Monitoring Lake Crab Aquaculture with Dynamic GIS: Spatio-Temporal Analysis Between Aquaculture Extent and Water Quality in Yangcheng Lake, China

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Abstract
This study employs a robust remote sensing framework to analyze the spatio-temporal dynamics of cage aquaculture and its effects on water quality in Yangcheng Lake, China. Utilizing time-series Landsat 8 data (2013-2024), we accurately mapped the aquaculture extent by combining spectral water indices for water body delineation with spectral vegetation indices and Gray-Level Co-occurrence Matrix (GLCM)-based texture analysis. This approach achieved high mapping accuracies, with overall accuracies ranging from 95.96% to 98.74% and Kappa coefficients between 0.84 and 0.94, demonstrating the effectiveness of integrating spectral and textural information. Spatio-temporal analysis revealed a significant 40% reduction in aquaculture extent, from 30.41 km² in 2013 to 17.86 km² in 2024, directly linked to the Yangcheng Lake Action Plans. Water quality analysis using high-resolution monthly total nitrogen (TN) and total phosphorus (TP) data showed improvement from predominantly Grade IV to Grade III status, with the mean TP concentration exhibited a decrease by approximately 6.2% (from 0.0660 mg/L in 2013 to 0.0619 mg/L in 2023). Notably, a distinct lag between aquaculture reduction and water quality improvements was observed, highlighting the need for a sustained ecosystem recovery period. This research highlights the vital role of dynamic GIS for environmental monitoring and policy evaluation for fostering sustainable aquaculture and protecting lake ecosystems.

1. INTRODUCTION

Lake ecosystems are indispensable for maintaining ecological balance and supporting human water resources, which face increasing stress from anthropogenic activities (Kamaruzzaman et al., 2025). Intensive aquaculture exemplifies these pressures, contributing to water quality deterioration through nutrient enrichment (Ma et al. 2022). In China, Yangcheng Lake is nationally renowned for its high-quality aquatic products, particularly the esteemed Chinese mitten crab aquaculture. Since the 1980s, spurred by China's reform and opening-up policies, the aquaculture sector in Yangcheng Lake has undergone a gradual modernization and industrialization, evolving into a distinctive aquatic industry centered on the Chinese mitten crab.

Despite its considerable economic significance, the rapid growth of aquaculture, particularly high-density cage farming, has progressively exacerbated ecological and environmental challenges. Current assessments indicate that the water quality of Yangcheng Lake primarily falls into categories III and IV, with total phosphorus (TP) and total nitrogen (TN) frequently exceeding the national Class III standards (Luo et al., 2020; Huang et al., 2021). Historical monitoring data reveal that Yangcheng Lake has experienced extensive aquaculture operations. Among the various factors contributing to the deterioration of lake water quality, the large-scale, high-density, and unregulated nature of cage aquaculture has been identified as a significant contributor (Suresh et al., 2023).

In response to the urgent need for water environment quality improvement in Yangcheng Lake, local government successively implemented three rounds of optimization action plans for Yangcheng Lake between 2013 and 2021. This commitment was further solidified in 2023 with the “Yangcheng Lake Ecological Environment Joint Protection and Co-Governance Action Plan”. While these policy interventions have led to a noticeable reduction in cage aquaculture area, a commensurate improvement in Yangcheng Lake's water environment has not been distinctly observed. This discrepancy necessitates a more systematic assessment of how cage aquaculture impacts water quality, particularly focusing on nitrogen and phosphorus indicators, to understand the effectiveness and lag effects of these policy measures.

Traditional methods for monitoring aquaculture extent rely on laborious field measurements, which are time-consuming and resource-intensive, often failing to provide historical information on cage farming dynamics. In contrast, remote sensing technology offers a powerful and efficient alternative for long-term large-scale environmental monitoring due to its advantages (Wasehun et al., 2024; Li et al., 2024).

Recent years have witnessed advancements in extracting cage aquaculture information from remote sensing imagery, moving beyond general approaches to more refined and accurate methodologies. For instance, a contour-based regularity measurement for water segments was proposed, combined with Support Vector Machine (SVM) classification on medium resolution multispectral images to effectively distinguish aquaculture ponds from natural water bodies based on geometric features (Zeng et al., 2019). Building upon these foundational remote sensing techniques, further advancements have enhanced the precision and scale of aquaculture monitoring. A robust framework for automatic extraction of aquaculture ponds was developed by leveraging multi-source remote sensing data on the Google Earth Engine (GEE) platform, employing Multi-threshold Connected Component Segmentation and Random Forest algorithms, achieving high overall classification accuracies for extensive aquaculture mapping (Xia et al., 2020). Similarly, the GEE platform was also utilized to combine spectral and spatial features with morphological operations to achieve high accuracy in extracting aquaculture pond regions in coastal waters of Southeast China, with total accuracy of 93% and a Kappa coefficient of 0.86 (Wang et al., 2022). These sophisticated approaches underscore the increasing capability of remote sensing to accurately delineate aquaculture areas across diverse aquatic environments.

