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The Temporal and Spatial Analysis and Assessment of Water Quality in the Tuo River (Suzhou Section) based on the CCME-WQI Method

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Abstract

To investigate the spatiotemporal variations and disparities in water quality within the Suzhou section of the Tuo River, as well as to identify the key pollution factors and influencing elements, this study utilized monitoring data from five water quality monitoring stations along the Tuo River in Suzhou, collected between 2020 and 2022. After analyzing the spatiotemporal variations in water quality indicators, the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) was employed to assess the river's water quality status. The study also examined the causes of water pollution and proposed appropriate pollution control measures. The research results indicate that:(1) Total Nitrogen (TN), Chemical Oxygen Demand (COD), Permanganate Index (COD_{Mn}), and Fluoride (F) were identified as the main pollution factors, with COD and TN being the primary pollutants exceeding standard limits, with exceedance rates of 55.66% and 37.14%, respectively;(2)From 2020 to 2022, the concentrations of CODMn, COD, and TN were significantly higher during the flood season compared to the non-flood season, suggesting that non-point source pollution is the major contributor to the pollution load;(3)Temporally, the study area exhibited significant seasonal variations in water quality, with water quality being better during the non-flood season than during the flood season. Spatially, the study area showed notable spatial differences in water quality, with the S1 monitoring station recording the poorest water quality, while the S3 station exhibited the best;(4)The water quality of the Tuo River was significantly influenced by precipitation, with increased rainfall during the flood season exacerbating urban runoff, agricultural non-point source pollution, and internal pollution within the river channels.

Keywords

Tuohe River; Suzhou; Water Quality Assessment; Spatiotemporal Variation; Causes of Water Pollution; Control Measures.

1. Introduction

With the increasing emphasis on water environment protection by national and local government authorities, China has undertaken significant initiatives in watershed water environment management, leading to a notable improvement in water quality and marked progress in environmental protection efforts. However, water pollution in certain watersheds remains a significant challenge, with some regions and sections still failing to consistently meet regulatory standards [1-3]. According to the "2022 China Ecological Environment Bulletin," 9.8% of the 3,115 national monitoring sections of surface water quality are classified below Class III, with 15.5% of the sections in the Huai River Basin falling into this category, indicating the severe water pollution situation in the Huai River Basin.

Research indicates that analyzing the spatial and temporal distribution characteristics of river water quality and conducting comprehensive evaluations can significantly contribute to targeted watershed water environment management, providing crucial support for the overall management of water environments [4]. Jiang et al. [5] utilized a combination of Hierarchical Cluster Analysis (HCA) and Positive Matrix Factorization (PMF) to identify non-point source pollution in the Huai River Basin. Hao Yongfei et al. [6] analyzed the spatial and temporal distribution characteristics of total phosphorus and heavy metal pollutants in the main stream of the Huai River from 2014 to 2017. Ming et al. [7] examined the characteristics of pollutant concentrations in the Huai River Basin from 2003 to 2012 and used statistical analysis to evaluate their spatial and temporal characteristics, trends, and seasonal variations. Jun et al. [8] applied multivariate statistical analysis to assess the spatial distribution of NH_{4+}-N, COD_{Mn}, TN, and TP in the Huai River Basin. Most existing studies on the Huai River Basin focus on the overall water quality assessment of the main stream, with few studies examining the spatial and temporal variations in the water quality of the Huai River tributary, the Tuo River.

As a significant tributary of the Huai River, the water quality of the Tuo River directly impacts the water pollution control efforts in the Huai River Basin. The Tuo River is not only a crucial river within Suzhou City but also the main receiving water body for the city, accommodating a large amount of domestic and industrial wastewater from Suzhou and surrounding areas [9]. In recent years, rapid population growth in towns along the Tuo River and the fast development of industrial and agricultural activities have led to the over-discharge of agricultural, industrial, and urban domestic wastewater, resulting in a continuous deterioration of water quality, which severely affects local socioeconomic development and public health [10]. Therefore, to improve the water environment quality of the Tuo River Basin, enhance the water quality of the Tuo River and the Huai River Basin, and effectively control sources of water pollution, it is essential to study the spatial and temporal variations and characteristics of the Tuo River's water quality, and to conduct a scientific and systematic evaluation of its water environment quality.

