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A review of typical water pollution control and cost-benefit analysis in China

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This study summarized and evaluated the cost-benefit analysis methods for typical water environment pollution control measures in China. We conducted a comprehensive comparison of these measures, whose advantages and disadvantages were examined, so the application models and characteristics can be delved into. Through integrating methods and analyzing application cases, we refined a combination of measures with high efficiency and low cost in controlling China's water environment. In our analysis of cost-benefit, we emphasized the importance of implementing scientifically designed control measures and employing rigorous methods to addressing water environment pollution. In order to achieve rapid response and efficient treatment of China's environmental problems, we advocated for establishing a cross regional pollution control mechanism. That is, the collaborative platform and scientific suggestions for all participants in this field should be provided, through interdisciplinary integration, development of domestic models, and expansion of databases.

KEYWORDS

receiving water, non-point source pollution, BMPs, evaluation of measures effectiveness, development strategies

1 Introduction

Water resources are essential for the development of human society. With the rapid development of social economy and the continuous advancement of urbanization process, the problem of water environment pollution in Rivers and Lakes in China has become increasingly prominent. 75% of lakes in China have experienced varying degrees of eutrophication (Yang, 2018). A survey conducted in 118 large and medium-sized cities in China revealed a concern in trend in groundwater quality. From 2012 to 2017, the proportion of groundwater with excellent and good water quality declined, while the proportion of poor-quality groundwater increased. Between 2018 and 2021, less than 15% of China's groundwater met the criteria for Class I–Class III quality, while over 85% fell into the Class IV–Class V categories. Additionally, groundwater contamination has been observed in 11 cities, with severe pollution accounting for approximately 40% (Xu, 2014; Yang, 2023; Zeng and Wu, 2023). Water pollution not only diminishes the functionality of water bodies but also exacerbates water resource shortages, impeding the implementation of China's sustainable development strategy. The article mainly elaborates on the research work and future development suggestions of China's control of non-point source pollution in water environment.

In the 1980s, China began to conduct research and investigation on the eutrophication of reservoirs and lakes, and carried out exploration and planning for river water quality control, including research on non-point source pollution in major cities such as Beijing. With the acceleration of industrialization and urbanization, more and more socio-economic factors are being considered for their impact on non-point source pollution, which exacerbates the damage to the ecological environment and increases the degree of agricultural non-point source pollution (Sun et al., 2011; Liu et al., 2023). At the same time, the country has neglected the control of pollution caused by agricultural development, and effective prevention and control of agricultural non-point source pollution is also a major challenge faced by local governments in China under the background of rural revitalization (Tang and Li, 2023).

Water pollution in China is a significant issue, with 90% of cities suffering from severe pollution, and 60%–70% of water shortages in southern cities being attributed to pollution (Chen, 2013; Yang, 2018; Yan, 2020). The adverse effects of non-point source pollution caused by urban runoff erosion are becoming increasingly severe. Due to the complexity of its composition, randomness of occurrence, intermittency of emissions, widespread harm, and difficulty in research and prevention, it has become a top priority in water environment pollution research, attracting extensive research and high attention from scholars and urban managers (Ma et al., 2021; Ma and Zhao, 2022).

In summary, it is urgent to study the control and treatment of non-point source pollution in water environment and the sustainable development of environmental economy.

2 Analysis of water pollution source types and research trends

The reasons for the deterioration of water environment quality usually include two aspects. Firstly, point source pollution directly from pipeline wastewater discharge, including household, industrial, and commercial water use; The second is non-point source pollution, which can be further divided into agricultural non-point source pollution and urban non-point source pollution according to their different sources. Rainfall runoff is the main driving force of non-point source polluted water bodies, and it is the driving force and transport carrier of pollution load generation (Wang, 2014; Gossweiler et al., 2021). Under the action of rainfall erosion or surface infiltration, pollutants on the surface merge into receiving water (lakes, rivers, reservoirs, bays, etc.) along with runoff.

In recent years, the government has made significant efforts in controlling water pollution, resulting in effective management and treatment of point source pollution (Rissman and Carpenter, 2015; Peng, 2019). However, non-point source pollution has emerged as a prominent issue and has become a primary factor in water pollution worldwide. The occurrence of non-point source pollution is unpredictable, making it challenging to monitor, control, and treat due to uncertainties regarding its source, quantity, and complex processes and mechanisms (Xia et al., 2020; Xue et al., 2020). There are significant differences between urban non-point source pollution and agricultural non-point source pollution control in terms of research areas, governance measures, and cost-benefit impacts (Sousa et al., 2021).

