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Original Research

Efficacy of Wetlands on Urban River Water Quality: A Case Study of Pudong New Area, Shanghai

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Abstract

Urban wetlands provide essential ecological services but are highly threatened by rapid urbanization. Urban river water quality is markedly influenced by seasonal dynamics and extensive anthropogenic activities. This study evaluates the role of wetlands in improving urban river water quality in the Pudong New Area by considering key water quality parameters (pH, DO, NH_3-N, BOD_5, COD, TP, and TN) across multiple river and adjacent wetland sites from June 2023 to May 2024. The Water Quality Index (WQI) classified urban river water as "Unsafe" (WQI: 119-123) during summer, mainly due to elevated nutrient inputs from domestic and industrial discharges. In contrast, wetland sites demonstrated "Excellent" water quality (WQI: 8.47-57.9) across all seasons. Compared with river sites, wetlands exhibited substantial reductions in NH_3-N by 47.9-54.8%, BOD_5 by 48.0-61.1%, TP by 72.3-77.3%, and TN by 77.0-80.1%, indicating their strong pollutant mitigation and nutrient removal capacity. The seasonal rise in nutrient concentrations during summer was attributed to hydrological fluctuations and intensified anthropogenic inputs. Principal Component Analysis (PCA) exhibited widespread seasonal associations among selected water quality parameters, showing that nutrients and organic pollutants determined by anthropogenic activities contributed significantly to water quality variability. Overall, the results show that rapid urbanization markedly degrades river water quality, while wetlands represent effective nutrient reducers, which stabilize ecosystem conditions. The current study emphasizes the importance of wetlands in mitigating eutrophication risks

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and improving urban water quality, proposing valuable insights for policymakers aiming to implement nature-based reforms in rapidly developing regions like Pudong New Area.

Keywords: urban river, wetlands, seasonal variations, water quality index, principal component analysis

Introduction

Wetlands are transitional zones between aquatic and terrestrial ecosystems, which offer essential ecological services due to their geographical distribution [1]. Despite covering around 1% of the Earth's surface, freshwater wetlands support more than 40% of the global biodiversity and contribute approximately 40.6% of total ecosystem services [2, 3]. These systems play vital hydrological, ecological, and biogeochemical roles, providing services such as water supply, flood control, pollutant degradation, and climate regulation [4]. As reported in global assessments, wetlands harbor over 40% of the world's diverse species, occupying a small fraction of land area, mainly freshwater ecosystems [5]. However, wetland areas are rapidly declining due to intensifying anthropogenic pressures [6]. Their ecological integrity has been significantly disrupted, leading to environmental challenges such as soil erosion, riverbank degradation, and water pollution that directly affect human populations [7-10]. Wetlands are degrading due to urbanization and agricultural runoff, which alter natural hydrological processes and pose major environmental concerns worldwide.

The economic growth and well-being of society are associated with clean and safe water resources [11]. Water quality degradation has emerged as a major global issue arising from multiple point and non-point pollution sources, including nutrient runoff from agriculture, domestic wastewater, and industrial effluents [12, 13]. Managing non-point pollutants from diffuse sources is highly challenging and has contributed to significant declines in surface water quality [13]. Urban water pollution has gained considerable attention due to city expansion [14, 15]. It is projected that nearly 60% of the global population is expected to reside in urban areas by 2050 [16, 17]. Rapid urbanization pressures water resources and aquatic ecosystems, highlighting the need for effective management strategies to protect water quality for ecological balance and sustainable development [18]. Advanced techniques such as remote sensing and machine learning have improved the prediction of water quality, enabling more efficient monitoring of hydrological ecosystems [19-21]. For instance, AI-based models and satellite-derived indicators have improved the accuracy and reliability of WQI and other hydrological assessments [22, 23]. These tools are highly effective for the sustainable management of aquatic ecosystems, particularly in rapidly urbanizing regions.

Urban rivers across diverse regions are highly degraded by pollutants originating from different sources [24], leading to significant variations in water quality composition [25]. While previous studies have well documented how different sources influence water quality in diverse environments [11, 26, 27], agricultural practices and urban expansion are key contributors to degradation [28]. Particularly, urbanization increases impervious surfaces, which alters soil topography and natural hydrological connectivity, thereby affecting surface-water distribution [29, 30]. Adjacent water bodies are further affected by pollutant runoff from construction and increased stormwater discharge [31, 32]. Collectively, these changes drive complex ecological disturbances, especially in river water quality in urbanizing regions [28]. Moreover, pollutants from agricultural runoff, industrial discharge, and domestic sewage are introduced into these rivers [33, 34], increasing ecological decline.

The Pudong New Area of Shanghai, located on the eastern edge of the Yangtze River Delta, represents a distinct case study for these challenges. The region's river network has experienced considerable hydrological and morphological changes due to rapid urbanization over recent decades. Local reports have documented several water quality issues, warranting further queries. For instance, rapid urbanization between 1965 and 2010 resulted in river network fragmentation and a decline in water surface area from 10.6% to 7.2% [35]. This decline, combined with an impervious surface rate of 42.8%, has increased surface runoff and waterlogging, thereby reducing their hydrological resilience [36]. Moreover, antibiotics have been detected in the surface water of the Pudong New Area, with higher levels during dry seasons, indicating chemical pollution and a relatively weak self-purification capacity of the river network [37]. These results emphasize the need for a better understanding of the hydrological status in the area.

Despite increasing attention to pollution from urbanization and anthropogenic activities in the study area [35-37], the role of adjacent wetlands in improving river water quality remains poorly reported. Wetlands serve as essential aquatic habitats for diverse organisms and function as natural biofilters, facilitating nutrient cycling and mitigating pollution [38, 39]. Therefore, the current study aims to examine the role of wetlands in improving river water quality in the Pudong New Area. The main objectives are to (1) determine the water quality status across diverse localities, including river and adjacent wetland sampling points, and (2) examine the seasonal variations in key water quality parameters. By evaluating wetland performance in mitigating pollution under conditions of urbanization and climatic variability, this study aims to support effective water management plans for the Pudong New Area.

