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Progress of Research on Water Quality Pollution and Treatment Countermeasures in the Yellow River Basin

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Abstract. The Yellow River, China's second longest river, plays a crucial role in the nation's economic and social development as well as ecological security. Currently, water quality issues in the Yellow River Basin threaten water supply security, farmland ecosystems, and crop production, leading to reduced yields and degraded crop quality. At the same time, there are fewer relevant studies evaluating the current status of water quality in the watershed (especially in the Yellow River Basin) and the pollution sources of industrial enterprises. Based on the existing literature and data, this paper presents a systematic review of the research on water quality pollution and management countermeasures in the Yellow River Basin. The study reveals that urban clusters in the middle and lower reaches of the Yellow River Basin have formed a pollution agglomeration pattern, indicating that in the spatial management of water pollution, focusing on the pollution control of a single city has a limited impact on the improvement of the overall water quality of the basin, and that there is a need to further utilize inter-regional synergies and to strengthen the synergistic control and management of the pollution in the middle and lower reaches of the basin in the areas of population agglomeration and urban agglomerations.

Keywords: Yellow River Basin, Water Quality Pollution, Basin Management, Water Environment Monitoring, Basin Water Safety

1. Introduction

The Yellow River traverses nine provinces in China, extending 5,464 kilometers, which constitutes 8% of the nation's total area. A watershed, defined as the catchment area of a river or water system, has clear boundaries [1]. Nowadays, the concept of a watershed is not only a hydrological unit of a self-contained system, but also a whole spatial unit filled with a social system. As a multifaceted national space with water as the core element, the natural flow of rivers in a watershed across multiple administrative regions is affected by a variety of coupled watershed factors such as precipitation, topography, bedrock, soil, vegetation, and other natural factors such as runoff, water level, sand content, and other dynamic feedback factors, and there is a positive correlation between the pollutant capacity of the river and its runoff, i.e., the pollutant capacity of the river with a small river flow is low, and the pollutant capacity of the river with a large river flow is high. In other words, the river's pollution capacity is lower during low-flow periods and higher during high-flow periods. On the other hand, the differing water use cultures on both sides of the river, along with the

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structured industrial chain arrangements and other land development activities, also contribute to the river exhibiting differentiated water pollution basin characteristics. As a result, the water pollution, like the water resources, exhibits basin-specific characteristics. This highlights that the fragile ecological environment of the Yellow River has intensified the complexity of water pollution control. Drawing on existing literature and data, this paper provides a systematic review of the research on water quality pollution and management countermeasures in the Yellow River Basin.

2. Analysis of the current situation of water quality pollution in the Yellow River Basin

2.1. Pollution sources, main pollutants and their effects

Water pollution in the region is primarily attributed to agricultural and domestic sources. Agricultural pollutants mainly stem from livestock and poultry farming, while domestic pollutants originate from urban sewage. In 2020, the sewage discharge in the Yellow River Basin will reach 4.5 billion tons, of which the domestic sewage discharge will reach 1.1 billion tons, accounting for 24%; and the sewage discharge from the secondary and tertiary industries will be 2.8 billion tons and 0.6 billion tons respectively, accounting for 62%. The proportion of sewage discharge is 62% and 14% [2]. Due to industrial and socioeconomic activities in the basin, pollutant intensity (per unit of industrial/agricultural output and per capita) decreases from upstream to downstream. The industrial chain structure of the Yellow River basin is heavy, with industrial wastewater and domestic sewage and other sources of pollution flowing into the Yellow River, resulting in complex water pollution. In the process of flowing from the source of the river to the mouth of the sea, the river is constantly subjected to the pressure of pollution transported from upstream to downstream. The middle and upper reaches host numerous energy-intensive, heavy chemical, and coal chemical industries, which contribute to the progressive water quality degradation from upstream to downstream.

