

Integrating Land Use Changes, Biomass Dynamics, and Water Quality for Wetland Restoration: A Case Study of Chaohu Lake Shibalianwei Wetland, China

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Abstract

Wetlands are essential ecosystems that provide critical environmental services, including nutrient retention, water purification, biodiversity conservation, and climate regulation. However, anthropogenic activities such as urban expansion, agricultural runoff, and industrial pollution have severely degraded these ecosystems, necessitating targeted restoration efforts. This study assesses the effectiveness of restoration interventions in the Shibalianwei Wetland, a key component of the Chaohu Lake basin, by analyzing land use changes, biomass recovery, and water quality improvements. Restoration strategies included vegetation re-establishment, hydrological modifications, and adaptive seasonal management over multiple years. Key findings indicate substantial improvements in water quality, with Total Nitrogen (TN) and Total Phosphorus (TP) concentrations in the wetland outflow reduced by up to 52% and 50%, respectively, during peak vegetation productivity. Dissolved Oxygen (DO) levels consistently remained above 6.2 mg/L, while Chemical Oxygen Demand (COD) declined by 38% during the summer months. These enhancements were strongly correlated with increased aboveground biomass (AGB), particularly in areas of restored vegetation, which peaked at 10,211 tons in 2021. However, subsequent declines in vegetation cover emphasized the challenges in sustaining long-term ecological gains due to seasonal variability and external pressures. This study highlights the importance of integrated ecological restoration strategies and positions the Shibalianwei Wetland as a significant buffer against eutrophication, contributing to the overall water quality improvement of Chaohu Lake.

The results offer a scalable framework for restoring degraded wetland ecosystems and underscore the necessity for long-term monitoring, adaptive management strategies, and policy interventions to ensure sustainable restoration outcomes. By integrating land use, biomass recovery, and water quality assessments, this research provides valuable insights for future wetland conservation initiatives worldwide.

Keywords

Wetland Restoration Assessment, Chaohu Lake, Land Use Changes, Aboveground Biomass, Water Quality

1. Introduction

In this ecosystem, wetlands are considered an important part of the ecology in terms of biodiversity conservation, water pollutant filtration, carbon sink, and some other areas including social benefits and economic entertainment (García et al., 2020; Ramachandra et al., 2024). Wetlands alleviate the impact of greenhouse gases by providing complex habitat provision to the different species, acting as a natural filtration system for climate change, and although the largest species supporting essential ecosystem services (ESSs) in millions (Zedler & Kercher, 2005). Despite their international significance, wetlands are gradually inclined by anthropogenetic activities, such as urban development, agricultural escalation, and industrial effluence (Xiong et al., 2023). Afterward the 1970s, more than 35% of the wetlands around the world have degraded, with emerging countries experiencing predominantly alarming rates of deprivation (Ramsar Convention Secretariat et al., 2018; van Dam et al., 2023). In China, rapid economic advances since the 1950s have led to the destruction of natural coastal wetlands approximately 60%, significantly affecting freshwater structures and biodiversity (Guo et al., 2022; Zhang et al., 2022). Chaohu Lake is positioned in China's major freshwater lakes and a vibrant ecological county supporting different species and providing indispensable capital to millions of inhabitants (Fang et al., 2019). Nevertheless, land use and land cover changes (LULCC) have harshly altered the county's wetlands, plummeting their dimensions to deliver perilous ESSs such as water decontamination, habitat providing, and reduction of flood risk (Chen, Chi, & Li, 2019).

Development and agrarian runoff have intensified these challenges by significantly enhancing nutrient levels in wetland ecologies, triggering toward eutrophication, algal blooms, and deterioration of water quality (Wurtsbaugh et al., 2019; Lu et al., 2020). Degraded water quality intensely influences aboveground biomass (AGB) by shifting nutrient availability, introducing contaminated substances, and agitating plant physiological processes (Rao et al., 2024). The high levels of nutrients, like nitrogen and phosphorus, frequently support the gigantism of certain species, declining biodiversity, and weakening flora structure

(Hu et al., 2024). Contaminants, including heavy metals and insecticides more constrain plant growth by instigating physiological pressure and weakening photosynthesis (Souri et al., 2019). Additionally, hypoxic environments began by deficiency of dissolved oxygen (DO) and preminent Chemical Oxygen Demand (COD) deter root oxygen uptake, restraining biomass accumulation (Suriyakaew & Jampeetong, 2021). These interrelated challenges highlight the prerequisite for potent water management to tolerate AGB and sustain wetland functionality.

Reestablishing the degraded wetlands grants a cost-effective prospect to improve ESSs and boost human well-being by enhancing water quality and nourishment security, flood protection, and climate change adaptation (Gann et al., 2019). Nevertheless, wetland restoration frequently prioritizes a small range of amenities, including water flow regulation, by expanding the ecological processes, with biodiversity protection and nutrient cycling (Hambäck et al., 2023). Although the struggles to reestablish wetlands are prevalent, providing recommendations for recovered ESSs remnants is challenging because of the dearth of globally consistent methods for evaluating restoration achievement (Ruiz-Jaen, 2005; Tomscha et al., 2021). Traditional methods emphasize species diversity, plant structure, and hydrological parameters, but they are unsuccessful in integrating dynamic relationships among LULCC, WQ, and biomass (Falk & Palmer, 2006). Recent progress in Remote Sensing (RS) and geospatial studies improved the techniques for monitoring the wetlands assessment across large spatial and temporal scales. The techniques of UAV-based systems, satellite imagery, and hyperspectral imaging systems imply accurate measurements of terrestrial coverages, plant health, and ecosystem fluctuations, accompanying traditional field-based approaches (Adão et al., 2017; Mu et al., 2022). These techniques offer a scalable strategy for assessing wetland restoration improvement while addressing the limitations of labor-intensive and resource-demanding field surveys (Dronova et al., 2021).

In the study area, previous studies have shown the different impact of the restoration projects on minimal analyses that indicates some improvements and challenges. During these studies, it showed numerous metrics of better quality between 2001-2017, remarkably greater progress as comparison to other large freshwater bodies in China (Zhang et al., 2021), the water bodies overall water quality not improved. Total nitrogen (TN) and total phosphorus (TP) were found as major contaminants, with the worst environments found in the lake's western section (Wang et al., 2023). Despite significant progresses has been seen in chemical oxygen demand (COD) and ammonium nitrogen (NH₃) levels during 2016-2020 (Xie et al., 2022), cyanobacterial blooms raised intensely in 2018, particularly in the central part and eastern zones (Min et al., 2020). In 2017, assessment, the water quality of Chaohu Lake had been degraded to level of Class IV-V under China's water quality standards. This degradation of the WQ in the region highlights the urgent need for restoration of the ecosystem (Xie et al., 2022). To improve this,

the government implemented a series of restoration projects in three phases from 2018-2022. The objective of this study is to evaluate the restoration projects undertaken for the Shibalianwei Wetland within the Chaohu Lake basin. It integrates multiple parameters to assess the restoration progress of the wetland based on the projects' objectives. The specific objectives are: 1) Investigate land use and land cover changes across pre and post restoration; 2) Evaluate the fluctuations in aboveground biomass and its impact on nutrient retention; 3) Assess water quality changes in relative to the land use and vegetation variations. By implementing an integrative technique, this study provides insights into the effectiveness of wetland restoration efforts, contributing to the growing body of research on ecosystem restoration. Additionally, the findings offer evidence-based recommendations for sustainable wetland management and conservation policies.

2. Study Area and Methodology

This study employed an integrative approach to evaluate the effectiveness of restoration efforts in the Shibalianwei Wetland within the Chaohu Lake basin. Before-after-Control-Impact (BACI) model was implemented with multiple methods mixing to extricate the effects of restoration projects from natural erraticism and external influences. The BACI model compared data from 2017-2024 (pre- and post-restoration), directing on environmental indices including land use and land cover changes (LULCC), aboveground biomass (AGB), and water quality parameters. Multi-year datasets were examined using remote sensing, field measurements, statistical modeling, and spatial analysis tools to provide a holistic assessment of wetland restoration improvement (Lu et al., 2020; Ruiz-Jaen, 2005).

2.1. Study Area

The Shibalianwei is an important wetland around Chaohu Lake located in Changlinhe Town, Feidong County mentioned in **Figure 1**. Changlinhe Town is located in the southeastern part of Feizi, on the edge of Chaohu Lake. The town borders Cuozen and Qiaoji in the northeast, and is connected with Huanglu and Zhongmiao in the southeast. Its southwest is Chaohu Lake, and its northwest faces Hefei Binhu New District across the Nanfei River. The town has 20 villages (communities), a population of 51,000, and a total area of 157 square kilometers. Changlinhe Town is 24 kilometers away from the center of Hefei, the provincial capital. Whether it is highway, high-speed rail or water transportation, it is extremely convenient. The county has experienced extreme ecological deprivation due to anthropogenic activities, including urbanization, farming, and nutrient load, which have caused eutrophication and losses of habitat (Chen, 2019). Restoration projects conducted between 2018-2022, included hydrological engineering, replantation of vegetation, and pollution control. These efforts aimed to improve biodiversity, water quality, and wetland functionality, following global best practices in ecosystem restoration (Davidson, 2014; Davidson et al., 2022).