In light of this, this study analyzes the spatial and temporal variations and characteristics of water quality in the main stream of the Tuo River, based on water quality data from five monitoring sections in the Suzhou section of the Tuo River from 2020 to 2022. The Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) is used, in conjunction with the "Surface Water Environmental Quality Standards" (GB 3838-2002), to evaluate the water quality status. On this basis, the causes of water pollution are analyzed, and scientifically sound water pollution prevention and control measures are proposed, with the aim of providing a scientific basis for improving the water quality in the Tuo River Basin and offering strong support for the formulation of reasonable water environment management policies.

2. Materials and Methods

2.1. Study Area Overview

The Tuo River is a seasonal river primarily replenished by precipitation. From June to September, the region experiences abundant rainfall, leading to increased river runoff, marking the flood season. The Suzhou section of the Tuo River starts at the Tuo River inlet gate and ends at Fanjicun in Dinghu Town, Sixian County, with a total length of 103 km and a water surface area of approximately 3,195 km^2 [11]. Suzhou City, located in the southern part of the Huang-Huai Plain, is an important component of the Huaibei Plain. The annual precipitation ranges between 774 and 895.6 mm, with the majority of rainfall occurring in the summer. Suzhou is also one of the cities severely affected by water scarcity, with an average total water volume of 3.48 billion m^3 and a per capita water volume of 602 m^3, accounting for only 26% of the average in Anhui Province [12]. The land use in Suzhou City is predominantly agricultural, with major crops including corn, wheat, soybeans, and vegetables, making it an important grain production base in China [13].

2.2. Data Sources

This study utilizes monthly water quality monitoring data from five monitoring sections within the Suzhou section of the Tuo River, spanning from 2020 to 2022 (Figure 1). The water quality monitoring data were obtained from the Suzhou Environmental Protection Monitoring Station. Eleven water quality indicators were selected: Water Temperature (TW), Electrical Conductivity (EC), pH, Dissolved Oxygen (DO), Permanganate Index (COD_{Mn}), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD_5), Total Nitrogen (TN), Ammonia Nitrogen (NH_3-N), Total Phosphorus (TP), and Fluoride (F).

2.3. 2.3 CCME-WQI Evaluation Method

In this study, the Canadian Water Quality Index (CCME-WQI) was used to evaluate the current water quality status. Due to its flexible applicability, the CCME-WQI is widely employed for comprehensive assessments of surface water quality in China [14-15]. This method allows for both qualitative and quantitative evaluation of whether the target water body meets the specified water quality objectives [16]. By integrating information on the percentage of parameters exceeding the standard, the percentage of monitoring results that exceed the standard, and the extent to which these values exceed the standard, the CCME-WQI provides a clear and intuitive representation of the degree of pollution in a water body [17]. The calculation method for the CCME-WQI is as follows:

$$CCME\text{-}WQI = 100 - \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \tag{1}$$

$$F_1 = \frac{P}{N} \times 100 \tag{2}$$

$$F_2 = \frac{q}{M} \times 100 \tag{3}$$

$$F_3 = \frac{Q}{0.01Q + 0.01} \times 100 \tag{4}$$

$$Q = \frac{\sum S}{M} \tag{5}$$

In the formula, F1 represents the percentage of parameters that exceed the standard (Scope);P is the number of water quality parameters exceeding the standard and N is the total number of water quality parameters;F2 indicates the percentage of monitoring instances where parameters exceed the standard (Frequency); q is the number of exceedances and M the total number of monitoring instances;F3 measures the amplitude or the extent of exceedance (Amplitude);Q is the normalized parameter, calculated as the ratio of the sum of the exceedance ratios for each parameter to the total number of monitoring instances;S is the exceedance ratio for a specific parameter. The CCME-WQI values range from 0 to 100, with higher values indicating lower pollution levels and better water quality. The index is divided into five categories: Excellent (94–100], Good (79–94], Fair (64–79], Marginal (44–64], and Poor (0–44].