2.2. Pollution status

2.2.1. Characteristics of spatial distribution of pollution

The Yellow River Basin exhibits significant regional differences in water pollution discharge characteristics, with a pronounced step-type distribution from upstream to downstream areas. Currently, the primary water pollutants discharged in the Yellow River Basin exhibit a significant spatial agglomeration effect. Pollution agglomeration is particularly evident in the middle and lower reaches of the basin, with cities along the Yellow River in Shanxi, Henan, and Shandong provinces characterized by spatially contiguous pollution agglomeration, especially in the Jinzhong city cluster and the Central Plains city cluster. In particular, the hotspot discharge areas of Yuncheng, Lvliang, Jinzhong and Linfen accounted for 80% of the major water pollutants discharged in the Fen River basin, and the high-intensity pollution discharge is still a bottleneck factor for the improvement of water quality in the basin. The number of cold spots is much less than that of hot spots, indicating that there are fewer areas in the Yellow River Basin where the water pollution discharge does not show obvious spatial clustering distribution, and the spatial clustering effect of individual cities in the middle reaches of the Yellow River Basin, such as Ningxia Hui Autonomous Region and Gansu Province, is not obvious. There is no cold spot area for ammonia nitrogen emission. The formation of a pollution agglomeration pattern is influenced by industrial agglomeration, population density, economic level, technology level, industrial structure and so on.

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From four aspects of activity level, pollutant generation, pollutant removal and pollutant discharge, the characteristics of water pollution discharge in different areas of the Yellow River Basin can be divided into four categories: high discharge intensity area, high discharge performance area, pollution agglomeration area and low discharge performance area. Generally speaking, green development is a development mode characterized by low consumption, low emission and high efficiency, while the corresponding"black development"mode is characterized by high consumption, high emission and low efficiency [3]. According to the clustering results, only the high-emission performance area in the Yellow River Basin conforms to or is close to the characteristics of the green development of"low consumption, low emission and high efficiency", while the other three types of areas are characterized by different degrees of high consumption, high emission or low efficiency.

From the perspective of emission structure, COD and total phosphorus into the environment mainly come from agricultural sources (accounting for 62.93% and 73.48% respectively), ammonia nitrogen into the environment mainly comes from domestic sources (accounting for 65.54%), and the contribution of total nitrogen into the environment from agricultural and domestic sources is basically the same, accounting for 47% or so; the four pollutants in the emission structure of the industrial sources accounted for 2%-7%, and centralized sources accounted for about 1%. Industrial sources account for 2-7% of the emission structure for the four pollutants, while centralized sources constitute approximately 1%. In terms of pollutant intensity per source type, water pollutant intensity per unit industrial output value, per unit agricultural output value, and per capita discharge intensity all decrease from upstream to downstream areas; the average removal rate of the main water pollutants from the industrial sources and the agricultural sources in the upstream and downstream areas is similar, and the average removal rate of the main water pollutants from the agricultural sources in the upstream area is higher than the middle and lower reaches of the area by 3%, while that from the domestic sources is higher than that in the middle and lower reaches of the area. The average removal rate of major water pollutants from agricultural sources in the upstream area is about 3% higher than that in the middle and downstream areas, while that of domestic sources is higher than that in the upstream area. The loading rate of centralized wastewater treatment facilities increases from the upstream to the downstream area, and the difference between the upstream and the downstream area is 11.78% [4].

2.2.2. Comparison of pollution between tributaries and main streams

According to the Yellow River Water Resources Bulletin, the length of river sections in the Yellow River Basin that meet or exceed Class III water quality standards has increased from 38.7% to 73.8%. Meanwhile, the length of river sections with Class I-V water bodies and poor Class V water bodies has decreased from 37.3% and 24% to 13.9% and 12.4%, respectively. From 2006 to 2019, the proportion of state-controlled cross sections in the Yellow River Basin that meet or exceed Class III water quality standards increased from 50.0% to 72.9%. In contrast, the proportion of state-controlled sections with inferior V water quality decreased from 25.0% to 8.8%, and inferior V water bodies were completely eradicated from the main stream of the Yellow River. The main tributaries of the Yellow River, such as the Fen River, Shichuan River and Qingjian River, have continued to have poor water quality in the past ten years. Taking the conclusion of this report as a benchmark, the water quality of the Yellow River tributaries has been improved lately, the water quality is poor, and it is generalized, and the Yellow River tributaries have become the key units of the Yellow River's water pollution control. The runoff volume of the river is closely related to the polluting capacity of the river, and the polluting capacity of the tributaries is limited, which requires a longer period to improve the water quality, and thus is more prone to water quality pollution [5].