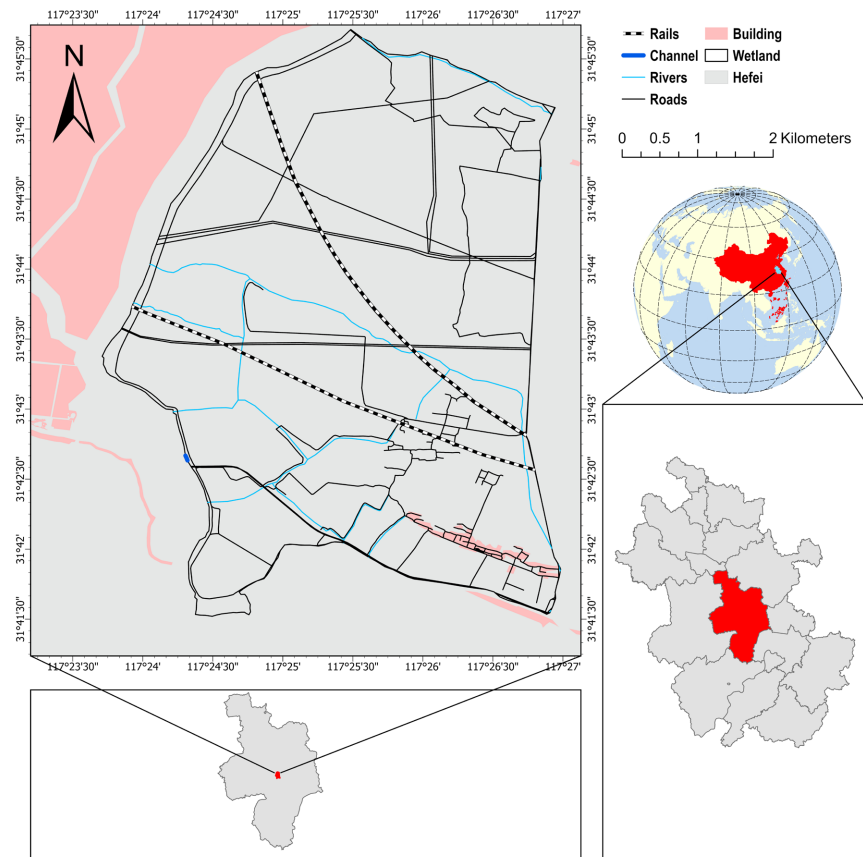


Figure 1. The study area: Geographical position of Shibalianwei Wetland within the Chaohu Lake basin (Sources: Tianditu and the National Catalogue Service for Geographic Information Resources).

2.2. Restoration Phases

Three phases of field surveys were carried out from 2018 to 2022 within the terrestrial area to provide support for classification and accuracy verification.

Phase 1 (2018): Focused on hydrological modifications, including water retention systems and initial vegetation planting. Water quality monitoring systems were also established during this phase.

Phase 2 (2019-2020): Introduced inlet and outlet systems to improve water circulation, increase biodiversity through native species planting, and strengthen water purification capabilities.

Phase 3 (2021-2022): Addressed pollution control, ecosystem restoration, public education, and landscape improvements, ensuring long-term ecological functionality.

2.3. Data Collection

The data were collected from several sources straddling a period from 2017-2024. These sources comprise remote sensing imagery, water quality monitoring, and climate data. The data collection process is described below.

2.3.1. Remote Sensing Data

The classification of land use and land cover change (LULCC) in the Shibalianwei Wetland was conducted using Sentinel-2 imagery accessed through the Google Earth Engine (GEE) platform. Sentinel-2, developed under the European Space Agency's Copernicus Programme, provides multispectral optical imagery with spatial resolutions of 10 m, 20 m, and 60 m, allowing detailed monitoring of wetland landscape variations.

In this study, Sentinel-2 Level-2A surface reflectance data were selected as the primary remote sensing data source. Spectral bands including Red, Green, Blue, and Near-Infrared (NIR) were used for image interpretation and vegetation index calculation. The Normalized Difference Vegetation Index (NDVI), derived from the Red and NIR bands, served as an important indicator for evaluating vegetation conditions and supporting above-ground biomass (AGB) assessment.

Initial preprocessing was conducted in GEE, including cloud and cloud-shadow masking, temporal filtering, cloud coverage screening, and cloud-free composite generation. The preprocessed imagery was subsequently exported to ArcGIS Pro for further spatial processing, LULCC classification, and accuracy assessment.

2.3.2. Water Quality Data

In the second stage of assessing restoration effectiveness, we gathered the required water quality data from the wetland's water quality monitoring stations. These stations provided consistent data on key indicators such as DO, COD, TN, and TP. The water quality samples were analyzed in certified laboratories according to standard protocols. We collected required parameters (DO, COD, TN, and TP) of the water quality according to the objective of the restoration by comparing the inflow and outflow from pre- and post-restoration and compared it with China Freshwater Standards (GB3838-2002).

2.4. Methodology

This section outlines the analytical methods employed to process the data and assess the impacts of restoration on land use/cover changes, biomass, and water quality in the Shibalianwei Wetland.

2.4.1. Land Use and Land Cover Change (LULCC) Analysis

The classification process utilized a supervised Decision Tree (DT) model within ArcGIS Pro, which was selected for its ability to handle complex spectral variations and classify land cover types with high accuracy. Training samples were identified using a combination of ground-truth data and high-resolution Google Earth imagery. The major land cover categories included cultivated areas, vegetation, barren land, built-up areas, and water bodies. Each training sample was manually digitized using ArcGIS Pro's Training Sample Manager to enhance classification precision. Following the training phase, the Decision Tree model was applied using NDVI, NIR reflectance, and additional spectral indices as classification parameters. The model systematically segmented the data based on spectral reflectance properties,

ensuring reliable classification of different land cover types. To evaluate classification performance, a confusion matrix was generated, yielding an overall accuracy of 91% and a Kappa coefficient of 0.88, indicating a high level of agreement between the classification results and actual land cover distributions. Post-classification refinements, including majority filtering, were employed to minimize classification errors and enhance spatial coherence. Additionally, independent validation points were utilized to further assess classification reliability. The application of Decision Tree classification provided valuable insights into LULCC dynamics and vegetation recovery following restoration efforts. The results illustrated how vegetation regrowth contributed to biomass recovery and improvements in water quality, reinforcing the effectiveness of remote sensing and machine learning techniques in wetland monitoring. This method proved instrumental in facilitating detailed ecological assessments, supporting evidence-based conservation strategies, and guiding long-term sustainable wetland management efforts.

2.4.2. Aboveground Biomass (AGB) Estimation

After classification of LULCC next step was to estimate the fluctuation in the vegetation bodies in the term of AGB, and it was processed by NDVI derived from the Sentinel-2 imagery. NDVI is a reliable indicator of vegetation health and density. It was calculated using the following formula:

$$\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}} \quad (1)$$

where NIR refers to the Near-Infrared band and Red refers to the red band from the Sentinel-2 imagery. We assessed the changes in AGB over time, using NDVI-based biomass estimates from 2017, 2019, 2021 and 2024. Temporal trends in AGB were analyzed to evaluate the effectiveness of restoration efforts in promoting vegetation recovery.

2.4.3. Water Quality Analysis

The data were collected by the concern monitoring department, and we started to analyze it by observing the impacts of restoration on key water quality parameters such as DO, COD, TN, and TP. We applied Descriptive Statistics to summarize the water quality data. T-tests were performed to test for significant differences in water quality parameters between pre-restoration (2017) and post-restoration (2024) periods. Water quality results were compared against China's Class III water quality standards for surface waters to determine whether restoration efforts brought the wetland closer to meeting the national water quality benchmarks.

2.4.4. Data Integration and Visualization

For effective visualization and integration of the results, we used ArcGIS Pro for spatial analysis. Time-series plots were created to show changes in biomass and water quality over time. Additionally, scatter plots and Heatmap were used to explore the relationships between biomass recovery and improvements in water quality.