Materials and Methods

Study Area

The Pudong New Area (31°03′-31°15′N, 121°05′-121°20′E) is located on the eastern side of the Huangpu River, forming an integral part of the Yangtze River Delta Economic Zone. The region has both urban and rural landscapes, including residential settlements, commercial zones, and cultivated agricultural land. The Pudong New Area experiences a humid subtropical climate, with an average annual temperature of 15.5ºC and mean annual precipitation of around 1056 mm, characterized by warm summers, mild winters, and diverse seasonal dry/wet variations. The summer (June to September) is relatively hot and humid, although June often experiences irregular precipitation patterns, decreasing river purification capability and affecting nutrient dynamics. Due to the area's economic growth from tourism, light manufacturing, and urban infrastructure development, significant pressure is exerted on water reservoirs. Consequently, river networks are primarily degraded by urban runoff, impervious-surface expansion, and anthropogenic activities, leading to ecological imbalance.

This study was conducted in a newly constructed urban wetland park located in Sanlin Town, Pudong New Area, Shanghai. Halin Road bounds the area to the east, the Xiaohuangpu River to the west, Sanlin West Road to the south, and the Sanlin Tanggang Canal to the north. It was completed in 2023, is not yet open to the public, and covers approximately 10.72 hectares. It forms part of the Sanlin Tanggang water system, an important waterway in southwest Pudong that ultimately flows into the Huangpu River. The wetlands within the park consist of small, artificial surface-flow units designed to improve the hydrological regime and enhance water purification before it enters the river system. This system receives stormwater inputs and treated flows from surrounding catchments. The landscape comprises woodland patches, grassland areas, which form a semi-natural ecological buffer capable of supporting pollutant reduction and nutrient transformation.

Six sampling sites were selected across the wetland park and its adjacent river system (Fig. 1), including three wetland sites (SL2-W, SL3-W, SL4-W) and three river sites (SL1-R, SL5-R, SL6-R). The wetland sites function as urban stormwater buffers designed to intercept pollutants before entering the main river system. SL2-W and SL3-W are surrounded by dense vegetation and marshy islands, whereas SL4-W is located near road infrastructure and receives direct urban runoff. On the other hand, the river sites reflect the downstream impacts of residential drainage, impervious surface runoff, construction activities, and canal flows. The site configuration enables direct comparison between the constructed wetlands and the adjacent river system to determine wetland-mediated improvements in water quality.

Sampling and Data Collection

A sampling campaign was conducted between June 2023 and May 2024 to evaluate water quality within the urban wetland park and its connected river system in the Pudong New Area. Sampling sites were selected

Fig. 1. Study area map showing different sampling locations.

to represent a gradient of human impact, ranging from river locations affected by domestic, industrial, and agricultural discharges to wetland sites experiencing comparatively minimal direct disturbance. A total of six sampling sites were designated, as described in the study area section.

Water samples were collected from about 0.3 m below the water surface, transported to the laboratory immediately after collection, and preserved at low temperature for subsequent analysis. Selected water quality parameters, such as pH and DO, were measured in situ using a Hydrolab Datasonde 5 sensor (USA). The remaining parameters, including ammonia nitrogen (NH_3-N), chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD_5), total phosphorus (TP), and total nitrogen (TN), were analyzed in the laboratory following standard procedures. Table 1 shows the analytical methods used for these parameters, while detection methods were adopted from Liu et al. [18], with slight modifications for COD, BOD_5, NH_3-N, TP, and TN analyses.

COD was determined using the potassium bichromate colorimetric method. TP concentration was measured using ammonium molybdate spectrophotometry, while NH_3-N was quantified via UV spectrophotometry. For TN detection, surface water samples were first digested with alkaline potassium persulfate and subsequently analyzed by UV spectrophotometry.

Methods

A sampling survey was initially conducted to assess key water quality parameters across the study area. Detailed investigations were carried out to compare spatial and seasonal fluctuations in water quality between river sites and wetland sites within the Pudong New Area.

Measurement of Water Quality Parameters

Accurate evaluation of water quality is essential for effective hydrological management. The water quality index (WQI) is widely recognized for its applicability, accessibility, and ability to integrate several environmental indicators into a single grading score [40, 41]. It is applied for the assessment of both surface and groundwater [41, 42], and the methodology adopted for the WQI calculation follows the standard procedure [43] and is expressed below:

$$WQI = \frac{\sum_{i=1}^{n} CiPi}{\sum_{i=1}^{n} Pi} \quad (1)$$

where n represents the total number of parameters, Ci denotes the normalized value of parameter i and Pi is the assigned relative weight (ranging from 1-4), which was determined on the basis of each parameter's ecological significance for aquatic organisms (Table 2).

Table 1. Water quality parameters and detection techniques measured in the laboratory.

Detection indices	Detection methods
Chemical oxygen demand (COD)	HJ 828
5-day biochemical oxygen demand (BOD_5)	HJ 505
Ammonia nitrogen (NH_3-N)	HJ 535
Total phosphorus (TP)	GB/T 11893
Total nitrogen (TN)	HJ 636

Table 2. Weights and normalization factors of selected parameters used in WQI calculation.