The relationship between aquaculture extent and its impact on water quality has been investigated in various aquatic environments. Studies consistently demonstrate that the scale of aquaculture operations, particularly high-density farming, can profoundly influence nutrient loads (e.g., nitrogen and phosphorus) and overall water quality parameters (Musinguzi et al., 2019). For instance, larger aquaculture areas are often associated with increased discharge of unconsumed feed and metabolic waste, leading to elevated concentrations of pollutants (Dunne et al., 2021). Assessing the relationship often involves spatio-temporal analysis of water quality indicators in conjunction with mapped aquaculture extents (Ji et al., 2019). However, the precise temporal dynamics and the lag effects between large-scale aquaculture management interventions and subsequent water quality improvements in specific lake ecosystems requiring further investigation.

The present study aims to contribute to a comprehensive understanding between policy-driven aquaculture reduction and water quality improvement in Yangcheng Lake, especially the temporal lag effects between aquaculture reduction and water quality improvement. We employ a robust remote sensing framework using time-series Landsat 8 imagery (2013-2024) to precisely map Yangcheng Lake's cage aquaculture evolution. Subsequently, we analyze the relationship between these aquaculture dynamics and water quality parameters (TN and TP) to evaluate their influence and quantify the lag effects of policy measures. This research advances spatio-temporal monitoring in Yangcheng Lake, providing a crucial scientific basis for sustainable aquaculture practices, effective policy evaluation, and long-term lake ecosystem protection.

2. MATERIALS AND METHODS

2.1 Study Area and Data

This study investigated the spatio-temporal dynamics of cage aquaculture in Yangcheng Lake, a 117 km² freshwater lake located in Jiangsu Province, China, renowned for its Chinese mitten crab aquaculture. To conduct this analysis, we employed a robust remote sensing approach integrated within a dynamic GIS framework. Landsat 8 Operational Land Imager (OLI) surface reflectance data was obtained from the Google Earth Engine (GEE) platform, spanning the period from 2013 to 2024. Landsat 8 carries two sensors: the OLI and the Thermal Infrared Sensor (TIRS). Landsat 8 maintains spectral and spatial consistency with previous Landsat missions (Landsat 1-7), offering a panchromatic band (Band 8) at 15 meters resolution, multispectral bands (Bands 1-7, 9) at 30 meters, and thermal infrared bands (Bands 10-11) at 100 meters. A total of 12 images were selected from the GEE (Figure 1), with the annual selection timeframe aligned with the Landsat 8 data availability and the implementation periods of the Yangcheng Lake optimization action policies by local government. To minimize seasonal variations and cloud cover, one high-quality scene per year was carefully chosen, typically between June and August for each year.

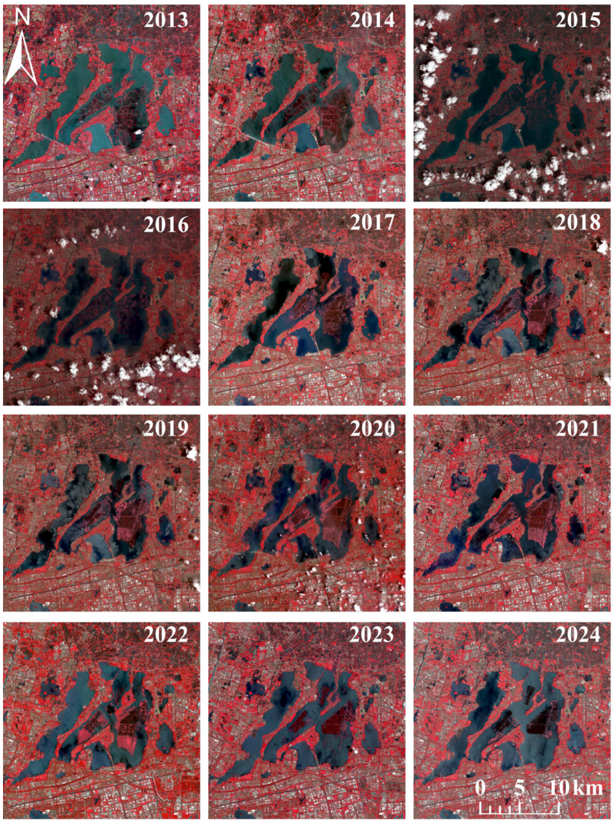

Figure 1. Time-series remote sensing images in the study area.