2.4.5. Statistical Correlation Analysis

The correlation analysis between LULCC, AGB, and Water Quality was conducted through a systematic approach to quantify the relationships and understand the impacts of restoration efforts in the Shibalianwei Wetland. To evaluate the correlation between LULCC and AGB, high-resolution satellite imagery from 2017 to 2024 was processed using supervised classification techniques, as recommended for land cover monitoring in wetland restoration studies (Foody, 2002; Guo et al., 2011). Vegetation cover, barren land, and built-up areas were extracted and quantified. Simultaneously, AGB was estimated using vegetation indices such as NDVI and EVI derived from Sentinel-2 imagery, which have proven effective in estimating biomass across diverse ecosystems (Xie et al., 2022). The AGB estimations were validated with field-collected biomass data using allometric equations tailored to local vegetation types (Xie et al., 2022). Spatial overlays of vegetation cover and AGB maps were created to identify patterns of biomass recovery, and a Pearson correlation coefficient was calculated to measure the relationship between vegetation cover percentage and AGB. Linear regression models further quantified this relationship, using vegetation cover as the independent variable to predict AGB. Scatter plots with regression lines were generated to visualize these correlations, highlighting regions with significant vegetation regrowth and corresponding biomass recovery (Lee & Chow, 2015).

The relationship between AGB and water quality was analyzed by integrating biomass data with water quality parameters, including DO, TN, TP and COD. AGB data for 2018 and 2024 were aggregated to seasonal and annual scales to align with water quality datasets collected from wetland inlet and outlet locations. Pearson correlation coefficients were calculated to determine the association between AGB and the retention of nutrients (TN, TP) and reduction of organic pollutants (COD). Multiple regression models were applied to quantify the contribution of AGB to water quality improvements, with AGB as the independent variable and water quality changes as the dependent variable. Reduction efficiencies for TN, TP, and COD were calculated to assess nutrient retention capabilities, using the formula:

$$\text{Reduction Efficiency (\%)} = \frac{\text{Inlet Value} - \text{Outlet Value}}{\text{Inlet Value}} \times (100) \quad (2)$$

Scatter plots and line charts were used to depict these relationships, demonstrating how biomass recovery mitigated nutrient enrichment and reduced pollutant loads (García et al., 2020; Zhang et al., 2021).

To understand the impact of LULCC on water quality, spatial overlays were created to examine the interplay between land use changes and water quality indicators. LULCC maps were overlaid with TN, TP, and COD hotspot maps to identify areas where land use changes, such as urbanization and vegetation loss, influenced nutrient and pollutant levels. Correlation coefficients were calculated to quantify the relationships between land use categories (e.g., percentages of barren land or built-up areas) and water quality parameters. Regression models were employed to predict water quality changes based on land use dynamics, with land

use change percentages as independent variables. The spatial analysis revealed zones where anthropogenic pressures, such as urban runoff, contributed to elevated nutrient levels and organic pollution (Liu et al., 2016).

Finally, the results from all three correlations were integrated using multivariate analysis techniques. Principal Component Analysis (PCA) was conducted to identify the primary drivers of water quality improvements by combining LULCC, AGB, and water quality data. The regression coefficients, R^2 values, and visual overlays collectively highlighted the interconnectedness of these factors. This comprehensive approach underscored the significance of managing land use and biomass recovery to achieve sustainable water quality improvements in wetland ecosystems (Falk & Palmer, 2006).

3. Results

This section presents the outcomes of the analysis on the LULCC, AGB dynamics, and water quality improvements in the Shibalianwei Wetland between 2017 and 2024. The findings are based on multi-year data collected through remote sensing, field measurements, and water quality assessments. The temporal shifts in land cover, biomass fluctuations, and water quality parameters provide valuable insights into the effectiveness of the restoration efforts implemented in the wetland. These results underscore the complex relationships between land use changes, biomass recovery, and water quality, revealing both the successes and challenges encountered throughout the restoration process. Detailed trends and correlations are presented to highlight the dynamic interplay between ecological restoration measures and their impact on the wetland's ecological health and functionality.

3.1. Land Use and Land Cover Changes (LULCC)

This study analyzed the temporal dynamics of land use and land cover from 2017 to 2024, assessing area study area prior to restoration and following the completion of the third phase of restoration initiatives. The observed landscape pattern elucidates the restoration efforts and their impact on the effectiveness of the restoration project. The analysis of the current state of the targeted area enabled examination of the restoration efficiency and its rate of success. 2024, assessing area study area prior to restoration and following the completion of the third phase of restoration initiatives.

The observed landscape pattern elucidates the restoration efforts and their impact on the effectiveness of the restoration project. The analysis of **Figure 2**, the current state of the targeted area enabled examination of the restoration efficiency and its rate of success.

3.2. Land Use Dynamics and Wetland Restoration

The wetland's ecological functionality was significantly impacted by land use changes, reflecting the complex interplay of restoration efforts, human intervention, and natural processes. Vegetation cover expanded from 14.3 hectares in 2017 to

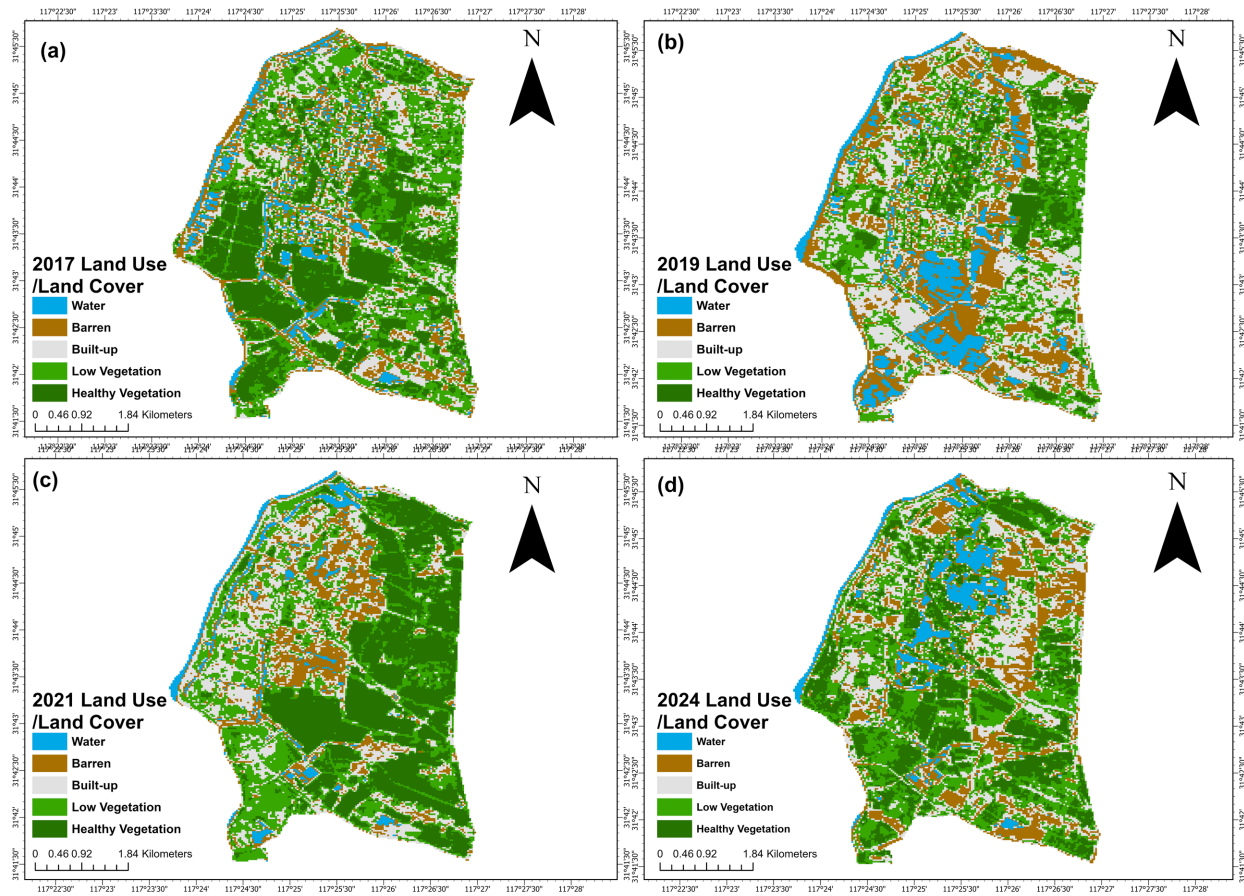


Figure 2. Land classification of Shibalianwei wetland during pre-post restoration. a) 2017, b) 2019, c) 2021 and d) 2024 (Sources: Data processing based on Sentinel-2 from Google Earth Engine).