Parameters	Weight (P*i*)	Normalization factor C*i*										
		100	90	80	70	60	50	40	30	20	10	0
pH	1	7	7–8	7–8.5	7–9	6.5–7	6–9.5	5–10	4–11	3–12	2–13	1–14
DO	4	⩾7.5	>7	>6.5	>6	>5	>4	>3.5	>3	>2	⩾1	<1
NH_3-N	2	<0.5	<2	<4	<6	<8	<10	<15	<20	<50	⩽100	>100
BOD_5	3	<0.5	<2	<3	<4	<5	<6	<8	<10	<12	⩽15	>15
COD	3	<5	<10	<20	<30	<40	<50	<60	<80	<100	⩽150	>150
TP	1	<0.2	<1.6	<3.2	<6.4	<9.6	<16	<32	<64	<96	⩽160	>160
TN	2	<0.8	<3.8	<7.5	<13	<18	<27	<48	<85	<149	⩽265	>265

Adopted from Pesce and Wunderlin [44] and Kannel et al. [45].

In this study, seven key water quality parameters, including pH, DO, COD, BOD_5, NH_3-N, TP, and TN, were used for the WQI calculation. Water quality was classified based on the scoring values into various levels (0-25: Excellent; 25-50: Good; 51-75: Poor; 76-100: Very Poor; >100: Unsafe).

Statistical Analysis

Boxplots were used to illustrate the variability and distribution of selected parameters across different seasons and sampling sites. Pearson correlation analysis was conducted to determine the relationships among water quality parameters, and the corresponding p-values were used to assess their statistical significance. Principal component analysis (PCA) was performed separately for each season to identify dominant seasonal patterns and major pollution gradients affecting water quality. As the datasets differed across seasons, the proportion of variance explained by PC1 and PC2 also varied among the four seasons. All statistical analyses were performed using Origin v2018 (Origin-Lab Corp., Northampton, MA, USA).

Results and Discussion

Seasonal Dynamics of Water Quality Parameters in Pudong New Area

Seasonal Variations in Water Quality

Fig. 2 shows the seasonal patterns of key water quality parameters across river and wetland sites. Wetland sites exhibited higher average pH values compared to river sites, indicating that wetland biodiversity and biologically driven processes contribute to buffering and regulating pH fluctuations. A similar trend was observed for DO, with wetlands maintaining higher average levels (8.90-10.6 mg/L) compared to urban river sites (6.97-7.65 mg/L), indicating enhanced aeration and biological activity.

Substantial seasonal reductions in NH_3-N, BOD_5, TP, and TN were noted at the wetland sites, ranging from 48% to 80.1% compared to the river sites. These reductions are consistent with previous findings from constructed wetland studies in different regions [46-48]. The considerable decline in TP and TN can be attributed to the strong sorption capacity of phosphorus to sediments and the microbial transformation of nitrogen facilitated by wetland vegetation [49, 50]. These findings emphasize the effectiveness of wetlands in mitigating pollutant loads and reducing nutrient levels, thereby contributing to improved water quality in the area.

The WQI integrates multiple water quality parameters into a single numerical value for classifying river water quality [51]. In this study, the WQI was calculated across all sampling points to enable a comprehensive assessment of spatial and seasonal variations. The study area is affected by polluted runoff from urban drainage systems, while the adjacent river receives additional inputs from surrounding residential and municipal discharges. Pudong New Area experiences four distinct seasons, including an intense summer (June-August), a cold autumn (September-November), a moderate and wet spring (March), and a colder winter (December-February). Overall, WQI scores ranged from 53.4 to 123 across selected sampling points between 2023 and 2024, as shown in Table 3.

At the river site (SL1, SL5, and SL6), WQI values during the summer season exceeded 100, classifying water quality as “Unsafe”, indicating severe impairment. The highest WQI scores in summer can be attributed to increased domestic water consumption, greater urban stormwater runoff, and intensified discharge loads associated with tourism. Moreover, elevated temperatures and minimal streamflow limit the river’s self-purification capacity, increasing pollutant levels during summer. Slight improvements were noted in autumn and spring, with WQI values between 53.4 and 72.8, representing “Poor” classification. These improvements likely result from higher rainfall, increased dilution, and reduced anthropogenic pressure. In winter, low runoff combined with ongoing industrial activities contributed to moderate improvements at some river sites (e.g., SL1 scored 74.9, classified as “Poor”). However, SL5 and SL6 remained in the “Very Poor” categories (scored 84.7 and 91.6), respectively. These spatial differences may reflect variations in hydrological connectivity and the proximity to areas with higher purification potential.

Wetland sites (SL2, SL3, and SL4) showed better water quality, achieving “Excellent” scores, particularly during autumn and winter. These findings highlight the strong pollutant-removal and buffering capacity of constructed wetlands, which were most effective when surface runoff and external pollutant loads were reduced. During summer, SL2 and SL4 showed “Good” water quality (43.7 and 44.1), while SL3 recorded a higher WQI value (57.9, “Poor”), likely due to nutrient accumulation and reduced retention efficiency in elevated inflow conditions. However, water quality improved in autumn and achieved “Excellent” value (WQI < 25) at wetland sites, mainly due to minimal runoff and lower pollutant inputs. This “Excellent” classification persisted into winter, with scores ranging from 14.9 to 21.3. In spring, SL2 and SL3 maintained “Good” (25.5) and “Excellent” (8.47) classifications, respectively. These seasonal variations clearly demonstrate the impact of hydrological conditions and pollutant loads on wetland water quality [52].

The WQI results illustrate that seasonal fluctuations and anthropogenic activities strongly influence water quality in the study area. The urban river sites are mainly affected by household discharges, municipal wastewater inputs, and stormwater runoff. Consequently, WQI values increased [50], particularly during the summer, resulting in “Unsafe” conditions at several sites.