3. Results and Discussion

3.1. Analysis of Water Quality Indicators

The statistical analysis of water quality indicator data from various monitoring sections between 2020 and 2022 is summarized in Table 1. The pH values ranged from 6 to 9, with an average of 8.25, indicating that the water was generally weakly alkaline. Electrical Conductivity (EC) varied between 79.7 and 2140 m^{S}/m, with an average of 408.81 m^{S}/m. The Dissolved Oxygen (DO) levels averaged 9.98 mg/L, suggesting a well-oxygenated environment in the water body.

The mean concentrations of Permanganate Index (COD_{Mn}), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD_5), Ammonia Nitrogen (NH_3-N), Total Nitrogen (TN), Total Phosphorus (TP), and Fluoride (F) were 5.48 mg/L, 20.23 mg/L, 2.94 mg/L, 0.20 mg/L, 1.29 mg/L, 0.10 mg/L, and 0.98 mg/L, respectively. Among these, (NH_3-N) and (TP) exhibited significant spatial and temporal variability, with coefficients of variation of 0.85 and 1.24, respectively.

According to the Class III water quality standards set by the "Environmental Quality Standards for Surface Water" (GB3838-2002), the exceedance rates for TN and COD were relatively high, at 55.66% and 37.14%, respectively. Fluoride, COD_{Mn}, BOD_5, and TP also exceeded the standards at rates of 30.48%, 27.6%, 18.1%, and 2.83%, respectively. Overall, TN, COD, COD_{Mn}, and Fluoride were identified as the main pollutants, with COD and TN being the primary factors contributing to water quality standard violations. The following sections will further explore the spatial and temporal variations of these four key water quality parameters.

Table 1. Statistical values of water quality indicators from 2020 to 2022

water quality indicators	exceedance rate	minimum value	maximum value	mean value	standard deviation	coefficient of variation
TW/℃	/	1.8	33.6	18.47	8.85	0.48
pH	0	8	9	8.25	0.43	0.05
EC/(ms/m)	/	79.7	2140	261.75	408.81	1.56
ρ(DO)(mg/L)	0	5.6	18.6	9.98	2.28	0.23
ρ(COD_{Mn})(mg/L)	27.6%	3	12.2	5.48	1.23	0.22
ρ(COD)(mg/L)	37.14%	11	39.1	20.23	4.32	0.21
ρ(BOD_5)(mg/L)	18.1%	1.3	5.2	2.94	0.70	0.24
ρ(TN)(mg/L)	55.66%	0.06	4.3	1.29	0.77	0.59
ρ(NH_3-N)(mg/L)	0	0.02	0.92	0.20	0.17	0.85
ρ(TP)(mg/L)	2.83%	0.01	1.08	0.10	0.12	1.24
ρ(F)(mg/L)	30.48%	0.65	1.8	0.98	0.24	0.25

3.2. Analysis of Temporal and Spatial Characteristics of Water Quality

Based on the hydrological characteristics of Suzhou City, June to September is the flood period (high water period), while October to May of the following year is the dry period (low water period) [18-19]. The temporal and spatial variations and significance of water quality indicators are illustrated in Figs 1 and 2.

For Total Nitrogen (TN), the mean concentration during the flood period ranged from 1.32 to 2.63 mg/L across different monitoring sections. The highest mean TN concentration of 2.65 mg/L was observed at section S1 during the flood period, classifying it as Grade V water quality, which is considered very poor. For Chemical Oxygen Demand (COD), the concentrations ranged from 11.0 to 39.1 mg/L, with the highest mean COD concentration of 25.47 mg/L recorded at section S1 during the flood period, corresponding to Grade IV surface water quality standards. For Permanganate Index (COD$_{Mn}$), the concentrations ranged from 3.0 to 12.2 mg/L, with mean COD$_{Mn}$ values at sections S1, S2, S4, and S5 during the flood period ranging from 6.05 to 7.47 mg/L, all exceeding the Grade III surface water quality standards. For Fluoride (F), concentrations ranged from 0.65 to 1.80 mg/L, with mean F concentrations during the dry period exceeding those during the flood period at all five sections. Specifically, the mean F concentrations during the dry period at sections S1, S3, S4, and S5 all surpassed the Grade III surface water quality standards.

