concentration. The barnacle larvae depend on this phytoplankton. If proper monitoring fails, levels of $NO_2^-$and PO_4^{3-}in Fort kochi and Chellanam can supports the primary productivity at a level that would degrade water quality or induce hypoxia.

The highest levels of $NO_2^-$and PO_4^{3-} were recorded in the Panagad region which indicates a serious condition of nutrient pollution. This leads to the decline in water quality and nutrient loading. This is the major reason for the slightly lower barnacle count compared to Fort Kochi and Chellanam. This station also marks highest concentration of Chl-a indicates a highly productive environment that may be fuelled by nutrient inputs. The lowest salinity suggests an estuarine influence, demonstrating the brackish water tolerance of barnacles. The strong relation between high $NO_2^-$and PO_4^{3-}levels and barnacle presence support the idea that barnacles serve as bioindicators of nutrient pollution, particularly in eutrophic areas influenced by wastewater discharge and agricultural runoff.

This study reveals barnacles as a potential biological indicator with respect to their population distribution which is greatly influenced by the water quality parameters. The interpolation technique and the in-situ data showed the highest barnacle counts were found in Fort Kochi, Chellanam, and Panagad, where $NO_2^-$and PO_4^{3-}concentrations were moderate to high and DO levels were lower. This implies that barnacles prefer nutrient-rich habitats. These factors are frequently associated with eutrophication and pollution. Another important factor was salinity; the highest barnacle population was found in Fort Kochi, which had the highest salinity, while the lowest was found in Udhayamperoor. Thus, barnacles are more prevalent in contaminated areas suggesting that they could be used as bio-indicators to track changes in water quality because they are known to react to environmental stress.

9. CONCLUSION

This study revealed a multidisciplinary approach to water quality assessment. This involved the combination of the in-situ data of the water quality parameter along with the remote sensing data awas also collected. Advanced technique like interpolation was used for parameter like DO to interpolate the values to the unknown location. The also focus on identifying barnacle as the potential biological indicator. So, the barnacle counts overlayed the interpolated map with the integration of the water quality parameters.

The study revealed three hotspots Fort Kochi, Chellanam, and Panagad. These stations displayed high nutrient concentration and Chl-a. Fort Kochi exhibited the highest barnacle abundance, which coincided with high salinity and slightly acidic conditions. The site recorded high PO_4^{3-} and NO_2^- levels, moderate Chl-a concentration suggesting that barnacle proliferation may be influenced by nutrient availability and salinity.

Chellanam has the second-highest barnacle count, the result indicates moderate salinity and a pH was slightly acidic. This station also had as moderate Chl-a concentration. The barnacle larvae depend on this phytoplankton.

The highest levels of $NO_2^-$and PO_4^{3-} were recorded in the Panagad region which indicates a serious condition of nutrient pollution. This leads a decline in the water quality and nutrient loading of the region. This is the major reason for the slightly lower barnacle count compared to Fort Kochi and Chellanam. This station also marked as highest concentration of Chl-a indicates a highly productive environment that may be fuelled by nutrient inputs. The lowest salinity suggests an estuarine influence, demonstrating the brackish water tolerance of barnacles.

In-situ sampling is not always possible and is a costly method and requires manpower but for regular monitoring, creating such frameworks and creating different models is a cost-effective system and also enables real time date. The present work reveals a framework for water quality analysis suggesting a regular monitoring in an ecologically significant ecosystem like the Vembanadu Lake of Kerala.

10. FUTURE PERSPECTIVES

This study extends beyond water quality assessment, offering insights into sustainable resource management, environmental monitoring, and conservation planning. Future approaches should integrate AI and deep learning with geospatial analysis to enable automated trend prediction and hotspot detection. Combining biological indicators, in-situ data, and satellite imagery can enhance accuracy, while platforms like NASA EOSDIS and Google Earth Engine support real-time analysis. Expanding biological indicators beyond barnacles to include microbes and macroinvertebrates, along with genetic and eDNA studies, can improve ecological understanding. Climate change impacts on Vembanad Lake's hydrology, nutrient dynamics, and salinity should be modeled to guide adaptive strategies. GIS tools help map species distribution and environmental patterns, while data centralization and visualization support faster, targeted decision-making. Linking environmental and socioeconomic data can inform better policy, and emerging technologies like IoT sensors and UAVs with hyperspectral cameras enable real-time, large-scale water quality monitoring.

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