Monthly TN and TP water quality parameters for Yangcheng Lake covering the period from 2013 to 2023 were extracted from a validated high-resolution lake water quality dataset (Luan et al., 2025). This comprehensive dataset was constructed using a Random Forest model integrating multi-source driving factors such as climate, soil properties, and human activities. Its reliability was verified against actual measured data from 217 monitoring stations across China provided by the China National Environmental Monitoring Center (CNEMC). The dataset offers monthly, individual lake-scale spatio-temporal resolution, aligning perfectly with the three rounds of ecological governance policies implemented in Suzhou City during the study period. This dataset is publicly accessible via the Figshare platform (https://doi.org/10.6084/m9.figshare.27626286.v2).

2.2 Aquaculture Area Extraction Methodology

Figure 2 illustrates the workflow for extracting aquaculture areas from Landsat 8 time-series imagery in Yangcheng Lake. The initial step involved delineating the lake's water surface extent using remote sensing water indices, recognized as the rapid and effective water body extraction method. Commonly used indices include NDWI (McFeeters, 1996), MNDWI (Xu, 2006), and WI (Ji et al., 2015). These methods effectively distinguish water from non-water regions leveraging water's higher visible light reflectance compared to near-infrared and shortwave-infrared bands. Following a thorough evaluation of their characteristics and applicability within the complex land-cover environment of Yangcheng Lake, the optimal water index was selected to ensure the accuracy and reliability of the initial water body extraction.

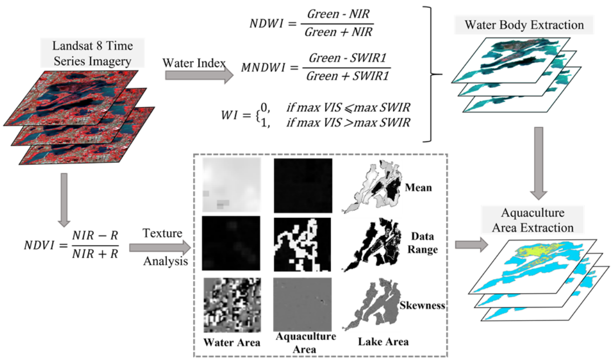

Figure 2. Workflow for aquaculture area extraction.

Subsequent to water body delineation, aquaculture areas within these defined boundaries were extracted by leveraging their distinct vegetation spectral characteristics and unique textural features associated with cage structures. As illustrated in Figure 3, aquaculture areas typically appear reddish in false-color composite images, indicating higher near-infrared reflectance. This spectral signature is primarily attributed to the cultivation of abundant floating herbaceous plants, which are strategically grown within the cages as essential components for crab growth. These submerged or emergent macrophytes are crucial for providing shelter and food for the crabs, and significantly alter the spectral response of the water surface. For capturing these vegetation characteristics, the Normalized Difference Vegetation Index (NDVI) was specifically employed, making it particularly effective for detecting aquaculture areas.

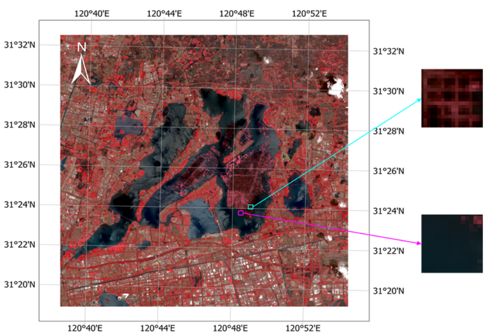

Figure 3. Visual comparison between aquaculture areas and natural water bodies.

Furthermore, aquaculture areas exhibit distinct regular spatial patterns from cage structures, differing significantly from the spatially uniform patterns of natural water bodies. For texture analysis, the mean derived from the Gray-Level Co-occurrence Matrix (GLCM) (Ohanian and Dubes, 1992) was selected as the optimal texture feature, demonstrating the smallest intra-class variance for aquaculture areas and maximum separability from water bodies. GLCM computation employed a 3x3 window with a 1x1 offset and 32 gray levels.

