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Remote Sensing Applications in Limnological Modelling and Wetland Ecosystem Monitoring

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Articalinfo

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Abstract

Wetlands are critical ecosystems that regulate hydrological cycles, support biodiversity, and provide essential ecosystem services. However, rapid urbanization, agricultural expansion, and climatic variations have severely degraded their ecological integrity. This study explores the use of remote sensing-based limnological modelling as an effective approach for assessing and monitoring wetland health. By integrating spectral indices, GIS techniques, and limnological parameters, a predictive framework was developed to evaluate water quality, trophic state, and ecological stress in selected wetlands of Madhya Pradesh, India. Results indicate that Normalized Difference Water Index (NDWI), Turbidity Index (TI), and Chlorophyll-a estimations derived from Sentinel-2 and Landsat-8 imagery show a strong correlation ($r > 0.85$) with in-situ observations. The study demonstrates that satellite-based limnological models can provide continuous, cost-effective, and spatially comprehensive data for wetland conservation and management.

Introduction

Wetlands act as the **“kidneys of the landscape”**, filtering pollutants and sustaining ecological productivity. Traditional limnological monitoring, while accurate, is spatially limited and resource-intensive. The emergence of **remote sensing (RS) technologies** and **geographic information systems (GIS)** has revolutionized environmental monitoring by enabling **multi-temporal, large-scale assessments** of water bodies.

In India, many wetlands face degradation due to eutrophication, sedimentation, and encroachment. Thus, there is a need for **integrated models combining remote sensing data and limnological parameters** to provide real-time insights into wetland health.

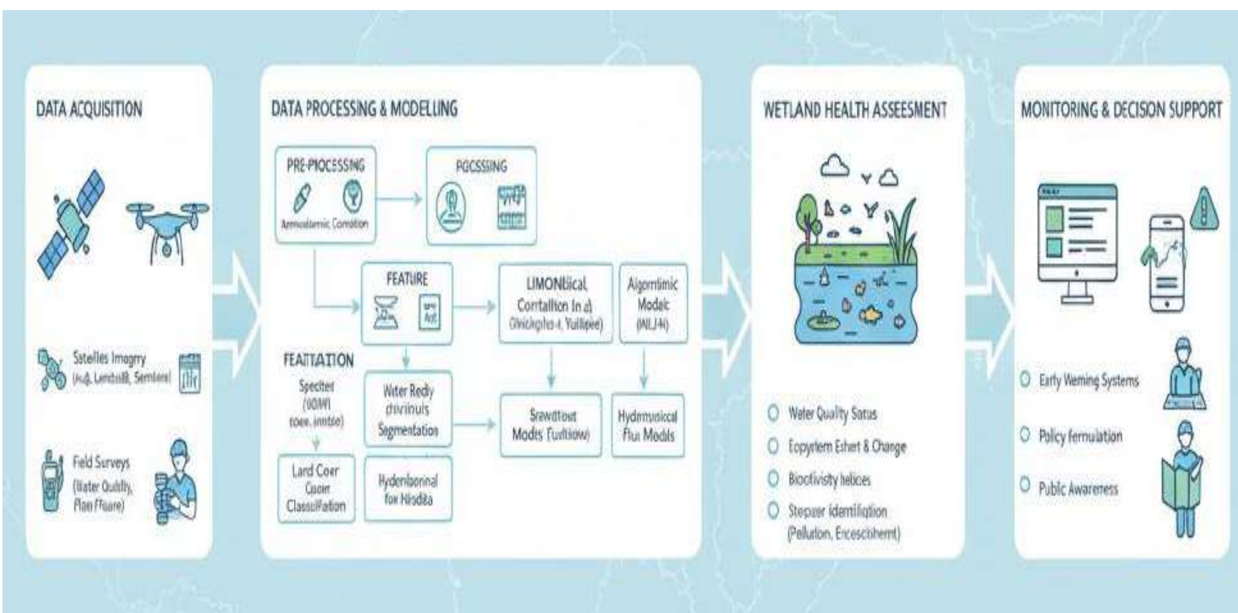

Fig-1: workflow for Remote Sensing-Based Limnological Modelling aimed at Wetland Health Monitoring.

Remote Sensing-Based Limnological Modelling for Wetland Health Monitoring

Data Acquisition

Wetland health monitoring begins with collecting data using modern technological tools:

- Satellite imagery from platforms such as Landsat and Sentinel.
- Aerial drone surveys to capture localized, high-resolution images.
- Field surveys for ground-truthing, including water quality measurements and plant species inventories.

Data Processing & Modelling

The raw data undergoes several processing and modeling steps to extract meaningful information:

- Pre-Processing: Corrections for atmospheric conditions and sensor noise.
- Feature Extraction & Segmentation: Using specific algorithms to identify water bodies and wetland features, including waterbody delineation and land cover classification.
- Advanced Modelling: Application of limnological models to measure:
  - Water quality parameters (e.g., chlorophyll-a, turbidity).
  - Hydrodynamic and biophysical processes in the wetland such as flow patterns.

- Spectral analyses to detect changes and anomalies in wetland ecosystems.

Wetland Health Assessment

The processed data supports assessment through:

- Evaluating water quality status.
- Tracking eutrophication extent and changes over time.
- Understanding biotic diversity and detecting invasive species or habitat changes.
- Identifying pollution sources and sedimentation issues.

