Water Pollution Characteristics and Remediation Technologies for Urban Rivers

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Abstract: This paper focuses on water pollution in urban rivers and summarizes the pollution characteristics of river water quality and the spatial distribution patterns of pollution sources based on water quality monitoring data from multiple river reaches. Methods including water quality indicator monitoring, pollution source apportionment, and numerical simulation were used to investigate the spatiotemporal variation characteristics of major pollutants such as COD, ammonia nitrogen, total phosphorus, and heavy metals. The results show that pollution in urban rivers exhibits significant spatial heterogeneity and seasonal variation, and the pollution level is markedly affected by urbanization, population density, and industrial layout. Point-source pollution is mainly associated with the discharge of industrial wastewater and domestic sewage, while non-point-source pollution primarily originates from urban stormwater runoff and agricultural non-point-source inputs. In response to these pollution characteristics, this paper reviews three types of river remediation technologies, namely physical, chemical, and biological remediation, including dredging and bank protection, flocculation and oxidation, constructed wetlands, and aquatic plant remediation. Engineering practices indicate that integrated remediation technologies are more effective than single technologies, with COD removal exceeding 85% and ammonia nitrogen removal reaching over 90%. The findings provide a reference for urban river water environment management and contribute to improving urban water environments and promoting sustainable urban development.

Keywords: urban rivers; water pollution; pollution characteristics; remediation technologies; water environment management

1. Introduction

Urban rivers are an important component of urban water bodies and play a significant role in flood control and drainage, environmental beautification, and ecological protection. However, with the rapid development of urban construction, pollution in urban rivers has become increasingly serious. According to the Bulletin on the State of China’s Ecological Environment issued by the Ministry of Ecology and Environment, although the quality of the national surface water environment improved during 2019–2023, pollution in urban rivers remained severe, with approximately 60% of urban river reaches failing to meet the requirements of their designated functional zones. Urban river pollution not only affects the safety of domestic water use and public health, but also has a substantial impact on urban ecological environments and sustainable development.

2. Investigation and Analysis of the Current Status of Water Pollution in Urban Rivers

2.1 Overview of the Study Area and Sampling Site Arrangement

This study selected typical urban rivers in the Yangtze River Delta as the research objects, including major rivers in Shanghai, Nanjing, Hangzhou, and other major cities. The urbanization rate of the study area was 72.3%, the population density was 1,127 persons per square kilometer, and its gross industrial output value accounted for more than 25% of the national total. Based on river functional zoning, pollution source distribution, hydrological characteristics, and other factors, 126 water quality monitoring sites were established within the study area, including 68 sites along trunk rivers and 58 sites along tributaries. The sampling sites were arranged according to the principles of representativeness, systematic coverage, and operational feasibility, so as to effectively reflect the water quality conditions of different river reaches and functional zones [1]. Monitoring was conducted twice per month for 24 consecutive months, yielding a total of 6,048 valid data sets, which provided a solid data foundation for analyzing pollution characteristics.

2.2 Detection and Evaluation of Water Pollution Indicators

The detected water pollution indicators included chemical oxygen demand (COD), biochemical oxygen demand (BOD), ammonia nitrogen, total nitrogen, total phosphorus, heavy metals, and other parameters, all of which were determined using national standard methods. The detection results showed that the water quality of urban rivers in the study area was generally at a moderate pollution level. The mean COD concentration was 45.2 mg/L, which was 1.25 times the Class III standard for surface water. The mean ammonia nitrogen concentration was 3.8 mg/L, with an exceedance rate of 68.7%. The mean total phosphorus concentration was 0.35 mg/L, with an exceedance rate of 71.2%. Regarding heavy metal pollution, the detection rates of copper, zinc, and lead were 89.3%, 92.1%, and 76.5%, respectively, although their exceedance rates were relatively low. Evaluation based on the single-factor pollution index and the comprehensive pollution index indicated that 78.3% of the monitoring sections had water quality inferior to Class V, with ammonia nitrogen, total phosphorus, and COD being the main indicators exceeding the standards. The degree of water pollution was closely related to surrounding land use types, population density, and industrial layout, and the most polluted river reaches were located near industrially intensive areas and densely populated areas.