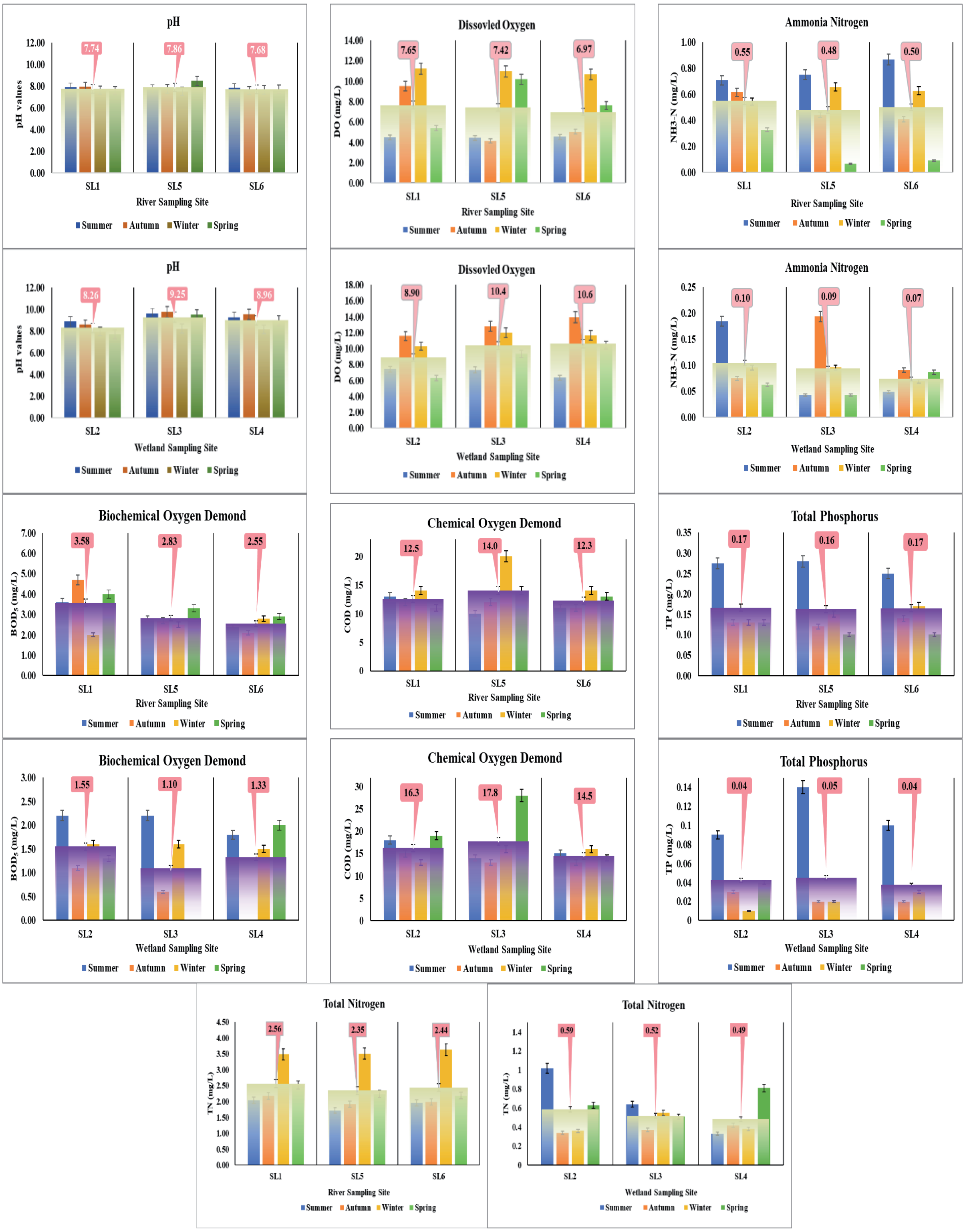

Fig. 2. Seasonal variations in selected water quality parameters across the study area.

In contrast, the wetland sites maintained "Excellent" water quality conditions across most seasons, indicating their vital role as natural hydrological filters. With growing urbanization and increasing anthropogenic pressures, preserving constructed wetlands and implementing effective management strategies are essential for sustaining urban water quality and ecological stability.

Seasonal Water Quality Assessment

Principal Component Analysis (PCA) was performed separately for each season to identify dominant water quality patterns and the basic pollution gradients in the study area (Fig. 3). As each season showed distinct water quality dynamics, the proportion of variance interpreted by PC1 varied accordingly. PC1 captured

Table 3. Water quality Index of varying sites in different seasons.

River site samples:							
Season	Site	Index value	Score	Season	Site	Index value	Score
Summer	SL1	121	Unsafe	Autumn	SL1	72.7	Poor
Summer	SL5	123	Unsafe	Autumn	SL5	70.0	Poor
Summer	SL6	114	Unsafe	Autumn	SL6	72.8	Poor
Winter	SL1	74.9	Poor	Spring	SL1	66.9	Poor
Winter	SL5	84.7	Very Poor	Spring	SL5	53.4	Poor
Winter	SL6	91.6	Very Poor	Spring	SL6	53.8	Poor
Wetland site samples:							
Summer	SL2	43.7	Good	Autumn	SL2	17.4	Excellent
Summer	SL3	57.9	Poor	Autumn	SL3	15.7	Excellent
Summer	SL4	44.1	Good	Autumn	SL4	17.6	Excellent
Winter	SL2	14.9	Excellent	Spring	SL2	25.5	Good
Winter	SL3	19.1	Excellent	Spring	SL3	8.47	Excellent
Winter	SL4	21.3	Excellent	Spring	SL4	10.7	Excellent

the majority of seasonal variability, explaining 81.15% of the variance in winter, 78.88% in autumn, 72.13% in summer, and 66.34% in spring. PC2 accounted for an additional 11-20% of the variance (Table 4), indicating relatively meaningful shifts.

To further justify these patterns, the PCA loading factors for PC1 and PC2 in each season are summarized in Table 4. Across all four seasons, PC1 represents a nutrient-organic pollution gradient, predominated by positive loadings of TN, DO, NH_3-N, and BOD_5.