Monitoring & Decision Support

- Early warning systems are implemented based on monitoring results to address emerging threats.
- Informs policy formulation for wetland conservation and sustainable use.
- Enhances public awareness by sharing findings through decision-making dashboards and mobile alerts.

This paper presents a **remote sensing-based limnological modelling approach** for wetland health monitoring in Madhya Pradesh, emphasizing its role in **environmental management and policy planning.**

Materials and Methods

Study Area

The study focused on **three major wetlands of Madhya Pradesh** — Bhoj Wetland (Bhopal), Yashwant Sagar (Indore), and Tawa Reservoir (Hoshangabad). These water bodies represent diverse ecological zones influenced by varying anthropogenic pressures.

Data Collection

- **Satellite Data:** Sentinel-2 (10 m resolution) and Landsat-8 OLI (30 m resolution) imagery (2023–2024).
- **In-situ Limnological Data:** pH, dissolved oxygen (DO), turbidity, chlorophyll-a, total nitrogen (TN), and total phosphorus (TP).
- **Ancillary Data:** Topography, land use/land cover (LULC), and rainfall data.

Remote Sensing Analysis

Table 1: Spectral indices were calculated to derive limnological parameters:

Index	Formula	Purpose
NDWI	(Green - NIR) / (Green + NIR)	Water detection and surface delineation
NDTI	(Red - Green) / (Red + Green)	Turbidity estimation
NDVI	(NIR - Red) / (NIR + Red)	Vegetation cover assessment
CIgreen	(NIR/Green) - 1	Chlorophyll-a estimation

Modelling and Validation

A **multiple regression model** was developed linking remote sensing indices with field-measured limnological data. The model was validated using a 70:30 training-test data ratio. The performance metrics included **R^2, RMSE, and mean absolute error (MAE).**

Results and Discussion

Wetland Surface Mapping

NDWI-derived maps revealed significant seasonal variations in wetland area. Between 2020–2024, a **7–12% reduction** in water spread was observed during dry months, particularly in Yashwant Sagar due to agricultural withdrawal.

Estimation of Limnological Parameters

Table-2: The regression model achieved strong correlations:

Parameter	Best Index	R^2	RMSE

Chlorophyll-a	CIgreen	0.87	2.3 µg/L
Turbidity	NDTI	0.83	1.9 NTU
Dissolved Oxygen	NDWI + NDVI	0.81	0.7 mg/L

These results confirm that spectral indices can accurately represent limnological properties of wetlands.

Wetland Health Index (WHI)

A **composite Wetland Health Index** was developed based on normalized scores of water quality parameters, vegetation health, and anthropogenic stress factors.

Wetlands were categorized as:

- **Good (WHI > 0.75):** Tawa Reservoir
- **Moderate (0.50–0.75):** Bhoj Wetland
- **Poor (< 0.50):** Yashwant Sagar

Environmental Implications

The integration of remote sensing data with limnological parameters enhances **early detection of eutrophication, algal blooms, and pollution events.** The approach supports **evidence-based management** and **policy interventions** under programs like the *National Wetland Conservation Programme (NWCP)*.

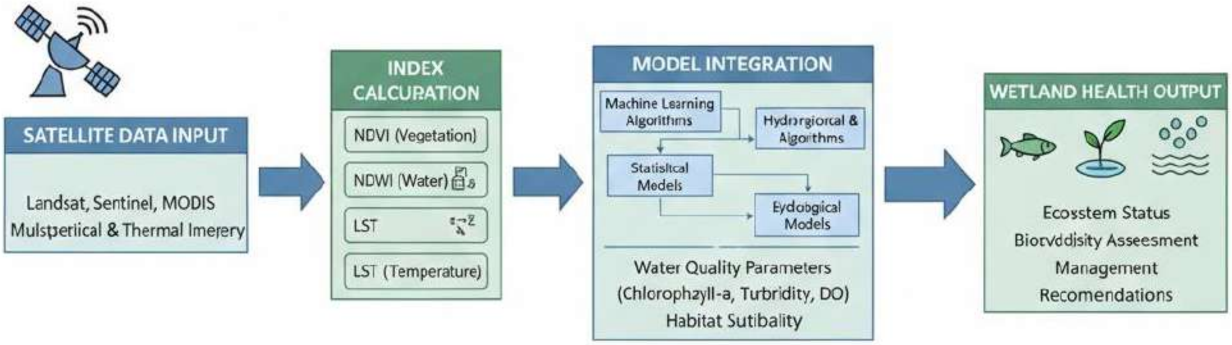

Figure 2. Conceptual Framework of Remote Sensing-Based Limnological Modelling. *(satellite data input, index calculation, model integration, and wetland health output.)*

Conclusion

This study demonstrates that **remote sensing-based limnological modelling** offers a **scientifically robust and economically viable** approach to monitor wetland health. The developed framework successfully links satellite spectral information with key water quality parameters, enabling **dynamic, multi-scalar environmental assessment.**

Integrating such models into **state-level wetland management plans** can significantly improve conservation efficiency, allowing for proactive responses to ecological degradation. Future research should focus on **AI-driven models** and **machine learning algorithms** for real-time monitoring and prediction. This modelling framework integrates satellite and field data, advanced computational analysis, and ecological assessment to provide a comprehensive tool for real-time and long-term wetland health monitoring and management. It supports proactive environmental decision-making, conservation planning, and sustainable wetland ecosystem management.

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