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The heavy pollution and slow treatment of tributary water bodies gradually lead to obvious differences in the water quality of the main and tributary streams of the Yellow River.

2.2.3. Pollution time change trend

Influenced by seasonal rainfall, the runoff of the main stream of the Yellow River and its main tributaries is concentrated in the flood season, and the runoff of the Yellow River during the flood season from July to October accounts for more than 60% of the annual runoff. The water resources of the Yellow River basin are unevenly distributed in time and space, and the total amount of water resources is gradually decreasing. The dual impacts of climate change and human activities render traditional water resources carrying capacity assessments—which rely solely on available water volume—unable to meet the stringent requirements of the strictest water resources management system. The upper and middle reaches traverse arid/semi-arid zones characterized by low precipitation and monsoon vulnerability, resulting in significant natural runoff reduction over recent decades." The low efficiency of water use in the basin and the large amount of surface water depletion in the way of water extraction have aggravated the shortage of water resources, and the depletion of surface water in the dry season is even more serious, exacerbating the water pollution in the Yellow River Basin. The Yellow River flood season is very prone to floods, and a large number of floods in the middle and upper reaches of the Yellow River flushed downstream to the polluted water bodies, which in turn affects the quality of the water downstream. Seasonal rainfall leads to seasonal sewage discharge; in the heavy rain season, the rain will carry a large number of pollutants through the sewage outfall backwash into the river, resulting in a seasonal rebound of the Yellow River water quality.

3. Progress of research on countermeasures to control water pollution in the Yellow River Basin

3.1. Ecological restoration and protection technology

River ecological restoration comprises a series of engineering and technical measures designed to restore or rebuild natural river functions and surrounding ecosystems. This enables the rehabilitation of original ecological structures and functions, water quality improvement, and environmental repair, ultimately achieving water body health, ecological diversity, and sustainable socio-economic development. Its core objective is to restore the ecological balance of water bodies, improve water quality, restore biological habitat and enhance the self-purification ability of water bodies. River ecological restoration includes both natural restoration and artificial intervention, which are complementary to each other and play a common role in realizing the restoration objectives. Natural restoration is the gradual restoration of the ecological function of the water body by reducing anthropogenic interference and pollution sources and relying on natural processes. Artificial intervention, on the other hand, is to introduce aquatic plants and optimize water flow on the basis of natural restoration to accelerate the ecosystem restoration process in a targeted manner.

3.1.1. Aquatic plant restoration

Aquatic plant restoration is an ecological restoration method to improve water quality by planting and maintaining aquatic plants. Aquatic plants play an important role in the river ecosystem, can absorb nutrients in the water through the root system, slow down the phenomenon of eutrophication, and release oxygen through photosynthesis to enhance the self-purification ability of the water body.

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Aquatic plant roots adsorb nitrogen, phosphorus, and other pollutants to mitigate eutrophication risk, while the plants biodegrade organic matter through biological absorption and metabolic processes. The photosynthesis of aquatic plants produces oxygen, which provides sufficient dissolved oxygen for aquatic animals, improves the dissolved oxygen conditions of the water body and promotes the growth of aquatic organisms.

3.1.2. Artificial wetland

Artificial wetlands are engineered systems that mimic natural wetland ecosystems, utilizing synergistic interactions among plants, soils, and microorganisms to remove nitrogen, phosphorus, organic matter, and heavy metals from water bodies. Artificial wetland physically removes suspended matter and large particle pollutants from water through the filtering effect of wetland soil and sediment layer. Wetland soil and plant roots have strong adsorption capacity, which can adsorb dissolved pollutants such as heavy metals, nitrogen and phosphorus in water. Microorganisms in the wetland can degrade organic pollutants in the water; especially in the anaerobic environment, the transformation of nitrogen and the degradation of organic matter are remarkable. Water body redox technology. Redox restoration technology enhances the self-purification ability of the water body, removes harmful pollutants and improves water quality by adjusting the oxygen concentration in the water body or introducing reducing agents. Through the introduction of oxygen, the oxidation reaction of organic pollutants and some reducing pollutants is promoted, so that they are transformed into harmless or low-toxic substances.