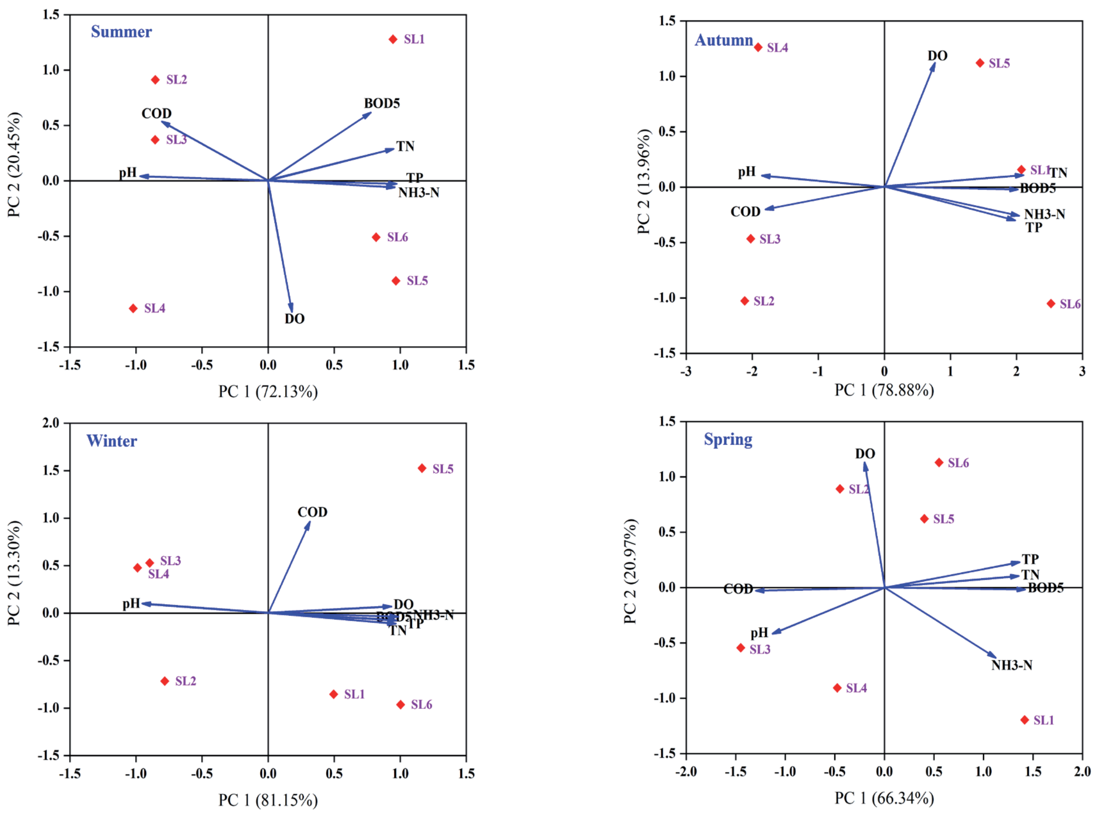

Fig. 3. Relationship between water quality parameters in various seasons.

Table 4. PCA loading factors for seasonal water quality parameters.

Parameters	Summer		Autumn		Winter		Spring	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
pH	-0.426	0.028	-0.370	-0.182	-0.400	0.096	-0.358	-0.303
DO	0.079	-0.800	0.301	-0.672	0.395	0.068	-0.063	0.817
NH_3-N	0.434	-0.039	0.401	0.210	0.417	-0.037	0.356	-0.456
BOD_5	0.350	0.427	0.360	0.499	0.396	-0.066	0.450	-0.011
COD	-0.362	0.369	-0.352	0.467	0.134	0.981	-0.408	-0.019
TP	0.437	-0.017	0.421	0.036	0.410	-0.080	0.434	0.164
TN	0.423	0.197	0.425	0.047	0.409	-0.110	0.429	0.073
Variance (%)	72.13	18.45	78.88	14.21	81.15	11.56	66.34	20.18

This indicates that variations in water quality parameters are brought about by nutrient enrichment and organic pollutants found in the study area.

In summer, TN, TP, and NH_3-N exhibited strong positive loadings on PC1, while BOD_5 showed moderate positive loadings, and COD showed negative loadings on PC1. This pattern illustrates that elevated nutrient levels and increased organic loading form a single pollution gradient during summer, while the oxidized organic matter is inversely related to the nutrient gradient. This nutrient signal likely reflects enhanced runoff and pollutant inputs under high temperature and intense rainfall, together with elevated domestic and industrial discharges [51, 53, 54].

In autumn, TN, TP, NH_3-N, and BOD_5 remained the dominant water quality contributors to PC1. This means that nutrient and organic inputs likely continue due to post-summer runoff and persistent urban discharges. DO illustrated a strong loading on PC2, indicating that oxygen dynamics are linked with temperature and hydrodynamics.

In winter, TP, NH_3-N, TN, and BOD_5 showed stronger loadings on PC1, indicating that nutrient pollution persists even during colder months. The strong correlation between NH_3-N and TN can be attributed to reduced biological activity and suppressed nitrification under lower temperatures [53, 55-57]. A distinct loading for COD was observed on PC2, indicating the role of chemically oxidizable organic matter when microbial degradation rates are reduced by colder conditions [13, 55].

In spring, TN, TP, and BOD_5 also dominated PC1, whereas DO showed a strong loading on PC2. This reflects improved oxygen conditions linked to moderate temperatures and spring turnover. Compared to other seasons, spring exhibited a relatively weaker clustering of nutrient parameters, which can be attributed to transitional hydrological conditions and variable runoff patterns.

The seasonal PCA results show that variations in water quality in the Pudong New Area are primarily shaped by nutrient and organic pollution linked to domestic wastewater, urban activities, and rainfall-driven runoff. Moreover, oxidation-related processes are essential in differentiating water quality conditions across seasons. Our results demonstrate that pollution in the urban river is affected not only by hydrodynamic factors such as runoff and temperature but also by urbanization and domestic discharge, which contribute considerably to water quality degradation [53, 55, 58].