Significance analysis indicates that concentrations of COD$_{Mn}$, COD, and TN during the flood period are significantly higher than those during the dry period ($P < 0.05$). This pattern, where pollutants predominantly from non-point sources are higher during the flood period compared to the dry period [20], suggests that surface runoff significantly impacts water quality in the study area, with non-point source pollution being a major contributor to the pollution load.

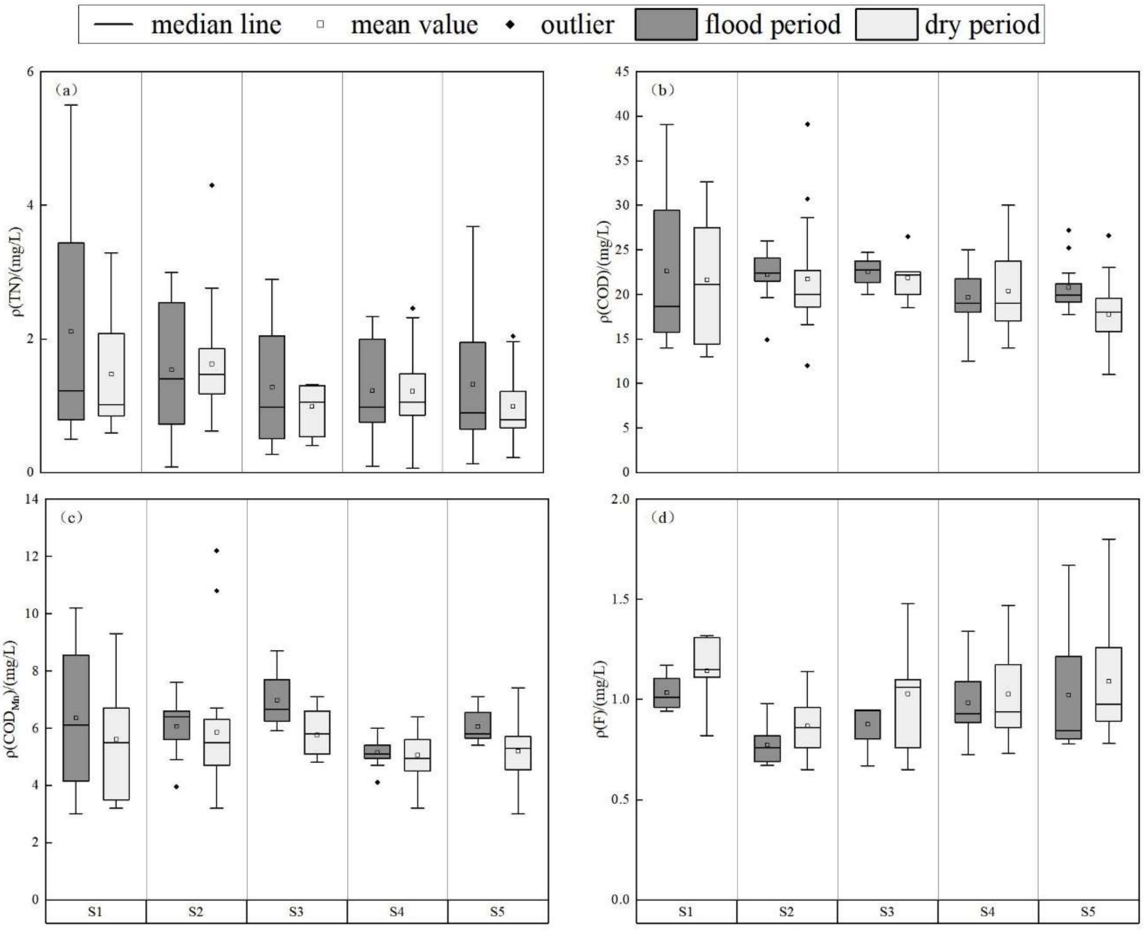

Fig. 1 Spatiotemporal variation of water quality indicators

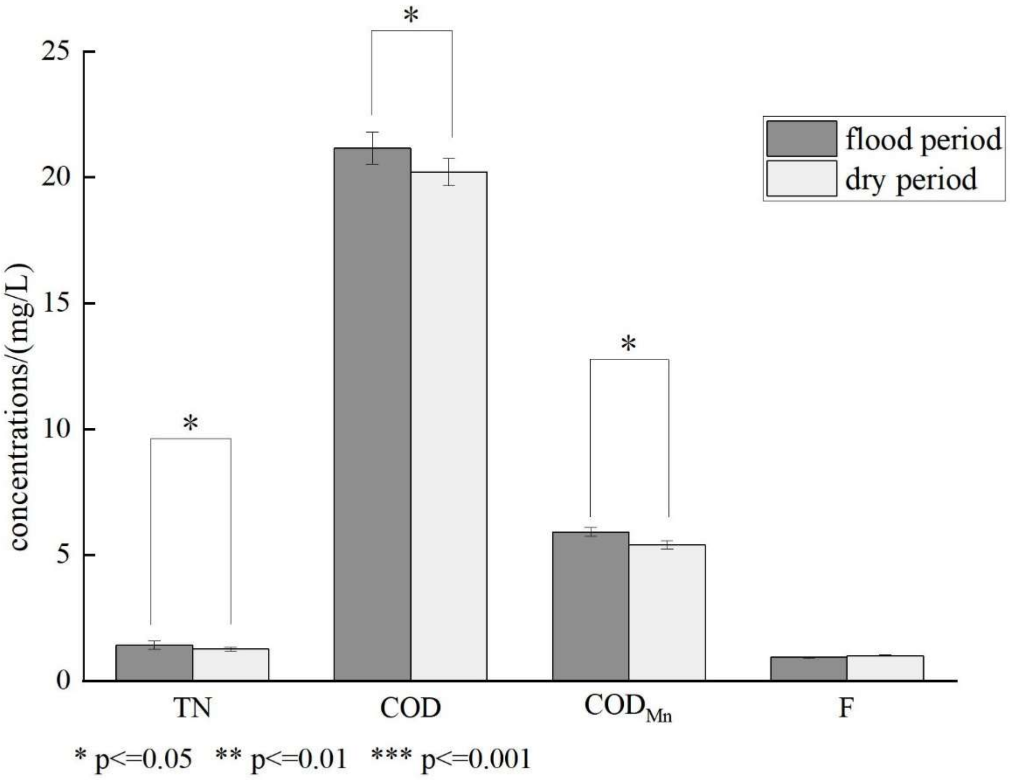

Fig. 2 Significance of water quality indicators

3.3. CCME-WQI Water Quality Evaluation

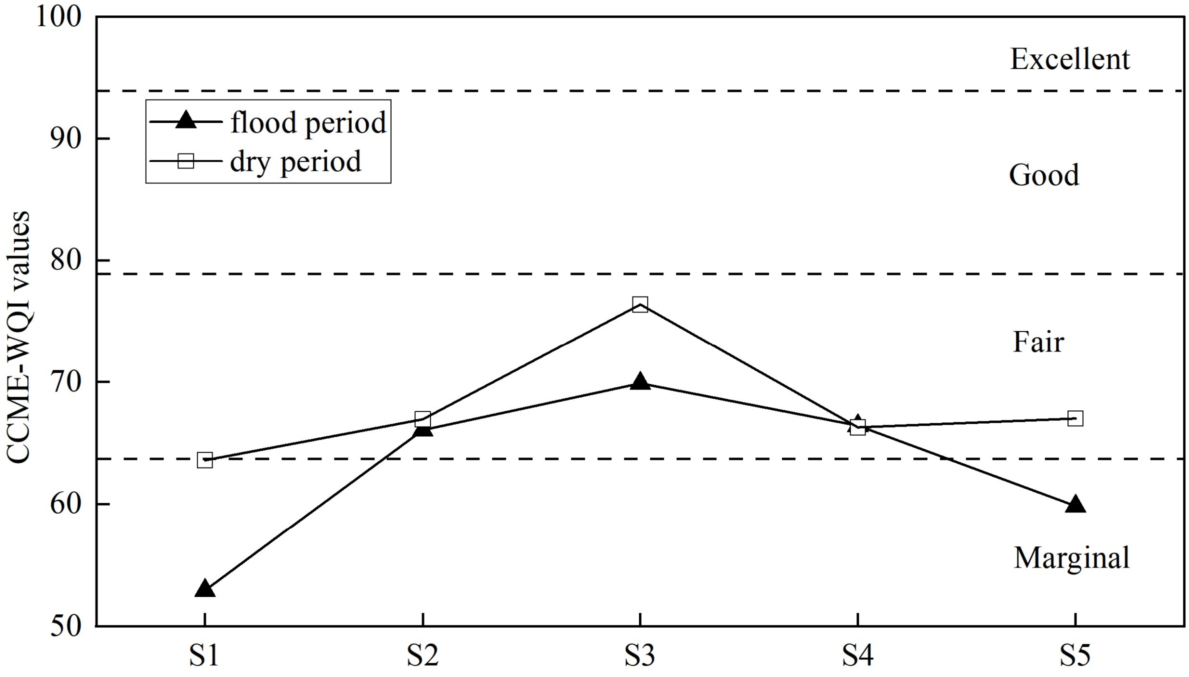

Fig. 3 CCME-WQI values of water quality monitoring sections in different periods

This study, based on the Class III water quality standards outlined in the "Environmental Quality Standards for Surface Water" (GB3838-2002), excluded parameters that met or exceeded Class III standards. The selected parameters for evaluation were Biochemical Oxygen Demand over 5 days (BOD_5), Permanganate Index (COD_{Mn}), Chemical Oxygen Demand (COD), Total Nitrogen (TN), Total Phosphorus (TP), and Fluoride (F). Using the CCME-WQI