17.5 hectares in 2019 due to restoration measures, as shown in **Figure 2**, but then declined to 15.1 hectares by 2024, driven by the encroachment of barren land and build-up areas. This loss diminished the wetland's capacity for nutrient retention and ecological balance. Barren land initially reduced from 3.9 hectares in 2017 to 2.5 hectares in 2021 through stabilization efforts, subsequently expanded to 5.2 hectares by 2024 exacerbating soil erosion and nutrient runoff. Similarly, build-up areas decreased from 2.3 hectares in 2017 to 1.8 hectares in 2019 but then grew to 1.9 hectares by 2024 due to urban pressures, complicating conservation goals. Water bodies increased from 3.2 hectares in 2017 to 5.3 hectares in 2021, aided by hydrological intervention, but declined to 3.8 hectares by 2024, likely due to sedimentation and seasonal variations. Cultivated land decreased consistently from 3.6 in 2017 to 1.2 hectares in 2024, reflecting urban expansion and land degradation.

3.3. Visualization of LULCC Trends

The analysis of land use and land cover changes in the Shibalianwei Wetland from 2017 to 2024, as depicted in **Figure 3**, reveals significant spatial and temporal dynamics influenced by restoration efforts and anthropogenic influences.

This trend offers critical insights into the interrelationships between various land use categories and their ecological implication. Initial increases in vegetation coverage, from 14.3 hectares in 2017 to 17.5 hectares in 2019, reflect the early successes of restoration initiatives such as reforestation. However, this positive trend was subsequently reversed, with vegetation cover declining to 15.1 hectares by 2024, due to the encroachment of barren land build-up areas, particularly in the northern and central regions of the wetland. This decline in vegetation cover was inversely correlated with the expansion of barren land, which decreases from 3.9 hectares in 2017 to 2.5 hectares in 2021 before increasing significantly to 5.2 hectares in 2024, likely driven by insufficient vegetation restoration and increased soil erosion. Similarly, the build-up areas within the wetland fluctuated over time, initially decreasing from 2.3 hectares in 2017 to 1.8 hectares in 2019. Possibly due to land management intervention, but subsequently rising again to 1.9 hectares in 2024, reflecting the persistent pressure of urban development.

These pressures exacerbated the obstacles associated with vegetation loss and water bodies retention, demonstrating the cascading impacts of urban expansion on the wetland ecosystem. Water bodies reached a peak of 5.3 hectares in 2021, supported by hydrological intervention, before declining to 3.8 hectares in 2024 due to sedimentation and rainfall variability. Cultivated land steadily decreased throughout the period, from 3.6 hectares in 2017 to 1.2 hectares in 2024, signifying a shift away from agricultural use toward urbanization and degraded landscapes. These visualizations provide a comprehensive understanding of the LULCC dynamics in the Shibalianwei Wetland.

The results showcase both the accomplishments of the initial restoration initiatives and the ongoing difficulties in maintaining long-term ecological improvement in the face of persistent human-induced pressures. By analyzing the interconnected patterns across the various land use categories, including vegetation,

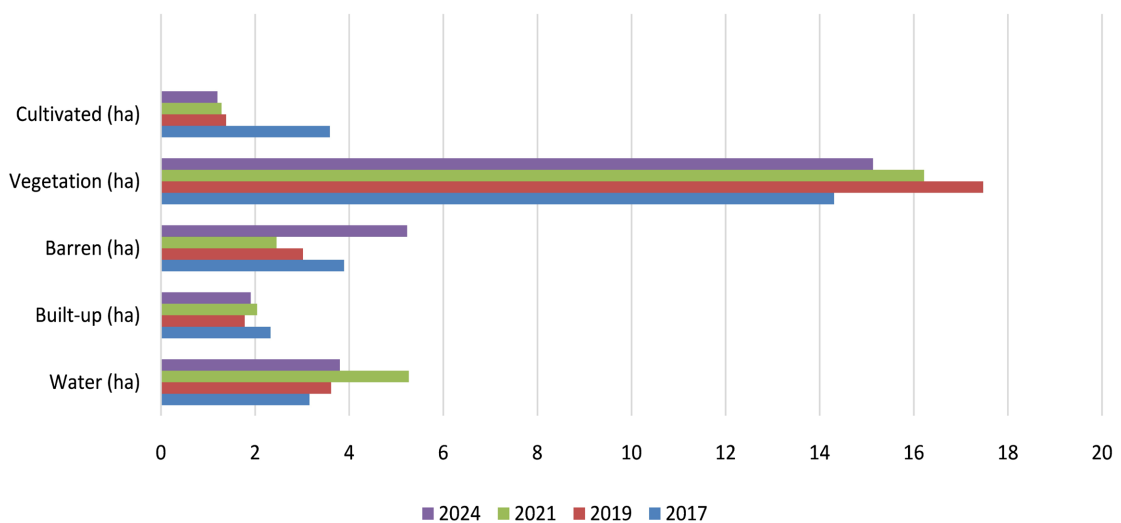


Figure 3. Land use and land cover changes (LULCC) in the Shibalianwei Wetland from 2017 to 2024.

barren land, build-up areas, water bodies, and cultivated land, this study underscores the critical necessity of implementing adaptive management strategies that can address the evolving dynamics of land use to ensure the wetlands ecological functionality.

In contrast, the data revealed a significant expansion of barren land, which increased by 33% over the study period. This pronounced increase after 2021 was likely attributed to soil degradation and insufficient vegetation recovery in certain areas of the wetland. The expansion of barren land underscores the need for targeted soil stabilization and reforestation strategies to mitigate further degradation. Regarding build-up areas, the analysis showed fluctuations, with an initial decline from 2.3 hectares in 2017 to 1.8 hectares in 2019, suggesting temporary successes in limiting urban development. However, by 2024, built-up areas stabilized at 1.9 hectares, reflecting the persistent challenges of urban encroachment despite management efforts. The water bodies within the study area exhibited significant variability in their spatial extent, reaching a peak of 5.3 hectares in 2021 before declining by 28% to 3.5 hectares by 2024. The initial increase was likely facilitated by hydrological improvements, including enhanced water retention and circulation. However, sedimentation reduction in water bodies size may be attributed to sedimentation processes and seasonal fluctuations, necessitating further hydrological management strategies to sustain stable water levels. Lastly, the cultivated land area showed a consistent decline of 66% between 2017 and 2024. This decrease in cultivated land was caused by the conversion of agricultural areas into barren land or other land cover types, driven by urbanization and soil degradation. While this trend reduced agriculture runoff, it highlights the need for sustainable land management to balance ecological restoration and socioeconomic considerations.

3.4. Aboveground Biomass Dynamics

The analysis of AGB from 2017 to 2024 unveiled substantial fluctuations across vegetation types, reflection the combined effects of restoration initiatives and land use alterations depicted in **Figure 4** as accordingly a) 2017, b) 2019, c) 2021 and d) 2024 Changes in vegetated and non-vegetated areas in 2017, 2019, 2021 and 2024.

These trends offer valuable insights into the wetland's productivity, resilience, and ecological functioning. The analysis of AGB across diverse vegetation types underscore the dynamic changes driven by restoration efforts and environmental factors. The water vegetation biomass experienced that showed during AGB trend analysis in **Figure 5** shows a substantial increase from 1688 tons in 2017 to 3,227 tons in 2019, indicating successful early restoration efforts to recover aquatic biomass. However, this trend was interrupted by a sharp decline to 1338 tons in 2021, which was likely caused by hydrological disruptions or nutrient loading. This drop was followed by a modest recovery, reaching 1968 tons in 2024. Similarly, the land vegetation biomass nearly doubled, rising from 4088 tons in 2017 to 7616 tons in 2019, driven by reforestation initiatives. Nevertheless, land vegetation biomass declined to 5199 tons in 2024, suggesting ongoing strain from land use changes. In

contrast, shrub biomass demonstrated resilience, rising from 6521 tons in 2017 to 9366 tons in 2019, before dropping to 6612 tons in 2021 and then recovering slightly to 7250 tons in 2024, reflecting their adaptability and stabilizing role in the degraded wetland environment.