Finally, the extracted aquaculture areas were validated against manually interpreted data. The accuracy assessment utilized a confusion matrix method, involving the calculation of several key metrics including True Positive, False Negative, False Positive, and True Negative. Based on these values, Producer's Accuracy (PA), User's Accuracy (UA), Overall Accuracy (OA), and the Kappa Coefficient were computed to quantify the accuracy and reliability of the extraction results.

3. RESULTS AND DISCUSSION

3.1 Aquaculture Extraction Accuracy

The GLCM mean was identified as the optimal texture feature for aquaculture area extraction due to its minimal intra-class variance for aquaculture regions and maximal separability from water bodies. Table 1 presents the accuracy assessment results for aquaculture area extraction using the proposed workflow for the years 2022-2024, using manually interpreted data as the reference.

Year	PA	PA	OA	Kappa
2022	86.18%	97.61%	95.96%	0.84
2023	96.93%	97.36%	98.74%	0.94
2024	89.64%	98.97%	97.95%	0.89

Table 1. Aquaculture Area Extraction Accuracy.

The results demonstrate high accuracy across these three years. The value of PA ranged from 86.18% to 96.93%, UA from 97.36% to 98.97%, OA from 95.96% to 98.74%, and Kappa coefficients from 0.84 to 0.94. Notably, the highest accuracy was achieved in 2023, with an OA of 98.74% and a Kappa coefficient of 0.94. While accuracies for 2022 and 2024 were slightly lower, their overall accuracies consistently remained above 95%. The validation results demonstrate the stability and reliability of the integrated spectral and textural feature-based extraction method for effectively delineating aquaculture areas within Yangcheng Lake.

3.2 Spatio-Temporal Aquaculture Extent Dynamics

The aquaculture area extraction workflow was then applied to time-series Landsat 8 imagery spanning 2013 to 2024. This enabled a comprehensive spatio-temporal analysis of Yangcheng Lake, focusing on its total water area, the Chinese mitten crab aquaculture area, and the proportion of aquaculture within the water body. Table 2 summarizes these statistical results.

Year	Water Area (km^2)	Aquaculture Area (km^2)	Aquaculture Proportion (%)
2013	111.15	30.41	27.36%
2014	112.72	23.40	20.76%
2015	109.49	23.36	21.33%
2016	112.32	20.19	17.97%
2017	110.58	28.10	25.41%
2018	111.97	27.77	24.80%
2019	111.15	25.84	23.25%
2020	106.39	20.24	19.03%
2021	109.10	29.02	26.60%
2022	106.99	23.97	22.40%
2023	109.41	23.92	21.86%
2024	108.86	17.86	16.40%

Table 2. Water Area and Aquaculture Extent.

As shown in Figure 4, the overall water area of Yangcheng Lake remained relatively stable between 2013 and 2024, exhibiting only minor fluctuations. The water area was approximately 111.15 km^2 in 2013 and 108.86 km^2 in 2024, demonstrating overall stability despite efforts like the 2013 Suzhou government's project to clear 29 “dead-end” waterways and promote ecological restoration.

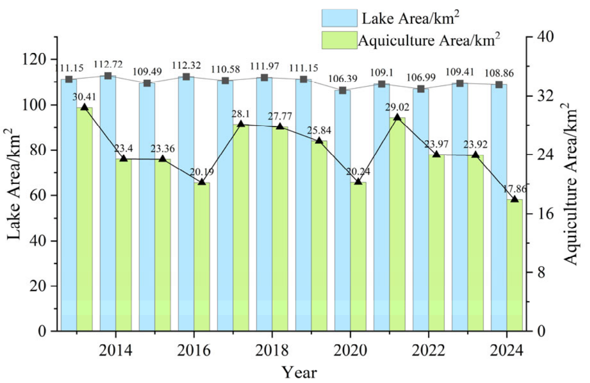

Figure 4. Changes in water surface area and aquaculture extent in Yangcheng Lake (2013-2024).

In contrast, the Chinese mitten crab aquaculture area exhibited more significant and directly policy-driven fluctuations. From 2013 to 2016, the aquaculture area decreased substantially from 30.41 km^2 to 20.19 km^2 driven by government policies aimed at protecting water sources, a reduction exceeding 30% with its proportion of the total water area falling from 27.36% to 17.97%. As depicted in Figure 5, primary removal efforts during this phase concentrated on the eastern and southern parts of Yangcheng Lake's East Lake, with the southeastern region showing the most pronounced contraction.