2.3 Pollution Source Identification and Quantitative Analysis of Pollution Loads

An investigation of pollution sources in typical urban rivers showed that point-source pollution and non-point-source pollution were the main causes of urban river pollution. Point-source pollution mainly included direct wastewater discharge from industrial enterprises, effluent from urban domestic sewage treatment plants, and scattered sewage outlets in riverside residential areas. Industrial wastewater discharge accounted for 42%–58% of the total discharge, while domestic sewage discharge accounted for 35%–45%. According to the water quality monitoring results of key urban rivers nationwide from 2019 to 2023, the pollution load intensity of rivers in highly urbanized areas such as the Yangtze River Delta and the Pearl River Delta reached 15–25 $kg/km^2 \cdot d$, much higher than the national average of 8–12 $kg/km^2 \cdot d$. Non-point-source pollution mainly originated from urban surface runoff, agricultural non-point-source inputs, and atmospheric deposition. Its contribution rate showed significant seasonal variation, and during the rainy season, non-point-source pollution loads could account for 60%–70% of the total pollution load [2].

Quantitative analysis of pollution loads was conducted through pollutant flux calculation and source apportionment. On this basis, a pollution load estimation method based on synchronous monitoring of hydrology and water quality was proposed. The results showed that COD pollution loads in urban rivers were mainly concentrated in industrially intensive areas and densely populated areas, and that the unit-area pollution load intensity was significantly positively correlated with the urbanization rate ($R^2 = 0.78$). The spatial distribution of ammonia nitrogen pollution loads was related to the coverage and treatment efficiency of sewage treatment facilities. For every 10% increase in the sewage treatment rate, the ammonia nitrogen pollution load in rivers could be reduced by 15%–20%. Heavy metal pollution loads mainly originated from electroplating, chemical, metal processing, and other industries, showing clear industrial clustering characteristics. The pollution contribution rates of copper, zinc, and lead were 28%, 24%, and 19%, respectively.

3. Study on the Characteristics of Water Pollution in Urban Rivers

3.1 Analysis of Spatiotemporal Distribution Characteristics

Water pollution in urban rivers exhibits clear spatiotemporal distribution patterns. Spatially, the pollution degree generally follows the pattern of “lighter pollution upstream and heavier pollution downstream, and lighter pollution in mainstream channels and heavier pollution in tributaries.” The COD concentration in downstream river reaches was 142% higher than that in upstream reaches, while the ammonia nitrogen concentration was 187% higher. River pollution was most serious in central urban areas and gradually decreased toward the periphery, showing an inverse relationship between pollution degree and distance from the urban center. Temporally, water pollution showed significant seasonal variation. During the dry season from November to March of the following year, pollutant concentrations were, on average, 35.6% higher than those during the wet season from June to September. Within a single day, pollutant concentrations showed two peaks, occurring from 8:00 to 10:00 a.m. and from 6:00 to 8:00 p.m., which corresponded to daily domestic activities and industrial production activities. Rainfall had a dual effect on water quality. Light rainfall, with daily precipitation of 5–15 mm, increased pollutant concentrations, whereas heavy rainfall, with daily precipitation greater than 50 mm, exerted a dilution effect, reducing pollutant concentrations by 20%–40%.

3.2 Source Apportionment of Major Pollutants

The chemical mass balance method and principal component analysis were used to quantitatively apportion the sources of major pollutants in urban rivers. The source apportionment results for ammonia nitrogen showed that domestic sewage had the highest contribution rate, reaching 42.8%, followed by industrial wastewater at 28.3% and agricultural non-point sources at 18.7%, while urban runoff contributed 10.2% [3]. For total phosphorus sources, domestic sewage and industrial wastewater contributed 39.5% and 31.2%, respectively, agricultural non-point sources contributed 20.1%, and other sources accounted for 9.2%. Heavy metal pollution mainly originated from industrial discharge. The industrial source contribution rate for copper reached 73.4%, while those for zinc and lead were 65.8% and 58.9%, respectively. Nitrate source apportionment based on stable isotope technology showed that nitrate from domestic sewage accounted for 56.2%, soil organic nitrogen mineralization contributed 23.4%, and fertilizer sources accounted for 20.4%. The contribution rates of pollutant sources showed clear spatial differences. In industrially concentrated areas, the contribution rate of industrial sources was 15%–25% higher than the average level, whereas agricultural non-point sources contributed relatively more in rural river reaches.