3.2. Pollution source control and emission reduction technology

3.2.1. Industrial sewage discharge

Effective industrial wastewater management necessitates integrated approaches encompassing policy frameworks, technological advancements, regulatory enforcement, and public engagement. In recent years, in order to strictly control industrial sewage discharge, the state and local governments have issued a series of policies and regulations, for example: the Outline of the Plan for Ecological Protection and High-Quality Development of the Yellow River Basin clearly puts forward the need for strict control of industrial pollution, and the strengthening of the construction and management of centralized wastewater treatment facilities in industrial parks; the Law on the Prevention and Control of Water Pollution and the Guiding Catalogue for Comprehensive Administrative Law Enforcement Matters of Ecological Environmental Protection and other laws and regulations have also set red lines for Enterprise emissions behavior set a red line, set strict legal responsibility for excessive emissions, emissions leakage and other behaviors [6]. In terms of technological innovation and promotion, the government should encourage and support enterprises to adopt cleaner production technologies, and reduce the cost of enterprise transformation through financial subsidies and tax exemptions.

3.2.2. Agricultural emissions

The total amount of livestock and poultry breeding in low emission performance areas (mainly upstream areas) is relatively small, but the pollutant generation and emission intensity per unit of agricultural output value are high. The focus of prevention and control should be on measures such as upgrading the comprehensive utilization of livestock and poultry breeding wastewater and manure, and reducing the intensity of pesticide and chemical fertilizer application, so as to reduce

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the potential probability of pollutants of agricultural origin entering the environment. Agricultural waste resource utilization technology is a technology that converts crop straw, livestock and poultry manure and other wastes into useful resources. Combined with measures such as returning straw to the field, harmless treatment of livestock and poultry manure, and biogas fermentation, the organic matter and nutrients in the wastes can be converted into soil fertilizers or energy sources, and the emissions and pollution of the wastes can be reduced. In particular, straw return technology, through mechanized crushing, deep tilling and other measures, evenly mixes straw into the soil, which can increase the content of soil organic matter, improve soil structure and enhance soil fertility. Precision fertilizer application technology is a method to precisely calculate the amount and time of fertilizer application based on soil nutrient testing and crop demand.

4. The current situation of the governance of the Yellow River Basin and the outlook of future research

4.1. Improve the policy and regulation system

Inter-provincial cooperation is essential for the management of cross-regional water pollution. To manage the Yellow River well, it is necessary to consider upstream and downstream, main and tributary streams, and left and right banks in an integrated manner, taking into account the coordination of development and protection, as well as the coordination of different regions, different industries and different stages. Water pollution management requires precise source control to enhance systematic governance, emphasize governance linkages, and establish regionally integrated synergistic management models. While the Yellow River Basin demonstrates overall water quality improvement, some tributaries remain severely polluted, necessitating targeted research on key tributaries and strengthened inter-provincial water policy coordination to ensure regional policy alignment [7]. Regarding the inter-provincial coordinated management of Yellow River water pollution, Shandong Province and Henan Province have signed the "Yellow River Basin (Yu-Lu Section) Horizontal Ecological Protection Compensation Agreement", which is the first inter-provincial ecological compensation agreement in the Yellow River Basin. The implementation of the joint meeting system not only strengthens the cooperation of water pollution control between provinces, but also facilitates inter-provincial supervision. Especially seriously polluted downstream areas can be in the middle and upper reaches of the governance work to put forward the views of the inter-provincial investigation and treatment of pollution incidents as well as tributary water quality monitoring results of the study, and scientific investigation of heavily polluted sections of tributary pollution sources. Given the spillover effect of cross-regional river pollution, administrative boundaries must be transcended in river management. For the Yellow River's fragile ecosystem, establishing a joint conference system for pollution control enables cross-regional cooperation, precise tributary supervision, and comprehensive monitoring of surface pollution. Improve the assessment of the effectiveness of water cross-section management in the river chief system, and the institutional innovation of the river chief system is conducive to the development of healthy rivers and lakes, and the sustainable development of river and lake functions. The river chief system focuses on the efficiency and effectiveness of river and lake governance and protection, really improves the appearance of rivers and lakes, promotes the optimization and upgrading of industrial structure, and realizes high-quality economic development [8].