Following standardized aquaculture reforms initiated by local government in 2017, the aquaculture area temporarily rebounded to 28.10 km^2 in 2017, with its proportion increasing to 25.41%. However, it subsequently decreased annually from 2017 to 2020, reaching 20.24 km^2 by 2020, a one-fifth reduction over three years. In 2021, the aquaculture area again rebounded to 29.02 km^2, accounting for 26.60% of the total water area, before consistently decreasing over the subsequent three years, reaching the lowest value of 17.86 km^2 by 2024, with a proportion of only 16.40%. This represents a cumulative contraction exceeding 30% in the last five years, with southern cage areas experiencing the most significant reduction, shrinking by almost half.

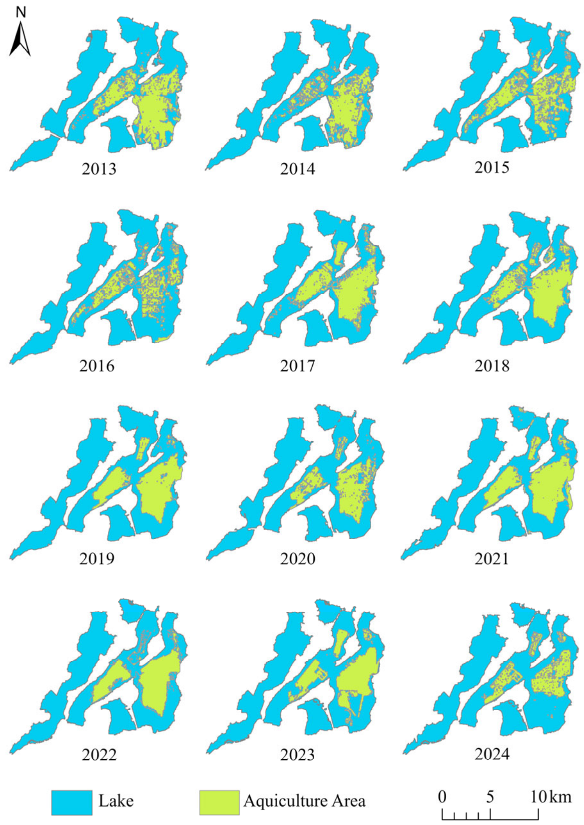

Figure 5. Distribution map of the Yangcheng Lake region and aquaculture area (2013-2024).

Overall, while the total water area in Yangcheng Lake remained stable, the Chinese mitten crab aquaculture area exhibited a clear policy-driven fluctuating decline from 2013 to 2024. Under government ecological protection policies, the aquaculture area underwent a process of "rapid reduction - temporary rebound - continuous decline," with a cumulative reduction of 40% and its proportion decreasing from 27.36% to 16.40%. Spatially, the most significant removals of aquaculture occurred in the southeastern and southern parts of East Lake. These changes reflect the effectiveness of local government efforts in water source protection and ecological restoration, as well as the adaptive adjustments of the Chinese mitten crab aquaculture industry in response to ecological constraints and policy shifts.

3.3 Spatio-Temporal Characteristics between Aquaculture Extent and Water Qualities

Figure 6 illustrates the mean annual concentrations of TP and TN in Yangcheng Lake from 2013 to 2023. Overall, the mean annual TP concentration showed a gradual decreasing trend, with a reduction from 0.0660 mg/L in 2013 to 0.0619 mg/L in 2023, representing an approximate 6.2%. Although a notable fluctuation occurred in 2015, with a peak of 0.0747 mg/L, it gradually declined and maintained relatively stable values between 0.0695 and 0.0713 mg/L from 2016 to 2021. A further slight decrease was observed in 2022-2023, indicating the progressive effectiveness of TP control measures in recent years.

The mean annual TN concentrations exhibited more pronounced fluctuations between 2013 and 2023. TN concentration was 1.6264 mg/L in 2013, significantly increasing to a peak of 1.8123 mg/L in 2016 (Figure 6). Subsequently, TN concentrations declined and remained relatively low in 2020-2021. In 2022, TN rebounded to 1.7727 mg/L before a slight decrease in 2023. Overall, TN concentrations fluctuated without a clear increasing or decreasing trend, suggesting more complex and diverse sources influencing nitrogen dynamics.