3.3 Migration and Transformation Patterns of Pollutants

Based on a coupled hydrodynamic–water quality model, the general patterns of pollutant migration and transformation in urban rivers were identified. Pollutant migration in river channels was mainly driven by advection, diffusion, and degradation, with advection being the dominant process. COD degradation in rivers followed first-order kinetics, with a degradation coefficient of 0.15–0.28 d^{-1} and a half-life of 2.5–4.6 days. The migration and transformation of ammonia nitrogen were relatively complex, involving both volatilization loss and nitrification, with a nitrification rate constant of 0.08–0.19 d^{-1}. Total phosphorus migration was mainly governed by adsorption–desorption processes. The adsorption coefficient was related to riverbed sediment properties, and river reaches with a higher proportion of fine particles had larger adsorption coefficients. The migration and transformation of heavy metals mainly depended on particulate matter sedimentation and resuspension processes, and the settling velocity was positively correlated with particle size and density. River flow velocity had a substantial effect on pollutant migration distance. When flow velocity increased by 50%, the pollutant migration distance increased by 80%–120%, indicating that hydrodynamic conditions were a major factor determining the spatial distribution of pollutants.

4. Development and Application of Water Quality Remediation Technologies for Urban Rivers

4.1 Mechanisms and Effect Evaluation of Bioremediation Technologies

Bioremediation removes pollutants by using microbial metabolism and the purification functions of aquatic plants, including the addition of highly efficient degrading bacterial strains to constructed wetlands [4]. Studies have shown that nitrifying bacteria and denitrifying bacteria play important roles in ammonia nitrogen transformation. Nitrification converts ammonia nitrogen into nitrite and nitrate, whereas denitrification reduces nitrate to nitrogen gas. The root systems of aquatic plants release oxygen to create an aerobic environment. Meanwhile, plant uptake and rhizosphere microbial activity contribute effectively to phosphorus removal. In practical applications, constructed wetlands can achieve COD removal rates of 75%–85%, ammonia nitrogen removal rates of 80%–92%, and total phosphorus removal rates of 70%–85%. Microbial enhancement technology can increase the ammonia nitrogen removal rate to more than 90% by adding specific functional bacterial strains. It can also effectively remove refractory organic pollutants and shorten the treatment time by 30%–40% compared with conventional biological treatment, making it a green and sustainable approach for urban river management.

4.2 Optimization of Physicochemical Remediation Technologies

Physicochemical remediation technologies use flocculation–sedimentation, advanced oxidation, membrane separation, and other methods for rapid pollutant removal and advanced treatment. A composite flocculant composed of polyaluminum chloride and polyacrylamide has a strong flocculation effect on suspended solids and colloidal pollutants at a pH of 6.5–7.5, with a turbidity removal rate of more than 95%. The ozone/ultraviolet advanced oxidation process uses highly oxidative hydroxyl radicals to effectively remove organic pollutants that are difficult to biodegrade, achieving removal rates of 85% for polycyclic aromatic hydrocarbons and 78% for heavy metal complexes. The combined use of ultrafiltration and reverse osmosis membrane technologies enables precise pollutant separation, with a retention rate of more than 99% for heavy metal ions, and the effluent quality can meet the Class IV standard for surface water. Studies on technological improvement have shown that appropriate regulation of flocculant dosage, oxidant concentration, and membrane flux can reduce overall treatment costs by 25%–35% while greatly improving treatment performance and the stability of effluent water quality.