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4.2. Enhancement of discharge standards and regulatory capacity

The water quality monitoring index is a key parameter to measure the degree of water pollution, ecological status and restoration effect. Data collection should ensure its representativeness, accuracy and reliability, and the collected data should cover the spatial distribution and temporal changes of the monitoring sites, and avoid pollution and bias in the sampling process. During the monitoring process, appropriate instrumentation are used and equipment calibration and standardization is ensured. Through time series analysis, monitor the trends of water quality indicators at different time points and identify the patterns of water quality changes; for example, analyze the improvement of water quality before and after restoration, and determine whether the restoration measures are effective. Through the comparison of data from different sampling points, analyze the differences in water quality in different regions and identify the location of pollution sources.

4.3. Research on the application of artificial intelligence technology in the field of water pollution control

The application of artificial intelligence (AI) in the field of water pollution management is gradually showing its potential and importance. Utilizing machine learning and deep learning algorithms, AI can predict the trend of water quality changes so that preventive measures can be taken in advance. In addition, intelligent monitoring systems combined with AI technology can monitor water conditions in real time and identify and deal with pollution problems in a timely manner. Although AI technology shows great potential in water pollution management, its application is still facing challenges such as data quality, algorithm accuracy and implementation costs. From the current status quo, the use of AI to treat urban wastewater still faces many challenges.

Traditional self-control systems for the treatment of polluted water bodies need to construct a set of extremely accurate mathematical algorithmic modeling framework, and need to adhere to a series of strict linear preset regulations. However, given the complexity, dynamics, nonlinearity, and numerous unpredictable challenges that characterize the nature of wastewater treatment, it is difficult to create mathematical models that are both accurate and responsive to real-world conditions, which can lead to significant fluctuations in water quality. Within wastewater treatment self-control systems, existing automatic detection instruments require optimization and upgrading [9]. Operational practice reveals these devices consistently fail to meet detection efficacy expectations while exhibiting significant measurement deviations [9]. Relying on this system for wastewater monitoring and treatment, it is difficult to ensure that the quality of the discharge meets the standards, and at the same time, it fails to achieve the goal of high efficiency and energy saving in terms of energy consumption. Currently, many researchers at home and abroad are trying to introduce artificial intelligence technology into urban wastewater treatment facilities to improve their treatment capacity and reduce energy consumption. Notable examples include attempts utilizing oxidation-reduction potential (ORP), dissolved oxygen (DO), and pH as control parameters. However, these methodologies remain plagued by unresolved operational challenges. For example, in the nitrification and denitrification stages of wastewater treatment, it is quite difficult to accurately set the ORP value, so many wastewater treatment facilities still use time as the basis for control. When the control system can not be adjusted based on ORP readings in emergency situations, it often falls back to the traditional time control strategy, which shows that this technology is still backward overall [10].

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5. Conclusion

With rapid industrialization and urbanization, water environment pollution in the Yellow River Basin has become a severe issue, significantly impacting the river ecosystem, riverbed shape, and watershed ecological management. To integrate ecological protection and high-quality development in the basin, adaptive countermeasures should be proposed based on an in-depth analysis of pollution discharge characteristics and spatial patterns, considering resource endowment and economic development. The study combines the Second National Pollution Source Census results, evaluates the overall pollution discharge status from a macroscopic level (upstream, midstream, downstream) using an evaluation index system, and compares the pollution discharge status of 60 municipalities and states at the mesoscopic level through cluster analysis and spatial feature analysis. This approach identifies pollution concentration, hot and cold spots, and regional differences, providing a basis for comprehensive ecological and high-quality development. Additionally, clarifying the responsibilities of ecological environmental protection authorities and promoting the construction of a platform for releasing water environment quality information are essential for effective watershed management.

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