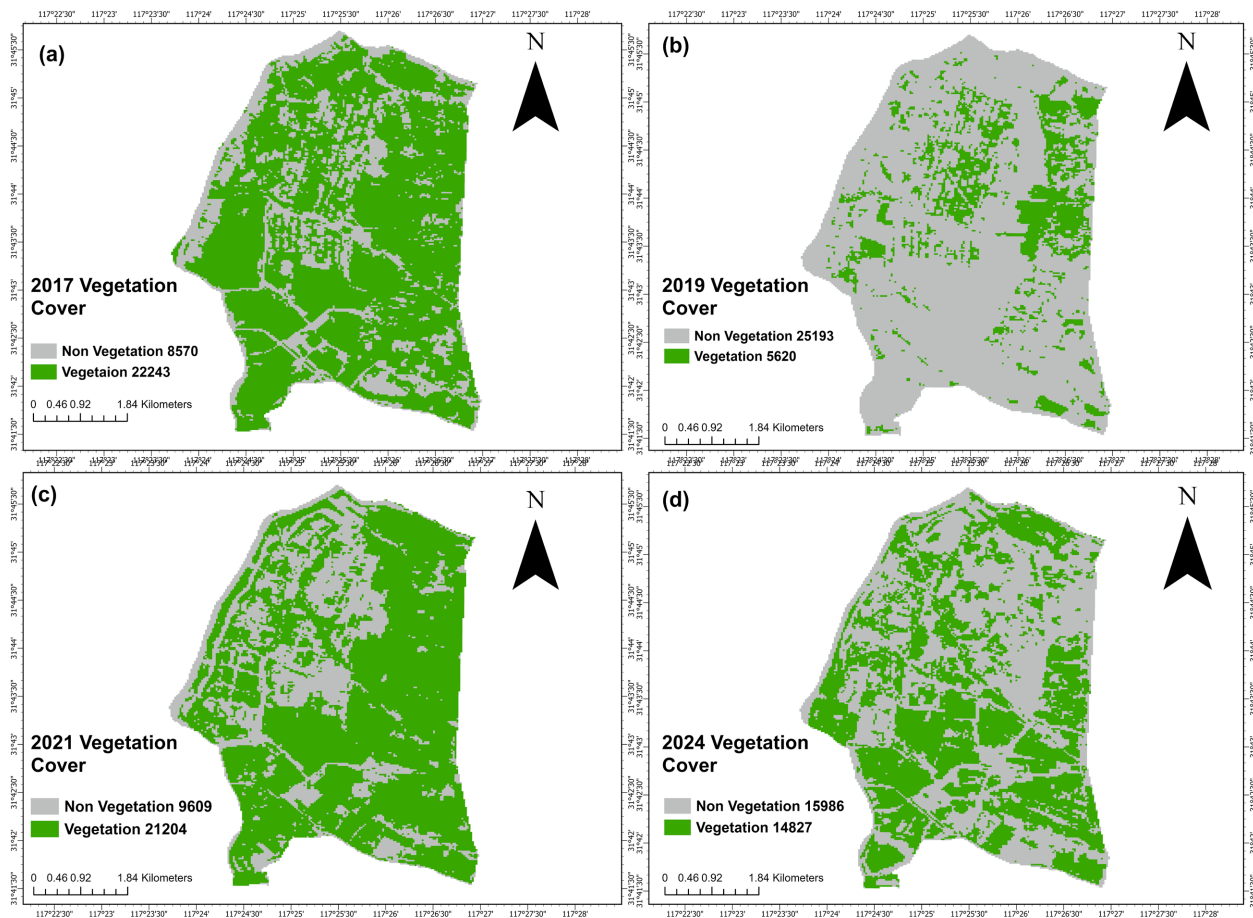


Figure 4. Changes in vegetated and non-vegetated areas in 2017, 2019, 2021 and 2024 (Sources: Data processing based on Sentinel-2 from Google Earth Engine).

The low-biomass vegetation exhibited relatively stable dynamics, fluctuating between 9567 tons in 2017 and 7501 tons in 2019 before recovering to 9262 tons in 2024. This pattern suggests a complex interplay between vegetation and environmental factors, without significant long-term degradation. In contrast, the high-biomass vegetation experienced more pronounced fluctuation, declining sharply from 8949 tons in 2017 to 3103 tons in 2019 due to land use changes. Restoration efforts enabled a recovery, reaching a peak of 10,211 tons in 2021, but this was followed by a decrease to 7133 tons in 2024, highlighting the vulnerability of the high-biomass vegetation to both restoration challenges and land use pressures. These trends emphasize the need for sustained restoration efforts and adaptive management to address the ongoing issues of land use pressure and ecological variability within the wetland ecosystem.

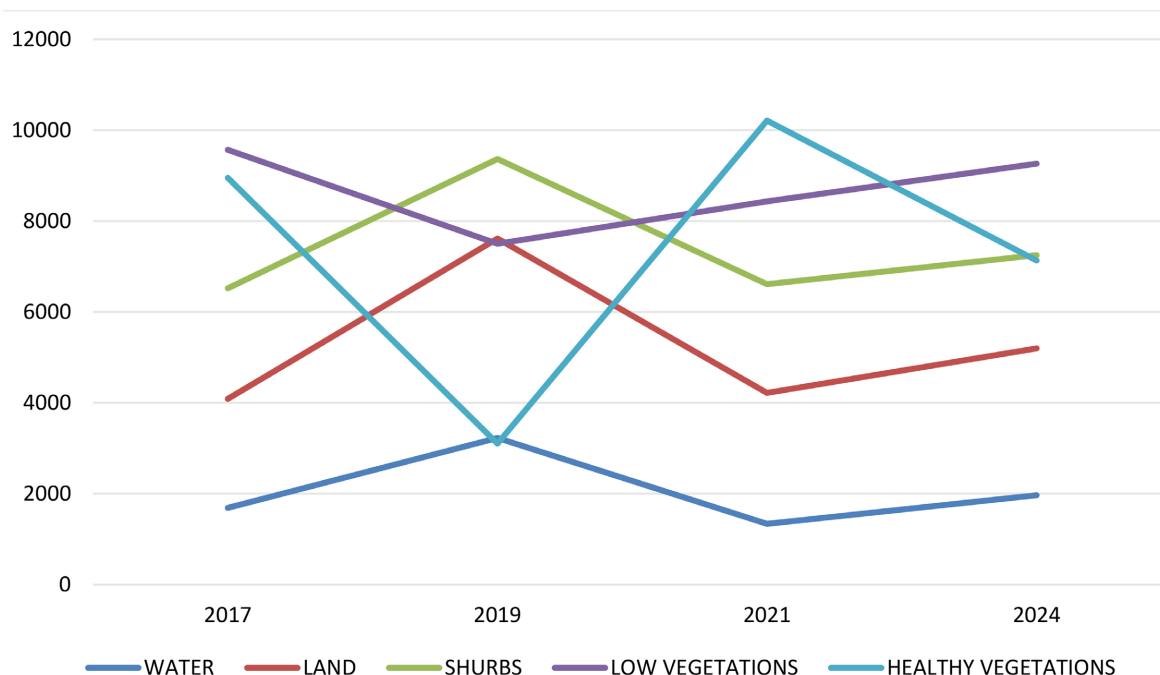


Figure 5. Above-ground biomass (AGB) trends by vegetation type (2017-2024).

3.5. Water Quality Responses

The scatter plot analysis presented in **Table 1** offers a comprehensive comparative assessment of water quality parameters before and after the restoration initiative, and their alignment with the Chinese Class III water quality standards. Dissolved oxygen exhibited a noteworthy improvement, increasing from an average concentration of 5.35 mg/L into 7.6 mg/L in 2024. This exceeded the Class III standard (≥ 5.0 mg/L) and approached Class I level, reflecting enhanced oxygenation and ecological recovery, attributable to the hydrological interventions and improved vegetation cover implementation during the restoration process. Similarly, Chemical Oxygen demand decreased from 22.0 mg/L in 2018, which slightly exceeded the class threshold, to a substantially lower value of 3.7 mg/L in 2024, well below the standard. This reduction underscores the effectiveness of the restoration efforts in terms of pollutant filtration and organic matter control.

Total phosphorus levels showed moderate improvements, decreasing from 0.09 mg/L in 2018 to 0.079 mg/L in 2024, thereby achieving Class II standards. This indicates the wetlands enhanced capacity to retain phosphorus and mitigates nutrient enrichment. However, total Nitrogen remained a challenge, as it improved from 2.4 mg/L in 2018 to 3.8 mg/L in 2024, yet still exceeded the class threshold of ≤ 1.0 mg/L suggesting the persistence of nutrient pollution from upstream agricultural and urban sources.

The variability in measurement represented by the error bars on the plot was higher in the 2018 data, indicating less stable ecological conditions prior to the restoration as shown in **Figure 6**. In contrast, the reduced variability observed in 2024 demonstrated more consistent and controlled ecological functionality after

the restoration. The distinct colored lines corresponding to the Class III standards provide clear visual indicators of compliance, emphasizing significant achievements in dissolved oxygen, chemical oxygen demand, and total phosphorus as shown in **Table 1**, while also highlighting the need for continued focus on nitrogen management strategies. These findings underscore the success of the restoration efforts, although the elevated total nitrogen levels point to areas requiring sustained attention to achieve comprehensive wetland recovery.