4.3 Integrated Application of Ecological Engineering Remediation Technologies

Ecological engineering remediation technologies use the self-restoration capacity of river ecosystems to achieve long-term water quality improvement and ecological function restoration. Ecological bank protection projects adopt a combination of porous concrete and vegetated slope protection, which ensures flood control safety while providing habitats for aquatic organisms. In addition, the joint action of plant roots and microbial biofilms continuously removes pollutants. River aeration and oxygenation technology involves installing microporous aeration devices on the riverbed to increase dissolved oxygen in the water, improve hypoxic conditions, promote the growth and reproduction of aerobic bacteria, and accelerate the decomposition of organic matter [5]. Aquatic plant configuration uses submerged plants, floating plants, and emergent plants for three-dimensional planting, thereby forming a complete aquatic plant community.

Experience from integrated applications shows that combining ecological engineering remediation with bioremediation and physicochemical remediation can significantly improve remediation effectiveness. In comprehensive remediation demonstration projects, river water quality was improved from inferior to Class V to Class IV. COD concentration decreased from the original 80–120 mg/L to below 25 mg/L, ammonia nitrogen concentration decreased from the original 15–25 mg/L to below 2 mg/L, and total phosphorus concentration was controlled below 0.3 mg/L. Meanwhile, ecosystem restoration also promoted an increase in biodiversity. Fish population size increased by more than 60%, and the frequency of waterbird habitation increased by more than threefold, achieving the objectives of water environment management and ecological protection.

4.4 Construction of a Monitoring and Evaluation System for Remediation Effects

In recent years, the urban river water environment management industry has developed rapidly. According to statistics from the China Association of Environmental Protection Industry, the scale of China’s water environment management market increased from CNY 1.2 trillion to CNY 1.8 trillion from 2019 to 2024, with an average annual growth rate of 8.5%. To ensure the effectiveness and sustainability of remediation technologies, a scientific and reasonable method for monitoring and evaluating remediation effects is required. This method is based on changes in water quality indicators and conducts comprehensive assessment from physicochemical, biological, and ecological perspectives. Automatic monitoring stations and mobile monitoring instruments are deployed along rivers to conduct real-time monitoring of major water quality indicators such as COD, ammonia nitrogen, total phosphorus, and dissolved oxygen. At the same time, ecological health indicators, including the biodiversity index, benthic animal community structure, and aquatic plant coverage, are considered to comprehensively reflect the effectiveness of river remediation.

The evaluation method combines the analytic hierarchy process with the fuzzy comprehensive evaluation method to construct a comprehensive evaluation model for remediation effects. Three first-level indicators, namely water quality improvement, ecological restoration, and landscape coordination, as well as 12 second-level indicators, are selected. Scores are assigned according to weight allocation and scoring criteria, thereby enabling quantitative evaluation of remediation effects. Monitoring data show that, after comprehensive remediation, the comprehensive water quality index of urban rivers increased by approximately 65%, the biodiversity index increased by more than 40%, and the stability of river ecosystems was greatly improved. Meanwhile, through the establishment of an early warning mechanism and a feedback regulation system, this evaluation method can promptly identify problems during the remediation process and improve the corresponding technologies, which is conducive to the development and promotion of urban river water quality remediation technologies.

5. Conclusion

Through an investigation of water pollution conditions and control measures in urban rivers, this paper summarizes the spatial distribution patterns of urban river water pollution and the composition of pollution sources, and proposes multiple river remediation methods. Water pollution in urban rivers shows considerable spatial heterogeneity and temporal variability. The degree of pollution is related to the level of urbanization, and the interaction between point-source pollution and non-point-source pollution leads to complex pollution conditions.

The application effect of integrated remediation technologies is far superior to that of single technologies. The combination of physical, chemical, and biological remediation technologies can achieve a COD removal rate of more than 85% and an ammonia nitrogen removal rate of more than 90%, thereby playing a positive role in promoting technological progress in the urban water environment protection industry [6]. The pollution characteristic identification method and remediation technology system proposed in this study provide guidance for urban river water environment management and are of great significance for improving the quality of China’s urban water environment and promoting the development of the water environment protection industry.

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