evaluation method, the water quality of five monitoring sections was assessed for the flood and non-flood periods from 2020 to 2022. The water quality evaluation results are shown in Fig.3.

Temporally, during the flood period, 60% of the sections had a water quality rating of "Fair," while the remaining were "Marginal." During the non-flood period, 80% of the sections had a water quality rating of "Fair," and the rest were "Marginal." The water quality ranking during the flood period was S3 (69.88) > S4 (66.28) > S2 (66.05) > S5 (59.82) > S1 (52.91), while the ranking during the non-flood period was S3 (76.38) > S2 (67.08) > S5 (67.00) > S4 (66.41) > S1 (63.58). Spatially, Section S1 had the poorest water quality, with CCME-WQI values of 52.91 and 63.58 during the flood and non-flood periods, respectively, both categorized as "Marginal." Section S3 had the best water quality, with CCME-WQI values of 69.88 and 76.38 during the flood and non-flood periods, respectively, both categorized as "Fair."

3.4. Analysis of the Causes of Water Pollution

(1) Inadequate Urban Stormwater and Sewage Infrastructure

Research by Hou Xikang et al. [21] indicates that urban sewage and runoff are major sources of COD in the Tuo River basin, contributing 60% to the pollution load. Currently, Suzhou City's urban areas commonly experience mixed stormwater and sewage systems, with existing pipelines suffering from misconnections, leaks, and inefficiencies. This incomplete separation of stormwater and sewage results in insufficient inflow and low concentration at sewage treatment facilities, frequent overflow during the rainy season, and low operational efficiency. Additionally, uncontrolled drainage from "small, scattered, and chaotic" sources exacerbates high-concentration runoff pollution following initial rainfall.

(2) Significant Agricultural Non-Point Source Pollution

Research by Yang Qin et al. [19] shows that land use types significantly impact river water quality in the Huai River basin. According to Hou Xikang et al. [21], rural domestic and agricultural activities are the primary sources of TN in the Tuo River basin, contributing 52% to the pollution load. Suzhou City, a key grain-producing area in Anhui Province, has a total arable land area of 599,200 hectares as of the 2022 land survey. With 939,000 hectares planted with grain crops in 2022 and a total yield of 4.8 million tons, the extensive use of pesticides and fertilizers during cultivation exacerbates agricultural non-point source pollution.