Table 5. Pearson correlation among water quality parameters.

	pH	DO	NH_3-N	BOD_5	COD	TP
DO	-0.46**					
NH_3-N	-0.59***	0.09				
BOD_5	-0.59***	-0.03	0.54***			
COD	0.31	-0.02	-0.37*	-0.49**		
TP	-0.49**	-0.11	0.84***	0.64***	-0.44**	
TN	-0.68***	0.34	0.71***	0.64***	-0.22	0.61***

Note: $p<0.01$: ***, $p<0.05$: **, $p<0.1$: *.

Correlation Analysis of Water Quality Parameters

Table 5 and Fig. 4 illustrate the correlations among key water quality parameters across multiple sampling sites. Pearson correlation analysis revealed strong inter-parameter relationships, indicating the interrelated ecological processes driving water quality variations within the river-wetland system. The analysis highlighted both positive and negative correlations, indicating the complex interactions among nutrient inputs, organic pollution, and physicochemical conditions in the study area.

Notably, strong negative correlations were observed between pH and several water quality parameters, including DO (-0.46, $p<0.05$), NH_3-N (-0.59, $p<0.01$), BOD_5 (-0.59, $p<0.01$), TP (-0.49, $p<0.05$), and TN (-0.68, $p<0.01$). These consistent opposing relationships are mechanistically explained by different processes predominant in contaminated urban rivers [59, 60]. For instance, microbial nitrification of ammonia (NH_3-N) releases hydrogen ions (H^+), acidifying the aquatic ecosystem [61, 62]. Similarly, the decomposition of organic matter produces carbonic and organic acids, further reducing pH in polluted systems [63]. Such acidification processes intensify under high nutrient and organic loads, which characterize urban drainage inputs [64]. Thus, the negative correlation between pH and nutrient indicators demonstrates chemically determined acidification linked to increased pollution levels.

Strong positive correlations were observed between NH_3-N and BOD_5 (0.54, $p<0.01$), TP (0.84, $p<0.01$), and TN (0.71, $p<0.01$), indicating a strong association among these parameters. This combined pollutant load is transported from various sources, causing elevated nitrogen levels in the urban river system. Excessive domestic and municipal discharges expose the adjacent river to a serious eutrophication risk [65].

BOD_5 also exhibited strong positive correlations with TP (0.64, $p<0.01$) and TN (0.64, $p<0.01$), suggesting that elevated nutrient levels facilitate organic matter accumulation and enhance microbial oxygen demand. Increased nitrogen and phosphorus levels are well documented to promote algal growth, leading to eutrophication and enhancing oxygen consumption during decomposition [65, 66]. Moreover, BOD_5 showed a strongly significant correlation with COD (0.49, $p<0.05$) and COD with TP (0.44, $p<0.05$), illustrating that chemical and biological oxygen demands are collectively influenced by nutrient-driven organic pollution [67]. These results emphasize the significance of monitoring nutrient inputs and minimizing pollution sources to prevent further degradation of urban water quality.

Assessing the Impact of Wetlands on Water Quality

The selected water quality parameters exhibited noticeable spatial and seasonal differences across

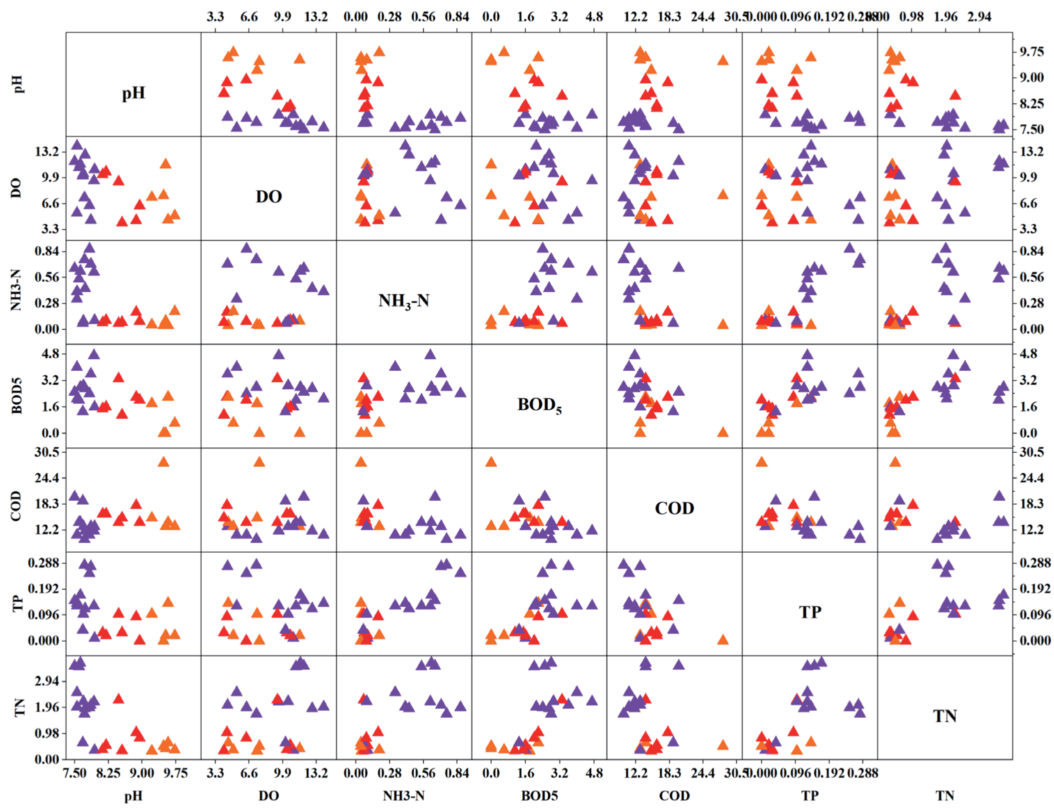

Fig. 4. Scatterplot matrix showing correlations among water quality parameters.

the sampling sites, as shown in Fig. 5. The top, middle, and bottom lines of boxplots represent the upper quartile, median, and lower quartile, respectively, while the whiskers indicate the threshold for identifying outliers.