3.6. Observed Trends and Their Link to Restoration Measures

The restoration measures in the Shibalianwei Wetland have substantially enhanced water quality and ecological function. Decreases in nutrient and organic matter loads, coupled with increased dissolved oxygen levels, underscore the effectiveness of interventions like vegetation re-establishment and hydrological adjustments. Nutrient concentrations exhibited marked declines, with total nitrogen diminishing from nitrogen concentrations declined from 6.89 mg/L in the February inflow to 2.08 mg/L in the August outflow, while total phosphorus dropped from 0.204 mg/L in the July inflow to 0.101 mg/L in the outflow. The restored vegetation's peak productivity coincided with the observed reduction, understanding its pivotal role in nutrient uptake. The wetland's capacity for nutrient retention was further highlighted by the recovery of healthy vegetation biomass, which reached a maximum of 10,211 tons in 2021. Furthermore, hydrological interventions resulted in a significant decrease in chemical oxygen demand, an indicator of organic pollution. Improved water circulation minimized stagnant zones, reducing COD levels from 5.8 mg/L to 3.6 mg/L. This highlights the effectiveness of the restored hydrological pathways in filtering out organic pollutants. Furthermore, the dissolved oxygen levels in the outflow consistently exceeded those in the inflow, maintaining values above 6.2 mg/L throughout 2024. This improvement reflects the synergistic impact of vegetation regrowth and enhanced water circulation, which have fostered conditions that support aquatic biodiversity and ecological stability.

Table 1. The concentration of DO, COD, TP, and TN before and after restoration.

Parameters	Years (2018-2024)		Class III Standard	Meets Standard (2024)	Improvement
	2018 (Before Restoration)	2024 (After Restoration)			
Dissolved Oxygen (DO)	5.35	7.6	5	Yes	Significant (Exceeds Class I levels)
Chemical Oxygen Demand (COD)	22	3.7	20	Yes	Significant (Far below Class III)
Total Phosphorus (TP)	0.09	0.079	0.2	Yes	Moderate (Achieves Class II)
Total Nitrogen (TN)	2.4	3.8	1	No	Minimal (Still exceeds Class V)

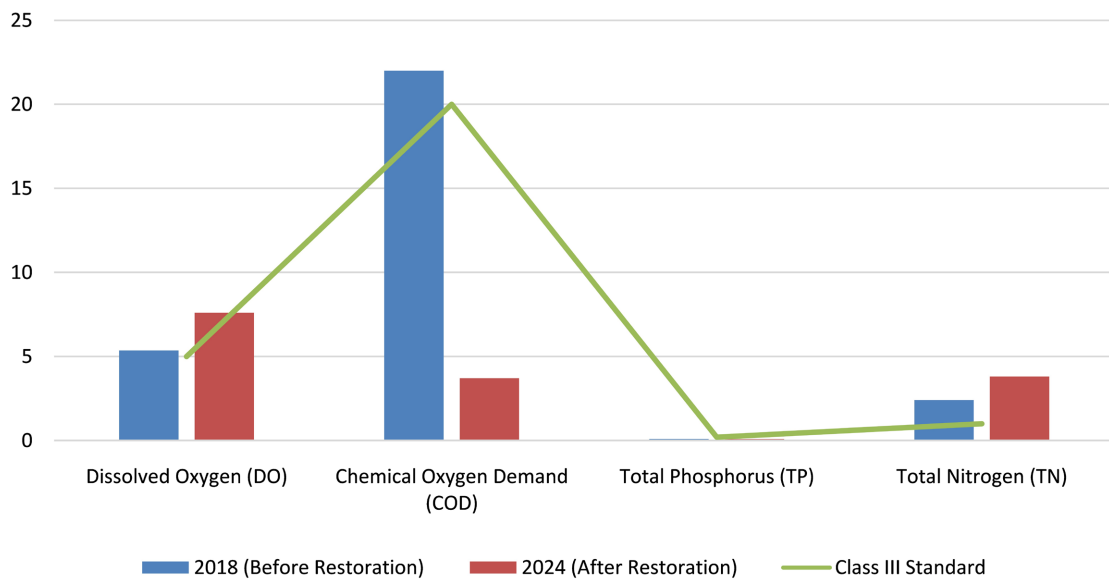


Figure 6. The scatter plot analysis of water quality parameters.

3.7. Heatmap Correlation Analysis

The correlation analysis presented in the heatmap of **Figure 7**, which explores the interrelationship between restoration metrics and water quality improvement, provides a comprehensive understanding of the dynamics between vegetation characteristics and water quality within the Shibalianwei Wetland. By examining the associations among vegetation cover, healthy vegetation biomass, and key water quality parameters, including TN, TS, COD, and DO, this study elucidate both the strengths and limitations of the restoration initiatives.

3.7.1. Vegetation Cover and Water Quality

The analysis revealed a weak inverse relationship between vegetation cover and decreases in total nitrogen (TN) and total phosphorus (TP) levels (-0.15 each). This indicates that vegetation plays a role in nutrient uptake by stabilizing soil and filtering pollutants. However, its overall effectiveness is limited by external factors such as nutrient-laden runoff from upstream agricultural and urban areas. These findings align with previous research highlighting that excessive nutrient inputs can overwhelm the nutrient retention capacity of wetlands, reducing their ability to mitigate eutrophication and water quality degradation (García et al., 2020; Lowrance et al., 1984). Runoff from urban and agricultural areas containing high nutrient concentrations could potentially overwhelm the wetland's capacity to filter these inputs, reducing the observed impact of vegetation cover on nutrient reductions. In contrast, a slight positive correlation (0.16) was noted between vegetation cover and dissolved oxygen improvement, indicating that vegetation may indirectly contribute to oxygenation, potentially through enhanced ecosystem functioning and reduced organic pollution.

3.7.2. Healthy Vegetation Biomass and Water Quality

The finding indicates that the recovery of healthy vegetation biomass exhibits a

modest positive correlation with improvement (0.14) in dissolved oxygen levels, but its direct influence on reducing total nitrogen, total phosphorus, and chemical oxygen demand is negligible. This suggests that while biomass recovery is critical for supporting the overall ecological health of the wetland, its capacity to directly mitigate nutrients and pollutant levels is limited. However, the slight positive correlation between vegetation biomass and dissolved oxygen improvement implies that higher biomass enhances the oxygenation process, creating favorable conditions for the microbial decomposition of organic matter (Dosskey et al., 2010). These results underscore the ecological significance of maintaining robust vegetation biomass, particularly during the early phases of restoration when biomass growth can substantially influence the recovery of water quality.

3.7.3. Interrelations among Water Quality Parameters

The analysis result underscores the critical role of dissolved oxygen levels in regulating water quality within the wetland ecosystem. A strong positive correlation was observed between DO improvements and reduction in TN, TP, and COD (ranging from 0.86 to 0.88). These relationships reflect the synergistic effects of improved oxygenation on nutrient retention and organic pollutant decomposition.

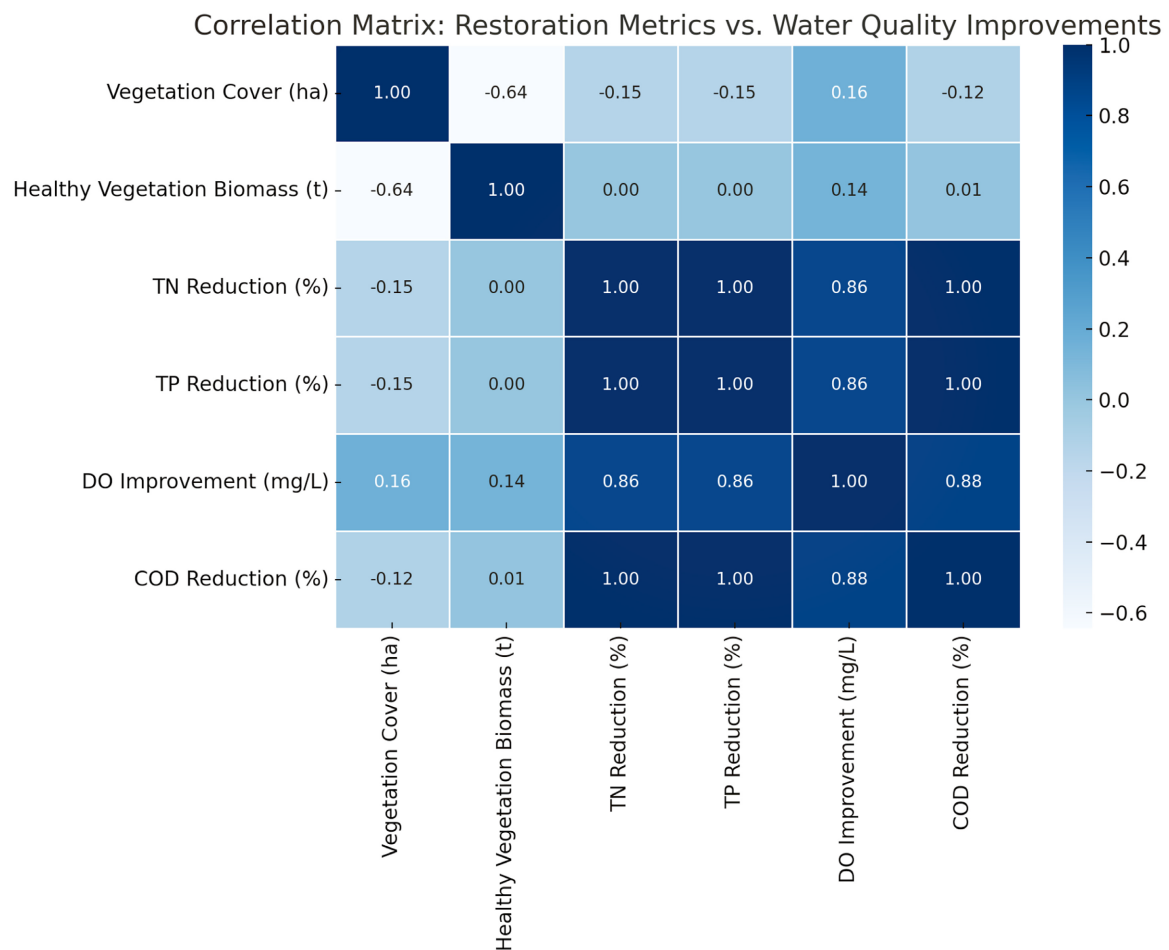


Figure 7. Heat map analysis of vegetation species and water quality parameters.