(3) Water Scarcity and Numerous Dams Intensify Pollution

Suzhou City is situated in a transitional climate zone with uneven spatial and temporal distribution of water resources. Approximately 70% of rainfall runoff occurs during the flood period from June to September, making water resource development and utilization challenging and highlighting water scarcity issues. As an industrial transfer and agricultural production hub in northern Anhui, Suzhou faces increasing demand for water for industrial and agricultural purposes, intensifying the supply-demand conflict.

The increasing number of dam and weir projects in Suzhou, combined with a dense network of artificial waterways and natural rivers, complicates the regulation of flow. This leads to many river and lake systems being in a state of storage without flow, with some river sources experiencing perennial flow interruptions. The loss of the rivers' self-purification capacity, combined with pollutant accumulation and reduced downstream flow due to interception, results in consistently high levels of water pollution with insufficient dilution.

4. Conclusion and Recommendations

4.1. Conclusion

Through the analysis of water quality indicators for the Suzhou section of the Tuo River from 2020 to 2022, the main pollutants identified include Total Nitrogen (TN), Chemical Oxygen Demand (COD), Permanganate Index (CODMn), and Fluoride (F). Among these, COD and TN are the primary factors causing water quality exceedances, with exceedance rates reaching 55.66% and 37.14%, respectively. The water quality evaluation results indicate significant temporal and spatial variations in the Suzhou section of the Tuo River. Temporally, the water quality is better during the flood period compared to the non-flood period, with ρ(CODMn), ρ(COD), and ρ(TN) being significantly higher during the flood period ($P < 0.05$). Spatially, regardless of the period, Section S1 has the poorest water quality, while Section S3 has the best. The primary reasons for the deterioration of water quality during the flood period in the Tuo River basin are the inadequate urban stormwater and sewage infrastructure and the excessive use of pesticides and fertilizers in agriculture. Therefore, targeted measures should be implemented to improve the water quality in the Suzhou section of the Tuo River.

4.2. Recommendations

(1)Enhance Urban Non-Point Source Pollution Control

Currently, Suzhou City lacks adequate stormwater and sewage infrastructure, and mixed stormwater and sewage flows are common. Therefore, efforts should be made to expedite the improvement of stormwater and sewage infrastructure, focusing on the collection, storage, and treatment of initial rainwater. Specifically, before the flood period, it is crucial to inspect and clean up accumulated pollutants, such as sewage and waste, from urban pipelines to prevent "zero retention and complete removal" scenarios. Additionally, effectively address "small, scattered, and chaotic" sources of wastewater and waste, renovate stormwater inlets in areas like dining zones and agricultural markets within urban built-up areas into new stormwater collection points, and install smart control systems with capture and sensor alarm devices.

(2)Strengthen Agricultural Pollution Control

As a key grain-producing area in the country, Suzhou City's arable land exceeds 50% of its total area. Implementing scientific and reasonable control measures can significantly reduce the impact of agricultural non-point source pollution. To this end, it is important to promote subsidy pilot programs for low-toxicity, low-residue pesticides, encourage farmers to use organic fertilizers instead of chemical fertilizers, and carry out green pest and disease control for crops. Additionally, efforts should be made to enhance field water-saving infrastructure by promoting advanced water-saving irrigation methods such as drip and sprinkler irrigation, and implementing soil testing-based fertilization and integrated water-fertilizer technology to improve water and fertilizer use efficiency. These measures will help effectively reduce agricultural non-point source pollution and ensure the sustainable development of agricultural production.

(3)Enhance River Channel Management and Ecological Restoration

The Suzhou section of the Tuo River has a high density of dams and weirs, leading to significant anthropogenic disturbance and poor self-purification capacity of the river ecosystem. It is necessary to strengthen river channel cleaning and dredging work, thoroughly remove accumulated pollutants from ponds, channels, and weirs before the flood period, and reduce and avoid the concentrated discharge of accumulated pollutants during the flood period to lower the risk to the aquatic environment. To purify water quality, intercept and reduce river pollutants, and increase biodiversity in the riverbank areas, it is essential to construct riparian buffer zones. Additionally, aiming to achieve a "fish and vegetation" environment, implement aquatic vegetation restoration in the Tuo River under effective management, and restore riverine ecosystems through habitat restoration, aquatic vegetation recovery, biodiversity protection, and the construction of ecological floating islands.

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