Except for COD, clear variations were observed in the other parameters across different seasons and sampling sites, indicating that the wetlands substantially improve water quality. The levels of NH_3-N, BOD_5, TP, and TN showed substantial seasonal fluctuations, with higher peak values at river sites compared to wetland sites. This pattern emphasizes the essential role of wetlands in pollutant reduction, as they function as natural filters, thereby improving the quality of aquatic ecosystems [50].

Elevated levels of NH_3-N, BOD_5, TP, and TN were recorded during summer, indicating increased pollutant loading compared to the rainy season. Excessive rainfall dilutes pollutant levels and improves continuous water circulation within the river systems [18]. In contrast, the relatively stable COD levels across all seasons suggest that wetlands effectively reduce pollution, reinforcing their role in preserving aquatic environments [55]. In a broad context, the removal efficiencies of TN and TP observed in the study area are comparable to those reported for other constructed wetlands in various

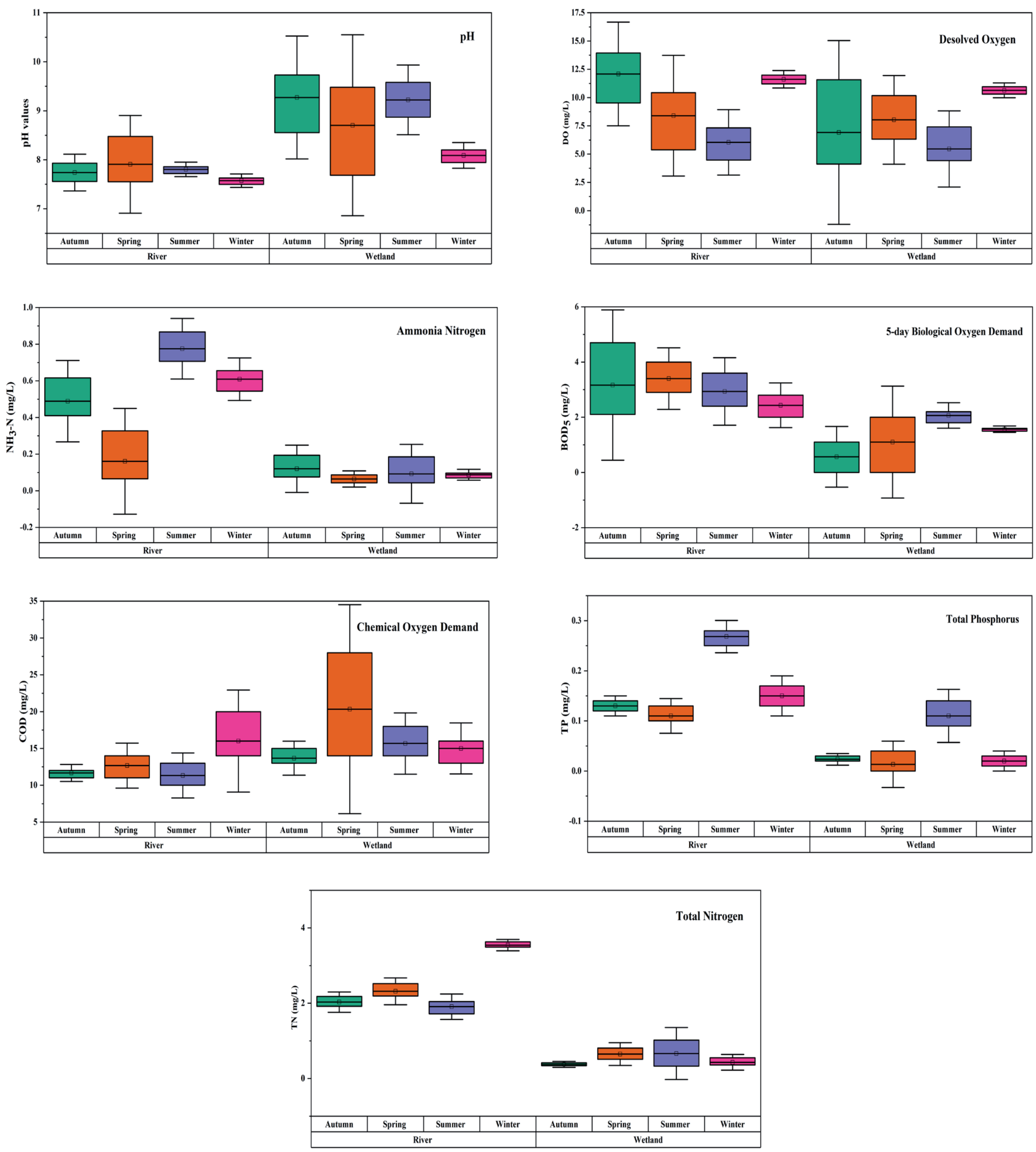

Fig. 5. Seasonal and spatial comparison of key parameters using boxplot analysis.