For instance, enhanced DO levels facilitate aerobic microbial activity, which accelerates the breakdown of organic pollutants and supports nitrogen cycling processes (Kaushal et al., 2023). The seasonal peak in DO levels and corresponding reduction in COD further highlight the role of hydrological intervention, such as water system combing, in promoting water circulation and mitigating organic pollution. These findings align with previous studies emphasizing the critical role of oxygenation in wetland water quality improvements (Cheng et al., 2022).

3.8. Implications and Future Directions

The weak negative correlations between vegetation cover and nutrient reductions underscore the need for adaptive management strategies. This may include targeted planting of high-productivity vegetation species capable of rapid nutrient uptake and stricter controls on external nutrient inflows, particularly from upstream agricultural and urban sources (Min et al., 2020). Additionally, the strong interdependence between DO improvements and reductions in TN, TP, and COD indicates that sustaining hydrological interventions will be critical for long-term water quality improvements. Continued monitoring of vegetation dynamics and water quality parameters is essential to ensure the persistence of these ecological benefits and to refine restoration strategies over time.

4. Discussion

4.1. Ecological Impacts of Land Use and Land Cover Changes (LULCC)

The Shibalianwei Wetland experienced significant land use and land cover (LULCC) transformations from 2017 to 2024, demonstrating the complex interplay between ecological restoration initiatives and ongoing human-induced pressures. The vegetation area initially expanded from 14.3 hectares in 2017 to 17.5 hectares in 2019, indicating the success of early tree planting and soil conservation efforts. This outcome aligns with the research of Zedler & Kercher (2005), which emphasized the quick initial advantages of targeted wetland restoration activities. However, the subsequent reduction to 15.1 hectares by 2024 illustrates the difficulties in maintaining ecological progress amid urban growth, particularly in the wetland's northern and central areas. Comparable patterns have been observed in wetlands near urban centers, where land development frequently surpasses conservation endeavors (Adão et al., 2017; Mu et al., 2022).

The relationship between barren land and vegetation cover showed an inverse pattern. Initially, barren land decreased from 3.9 hectares in 2017 to 2.5 hectares in 2021, attributed to stabilization efforts. However, it subsequently expanded to 5.2 hectares by 2024, corresponding to areas with insufficient vegetation recovery, which intensified soil erosion and nutrient runoff. This trend aligns with research by Huang et al. (2021), who noted that inadequate vegetation cover results in increased land degradation in restored wetlands. The steady growth of built-up areas, from 1.8 hectares in 2019 to 1.9 hectares in 2024, further challenges conser-

vation efforts, reflecting the combined pressures of urbanization and resource demands (Simpson et al., 2021).

Water bodies experienced notable fluctuations, expanding from 3.2 hectares in 2017 to 5.3 hectares in 2021 due to hydrological interventions, such as enhanced water circulation and retention strategies. However, sedimentation and seasonal changes led to a decrease to 3.8 hectares by 2024. These observations are consistent with Mitsch (2012), who emphasized the necessity of ongoing hydrological management for maintaining water retention in restored wetland ecosystems. The ongoing reduction in cultivated land, from 3.6 hectares in 2017 to 1.2 hectares in 2024, indicates a shift from agricultural use towards urbanization and degraded areas. While this trend reduces agricultural runoff, it also raises concerns about soil degradation and the socio-economic consequences of land conversion.

4.2. Aboveground Biomass (AGB) Dynamics and Ecosystem Functionality

The examination of AGB across various vegetation types highlights the wetland's dynamic response to restoration efforts and environmental stressors. Water vegetation biomass grew from 1688 tons in 2017 to 3227 tons in 2019, driven by aquatic restoration measures. However, a sharp decline to 1338 tons in 2021 suggests susceptibility to hydrological disruptions and nutrient loading. A modest recovery to 1968 tons in 2024 indicates partial success in stabilizing aquatic ecosystems. These findings are similar to studies by Teixeira et al. (2024), which observed comparable patterns in aquatic vegetation exposed to nutrient imbalances.

Land vegetation biomass almost doubled between 2017 (4088 tons) and 2019 (7616 tons), reflecting successful reforestation efforts. However, the subsequent decrease to 5199 tons by 2024 underscores the persistent challenges of land use pressures and soil degradation. Shrub biomass demonstrated resilience, rebounding to 7250 tons in 2024 after a decline in 2021, emphasizing the stabilizing role of low-maintenance vegetation in degraded wetlands (Simpson et al., 2021). In contrast, high-biomass vegetation experienced significant fluctuations, reaching a peak of 10,211 tons in 2021 before dropping to 7133 tons in 2024. This highlights the vulnerability of high-productivity vegetation to restoration challenges and nutrient stress.

4.3. Enhancements in Water Quality and Restoration Efficacy

The implemented restoration measures led to substantial improvements in water quality, as demonstrated by decreased nutrient loads and organic contaminants. The concentration of total nitrogen (TN) reduced from 6.89 mg/L in February inflow to 2.08 mg/L in August outflow, while total phosphorus (TP) levels declined from 0.204 mg/L in July inflow to 0.101 mg/L in outflow. These reductions showcase the ability of restored plant life to absorb nutrients, corroborating research by Simpson (2021) that highlights vegetation's role in mitigating nutrient excess in wetland ecosystems (Simpson et al., 2021). Nevertheless, the ongoing

issue of high TN levels surpassing acceptable limits underlines the impact of upstream nutrient influxes, aligning with findings from [Teixeira et al. \(2024\)](#).

Hydrological interventions, including water system integration and enhanced inflow/outflow regulation, played a crucial role in lowering chemical oxygen demand (COD) levels from 5.8 mg/L in inflow to 3.6 mg/L in outflow. Improved water circulation reduced stagnant areas, promoting microbial breakdown of organic pollutants ([García et al., 2020](#)). The noted rise in dissolved oxygen (DO) levels, consistently above 6.2 mg/L in 2024, emphasizes the combined effect of vegetation regrowth and aeration, supporting aquatic biodiversity and ecosystem stability.

4.4. Relationship between LULCC, AGB, and Water Quality

The minimal correlation between vegetation cover and nutrient reductions (-0.15 for both TN and TP) reveals the constraints of wetland filtration capacity under high nutrient loads, a pattern observed in nutrient-saturated systems ([Xie et al., 2022](#)). However, the slight positive correlation (0.16) between vegetation cover and DO levels indicates indirect benefits, such as enhanced oxygenation through improved ecosystem functioning. Healthy vegetation biomass showed limited direct impact on nutrient reductions but exhibited a weak positive correlation (0.14) with DO improvements, highlighting its role in supporting microbial activity and organic matter decomposition ([Guo et al., 2022](#); [Zhang et al., 2022](#)).

4.5. Wetland Management Implications

The results emphasize the necessity of incorporating adaptive management strategies to tackle persistent ecological and human-induced challenges. Focusing on high-productivity plant species, enhancing hydrological interventions, and implementing more stringent controls on upstream nutrient inflows can maximize restoration benefits ([García et al., 2020](#)). Decision-makers should consider synchronizing restoration activities with seasonal nutrient peaks and investing in long-term monitoring systems to track ecological changes and refine interventions.

4.6. Constraints and Future Research Directions

This study provides valuable insights into the restoration of the Shibalianwei Wetland, but several limitations should be acknowledged to offer a more comprehensive understanding of the restoration efforts, their long-term effectiveness, and their broader applicability to other regions and wetland types. These limitations, particularly regarding the study duration, lack of detail on hydrological interventions, and insufficient data on water flow dynamics, pose challenges for generalizing the findings to other ecosystems.