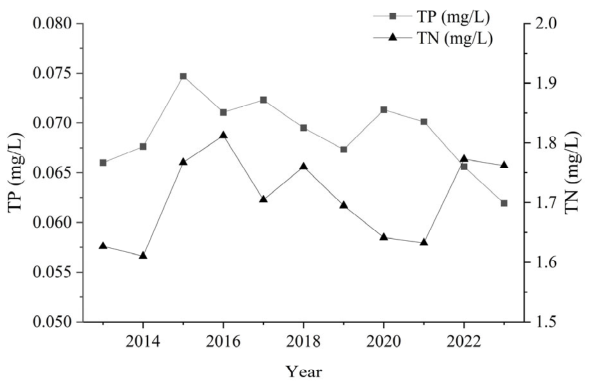

Figure 6. Trends in TP and TN concentrations in Yangcheng Lake (2013-2023).

The concentrations of TP and TN are critical indicators of lake water quality and eutrophication status, and their temporal variations are closely linked to aquaculture activities, particularly the fluctuations in aquaculture area. While the relationship is not a simple linear correlation, the scale and management practices of aquaculture significantly influence Yangcheng Lake's water quality environment. For TP, the overall decreasing trend aligns with the general reduction in aquaculture area. However, fluctuations suggest potential short-term or localized impacts from aquaculture. For instance, a notable increase in TP concentration to 0.0713 mg/L in 2020 followed an increase in aquaculture area in the preceding year. This suggests that unutilized feed residues and excretions rich in phosphorus may have a delayed entry effect, leading to cumulative increases in TP concentrations from earlier high-intensity aquaculture. This highlights the ongoing and complex nature of aquaculture pollution control. For TN, its greater annual variability implies more complex and diverse sources, yet aquaculture activities undeniably contribute significantly to the lake's nitrogen load. Animal excretions and uneaten feed that rich in nitrogenous compounds can significantly increase the lake's nitrogen load if not effectively managed. The peak TN concentration of 1.8123 mg/L in 2016 coincided with relatively high aquaculture areas from 2013-2015, suggesting a cumulative effect of prolonged high-intensity aquaculture. Overall, a dynamic and interactive relationship exists between TP and TN concentrations and the aquaculture area in Yangcheng Lake.

The fluctuations observed in aquaculture area are a reflection of both the industry's scale and the direct influence of local government policies, alongside advancements in aquaculture technology aimed at ecological protection. This dynamic interplay suggests that improving lake water quality goes beyond mere aquaculture area reduction. By implementing stricter environmental regulations, promoting ecological aquaculture models, optimizing structures, and enhancing wastewater treatment, pollutant discharge can be effectively decreased, leading to overall improvements in lake water quality.

4. CONCLUSION

This study provides a comprehensive spatio-temporal analysis of aquaculture dynamics in Yangcheng Lake using Landsat 8 time-series data alongside corresponding water quality data. The remote sensing framework integrating spectral and textural features demonstrated high accuracy and reliability in precisely delineating aquaculture zones. Our spatio-temporal analysis revealed a significant policy-driven reduction in aquaculture extent within Yangcheng Lake from 2013 to 2024, notably a cumulative 40% decrease in aquaculture area and a distinct shift in spatial distribution. This underscores the direct impact of the implemented Yangcheng Lake Action Plans and reflects efforts of local government towards water source protection and ecological restoration.

Despite the marked reduction in aquaculture area, the observed water quality improvements particularly concerning TP and TN concentrations exhibit a notable lag effect. While TP showed an overall gradual decrease, TN concentrations demonstrated more complex fluctuations, indicating diverse contributing sources. The dynamic relationship between aquaculture extent and water quality parameters highlights that while policy interventions have successfully reduced the area of aquaculture, the ecosystem's recovery is a slower process, potentially influenced by cumulative pollution from past high-intensity farming and other contributing factors. This crucial finding reinforces the need for sustained and adaptive management strategies to achieve ecological restoration.

This research underscores the vital importance of integrating dynamic geospatial techniques and long-term remote sensing data for effective environmental monitoring and policy evaluation in freshwater lake ecosystems impacted by aquaculture. The insights gained regarding the effectiveness and limitations of policy-driven aquaculture management provide a robust scientific basis for developing targeted and sustainable aquaculture practices. Future efforts should focus on not only regulating aquaculture scale but also promoting advanced ecological models and enhancing wastewater treatment to accelerate the restoration of water quality and ensure the long-term ecological health and resilience of lake ecosystems like Yangcheng Lake.

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