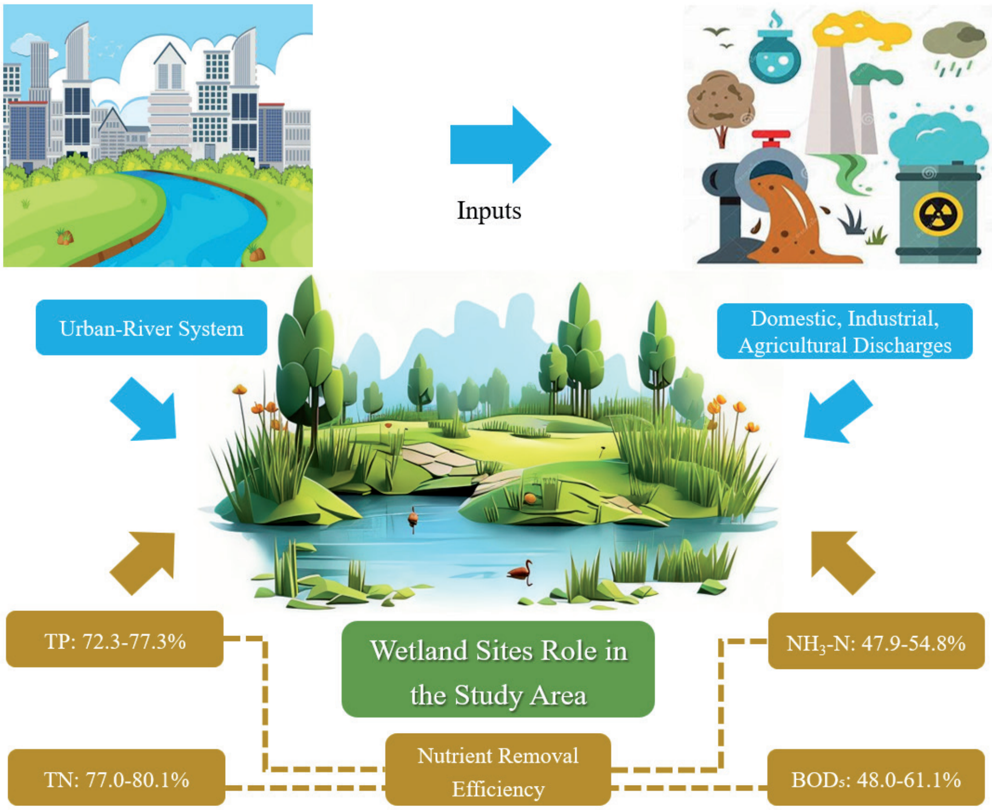

Fig. 6. The role of wetlands in urban water quality purification.

regions [46-48]. Notably, TP removal in the Pudong New Area is slightly higher, likely due to the strong binding and sorption capacity of the local substrates for phosphorus. Substrates with a rich elemental composition often facilitate phosphorus removal in constructed wetlands [68]. Moreover, macrophytes' dominance in the study area contributes significantly to phosphorus uptake and storage [48, 69]. These findings are consistent with studies indicating high nutrient removal efficiencies in constructed wetlands [70].

Elevated TP and TN levels during autumn and summer at river sites are consistent with previous studies [58], indicating their association with increased industrial and domestic wastewater discharge during these periods. Thus, the combined impact of anthropogenic activities, along with reduced water circulation, wastewater input, and riverbank development, likely contributes to elevated nutrient levels in the river [71]. Phosphorus reduction is primarily associated with adsorption onto soil particles and uptake by wetland vegetation [46]. Therefore, a noticeable phosphorus reduction at wetland sites was observed in our study, indicating that wetlands function as nutrient-absorbing sinks in these areas. Similarly, low TN levels suggest that nitrogen removal is facilitated by processes such as denitrification, microbial transformation, and plant assimilation [13, 53].

While rivers are directly exposed to pollution from several sources, such as urban runoff and agricultural discharge, wetlands regulate such macro-scale inputs to river systems. Wetlands help counter these pressures through filtration and absorption processes [72]. Furthermore, microbial decomposition and sedimentation within wetlands enhance their pollution removal capacity. As river water quality is susceptible to population growth, industrial activity, and land use patterns [65, 73], sustaining water quality requires enhancing wetland functions to manage pollutants from such sources. Therefore, monitoring wetland performance is essential for stabilizing ecological conditions and implementing sustainable water quality management strategies.

Considering the Pudong New Area, wetlands play an essential role in improving urban river water quality by reducing nutrient loads, transforming pollutants, and stabilizing ecological conditions. Fig. 6 provides a schematic representation of the study area, illustrating how wetland sites act as intermediate purification units within the urban river network.

These systems receive inputs from domestic, industrial, and agricultural sources and mitigate their impacts before water flows downstream. In this study, pollutant levels decreased substantially at wetland sites compared to river sites, indicating effective nutrient removal and improved water quality. Therefore, integrating constructed wetland parks into urban drainage networks would enhance nutrient removal efficiency, improve ecological resilience, and ensure the long-term sustainability of urban water quality.

Conclusions

This study provides quantitative evidence for the essential role of constructed wetlands in mitigating urban water pollution within the Pudong New Area. Besides the substantial differences in WQI values between river and wetland sites, our results illustrate how wetlands effectively alter nutrient dynamics within the area's urban drainage network. The strong removal efficacy for nutrients and organic pollutants indicates not only better performance of wetlands but also their capability to mitigate nutrient loads, the leading driver of eutrophication in urban rivers. Correlation and PCA analyses further demonstrated that nutrient pollution largely originated from anthropogenic activities and seasonal hydrological variations, which are major factors responsible for water quality variability in the study area. A key contribution of this study lies in evaluating wetland performance within a rapidly urbanizing region. Our results indicate that even relatively small constructed wetlands can markedly improve water purification, reduce nutrient loads, and support ecosystem stability and resilience. Therefore, for rapidly urbanizing areas, nature-based solutions such as constructed wetlands should be prioritized within integrated water management strategies. Incorporating wetlands into urban planning and river restoration frameworks can ensure long-term improvements in water quality, reduce eutrophication risks, and strengthen the overall resilience of urban river systems.

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Conflict of Interest

The authors declare no conflict of interest.

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