A key limitation of this study is the relatively short duration of the monitoring period, from 2017 to 2024. Wetland restoration is a complex and slow process that typically requires many years, if not decades, to manifest its full ecological benefits. Although improvements were observed in vegetation biomass, water quality

parameters such as dissolved oxygen (DO), and chemical oxygen demand (COD), the complete impact of the restoration measures may not yet be fully realized. Wetland systems, especially those undergoing restoration, often demonstrate delayed responses in ecosystem recovery due to the intricacies of nutrient cycling, hydrological stabilization, and vegetation regrowth. The persistence of high total nitrogen (TN) levels in the wetland outflow, despite improvements in other water quality parameters, highlights the need for continued monitoring to understand the long-term effects of restoration measures. Nitrogen pollution remains a challenge, particularly from external sources such as agricultural runoff and urban effluents. The study's short duration does not capture the long-term stability of the interventions and the potential seasonal or annual variations in water quality. Extending the monitoring period well beyond 2024 is essential to assess the sustainability of the observed improvements and determine whether the wetland's ecological health will stabilize or improve further over time. Future research should focus on establishing long-term monitoring programs that continue to track the progress of restoration efforts over decades, providing deeper insights into the restoration dynamics and the wetland's long-term resilience to external pressures.

The restoration of the Shibalianwei Wetland involved several hydrological interventions aimed at enhancing water retention, improving water quality, and reducing sedimentation. However, the specific nature and impact of these hydrological changes are not adequately detailed in the study. While the study notes the expansion of water bodies from 3.2 hectares in 2017 to 5.3 hectares in 2021, the exact interventions (e.g., flow regulation, sedimentation control, or structural modifications like weirs, levees, or floodplain restoration) were not sufficiently described. Understanding the nature of these interventions is essential for assessing their effectiveness and for comparing them to similar restoration projects globally. Hydrological interventions are a crucial component of wetland restoration, influencing water circulation, sediment transport, and nutrient retention. Detailed descriptions of these interventions, including the methods used for flow regulation, the design of water retention structures, and the impact of sedimentation management practices, would enable more accurate comparisons with other wetland restoration projects. Furthermore, understanding which hydrological measures were most effective will be critical for optimizing future restoration strategies. Future research should focus on providing a comprehensive account of the hydrological interventions implemented, including their design, methodology, and impacts on water quality. By doing so, this research would allow for more effective comparisons with other ecosystems and contribute valuable knowledge for enhancing hydrological management practices in wetland restoration.

Another critical limitation is the lack of data on water flow dynamics and residence time, which are essential for understanding nutrient retention and water quality improvement in wetlands. Water flow dynamics directly affect nutrient cycling, pollutant filtration, and overall ecosystem functioning. The Shibalianwei

Wetland exhibited fluctuations in its water bodies, with a reduction in the wetland's water area between 2021 and 2024, likely due to sedimentation and seasonal fluctuations. These changes in water body size suggest that the wetland's water retention capacity may have been compromised, but the study does not provide sufficient information on how these fluctuations relate to hydrological processes or the wetland's ability to retain nutrients. Residence time the amount of time water remains in the wetland plays a vital role in nutrient retention. Longer residence times allow vegetation and microbial communities to absorb more nutrients, thus improving water quality. However, this study did not measure or report on residence time or water flow patterns, which are critical to evaluating the effectiveness of hydrological interventions. Future research should focus on the incorporation of flow meters, velocity sensors, and hydrological models (e.g., HEC-RAS or SWAT) to measure water flow and residence times more precisely. Additionally, monitoring sedimentation rates and their effects on water retention and nutrient cycling will provide a clearer understanding of the challenges faced in restoring water bodies. Understanding the dynamics of water flow and sedimentation will be vital for developing strategies that optimize water retention and nutrient removal, ensuring the long-term effectiveness of wetland restoration efforts.

The study also falls short in fully addressing the role of external nutrient pollution, which continues to impede the wetland's water quality despite the internal restoration measures. While internal efforts, such as vegetation restoration and hydrological improvements, have led to some improvements in water quality, the persistence of high TN levels suggests that external nutrient sources, particularly agricultural runoff and urban effluents, continue to exert significant pressure on the wetland. External nutrient pollution is one of the most challenging factors in wetland restoration, especially in areas surrounded by agricultural or urbanized landscapes. Nutrient-laden runoff from upstream sources can overwhelm the wetland's natural ability to filter and retain nutrients, undermining the impact of restoration measures. The study should have incorporated a more detailed analysis of the sources and impacts of external nutrient pollution on water quality. Although it is clear that agricultural and urban activities contribute to nutrient loading, the study does not assess the specific contributions of these sources or quantify their impact on water quality. Future research should integrate nutrient flux modeling to better understand the role of external nutrient inputs in water quality degradation. Additionally, comprehensive watershed management strategies, including the establishment of riparian buffer zones, improved agricultural practices, and better control of urban effluents, will be necessary to reduce nutrient pollution in the long term. By integrating these strategies with the ongoing hydrological and ecological restoration efforts, the wetland's ability to manage nutrient pollution can be greatly enhanced, ensuring more sustainable restoration outcomes.

To address the limitations identified above and further improve the success of wetland restoration efforts, future research should focus on long-term monitor-

ing, more detailed hydrological assessments, and strategies to address external nutrient pollution. Future studies should focus on measuring water flow and residence times within the wetland, providing a clearer understanding of hydrological processes, and integrating strategies to reduce external nutrient inputs from agriculture and urban runoff. These strategies could include riparian buffer zones, land-use management, and enhanced wastewater treatment. By integrating these strategies with hydrological interventions, wetland restoration efforts can be more effective and sustainable in the long term. Extending the monitoring period will help assess whether the initial improvements observed are sustainable or whether additional interventions are required to achieve full recovery. Addressing these research gaps will improve our understanding of wetland restoration dynamics and contribute to developing more effective and sustainable restoration practices globally.

In conclusion, while the restoration of the Shibalianwei Wetland has yielded significant improvements in vegetation cover, water quality, and ecosystem functioning, the findings of this study are not fully generalizable to other wetland types or regions. The limitations of the study, such as its short duration, insufficient detail on the hydrological interventions implemented, limited data on water flow dynamics, and the continued challenge of external nutrient pollution, underscore the complexity of wetland restoration. Future research should focus on long-term monitoring, more detailed hydrological assessments, and strategies to address external nutrient pollution to ensure the long-term success and transferability of wetland restoration efforts globally. By addressing these gaps, restoration practices can be better tailored to local contexts and contribute to the broader goal of wetland conservation and ecological restoration worldwide.

5. Conclusion and Recommendations

This investigation explores the restoration trajectory of the Shibalianwei Wetland from 2017 to 2024, illuminating the intricate interplay between land utilization, biomass development, and water quality. Initial achievements in expanding vegetation cover and enhancing water conditions were observed; however, the enduring efficacy of restoration initiatives is constrained by persistent urbanization, nutrient influxes, and seasonal hydrological variations. Notable fluctuations in vegetation biomass, particularly in aquatic and terrestrial plant communities, indicate the ecosystem's susceptibility to external pressures. Although hydrological interventions have yielded positive outcomes for water quality, the continued presence of elevated nutrient levels in incoming water suggests that external factors continue to significantly impede restoration potential.

These observations underscore the necessity for a more holistic, adaptable approach to wetland management that reconciles ecological restoration with the pragmatic realities of urban expansion and agricultural demands. The Shibalianwei Wetland case, while demonstrating improvements in certain areas, emphasizes the critical importance of addressing anthropogenic impacts alongside eco-

logical recovery efforts. This research offers valuable insights into the challenges and strategies associated with wetland restoration, which can be applied on a global scale to enhance the resilience of these vital ecosystems.

Recommendations

1) Optimize Hydrological Regulation: Emphasize the improvement of water flow management and address seasonal nutrient fluctuations to sustain water quality and ecosystem functionality.

2) Emphasize Vegetation Rehabilitation: Promote the establishment of high-productivity, low-maintenance plant species to stabilize soils and enhance biomass recovery.

3) Mitigate Urban Expansion: Enforce more stringent zoning policies and develop green infrastructure to minimize urban impacts on wetland ecosystems.

4) Curtail Nutrient Pollution: Implement comprehensive watershed management practices to reduce agricultural runoff and upstream nutrient inflows.

5) Assess Ecosystem Health: Establish long-term monitoring protocols for ecological and microbial parameters to refine adaptive management strategies.

6) Foster Community Engagement: Involve local stakeholders in restoration initiatives to ensure sustainability and public support.

These recommendations aim to enhance the overall effectiveness of wetland restoration efforts and promote long-term ecological resilience, both for the Shibalianwei Wetland and similar ecosystems facing comparable challenges worldwide. By adopting an integrated and adaptive approach, wetland restoration initiatives can contribute to reversing ecosystem degradation and fostering biodiversity conservation in the face of ongoing environmental and anthropogenic pressures.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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