2.1 Agricultural non-point source pollution

Among various non-point source pollution problems, agricultural non-point source pollution has become the main source of water pollution, and is one of the most hidden and difficult problems to solve in pollution control (Ding, 2019). The main factors affecting agricultural non-point source pollution include economic development trends, land use patterns, agricultural cultivation patterns, fertilizer application, and natural environmental conditions.

To control agricultural non-point source pollution, the “3S (Remote sensing, Geography information systems, Global positioning systems)” technology, combining the natural characteristics of agricultural non-point source areas with social and economic development factors, can be used to construct the simulation and ecological regulation model for water and soil processes in a watershed. This model enables the analysis of spatiotemporal distribution characteristics of pollution loads in receiving water, identification of key pollution source areas, and the implementation of appropriate management measures in these areas. Evaluating the benefit of Best Management Practices (BMPs) in reducing agricultural non-point source pollution in key source areas is an essential approach. Researchers can establish optimal management measures for agricultural non-point source pollution in specific river basins based on local conditions, providing theoretical and technical support for local prevention and control of non-point source pollution (Geng et al., 2019; Gu et al., 2021).

2.2 Urban non-point source pollution

The rapid progress of urbanization has led to the expansion of impermeable surfaces such as roofs and roads in urban areas, resulting in higher runoff and peak runoff, thereby increasing urban flood risk and water quality degradation (Chen et al., 2004; Snodgrass et al., 2008; Hou J. et al., 2020). When runoff forms, pollutants enter the receiving water along with surface runoff, and when the receiving water is exposed to human production and living environment for a long time, it can bring great risks to human health (Deng, 2020; Morabito et al., 2021).

The United States first proposed the concept of “Low Impact Development (LID) Rainwater System Construction” to address urban non-point source pollution, which involves planning and deploying dispersed treatment facilities at the source to address hydrological and water quality issues, and has been widely applied (Tan and Ding, 2014; Sun, 2020). LID systems can effectively absorb, store, and purify rainwater during rainfall events and utilize the purified rainwater during periods of water scarcity, promoting the sustainable recycling of rainwater resources. In the context of urban non-point source pollution control, BMPs combined with LID rely on measures such as rainwater ponds, artificial wetlands, and infiltration ponds to manage rainwater and control pollutants (Geng, 2020; Rong et al., 2022). The implementation of LID-BMPs and the construction of reservoirs are effective approaches to address urban stormwater problems, promote the efficient use of urban energy, and ensure the stability and sustainable development of urban landscapes in China (Hou J. et al., 2020).

Currently, China is in the initial stage of controlling urban non-point source pollution. Universities and residential areas, as integral parts of cities, can contribute to the development of sponge cities by implementing the planning and development principles of sponge cities. By addressing local rainwater pollution and flood issues during construction and maintenance, these areas can facilitate the transition from point-based to area-based promotion of sponge city construction (Wang, 2020). In the past, water environment BMPs mainly focused on mitigating runoff pollution and restoring hydrological conditions at the process and end stages, but fell short of fully restoring the pre-development state (Rong et al., 2022; Zhang et al., 2023). Therefore, the implementation of low-impact development facilities is essential in controlling urban non-point source pollution in catchment areas (Mohammad et al., 2022). This research emphasizes the significance of BMPs and the System for Urban Stormwater Treatment and Analysis Integration Model (SUSTAIN) as the core components. We argued that the establishment of BMPs and rainfall runoff planning system, simulation based on different scenarios, and optimization of cost-benefit to determine the optimal scheme, provide a scientific basis for the quantitative analysis and decision-making of urban surface runoff pollution.

3 Main types and current situation of receiving water

3.1 Rivers and tributaries

According to the 2022 China Ecological Environment Status Bulletin, the seven major water bodies in China are severely polluted, with about 1/4 of freshwater drinking water sources failing to meet the national standard for healthy drinking water, and 12.1% of them are classified as V ~ VI water. Due to the lack of sufficient technical means to deal with the harsh and complex on-site inspection conditions and the lack of implementation of a working mechanism for data sharing and cooperation among various departments, the research on the pollution status of river tributaries only focuses on the major water systems. The coverage of pollution level surveys in a large number of medium and small-scale rivers and their tributaries are not comprehensive, thus the above data cannot truly reflect the overall water environment quality of China's entire river basin.

3.2 Reservoir

Reservoirs are crucial for regulating river flows and urban runoff. Reservoirs themselves can store water with lower hardness, but their wide surface, slow flow rate, strong settlement, and poor dilution and mixing ability can lead to excessive growth of algae, and then cause eutrophication (Yang et al., 2023). The soil around the reservoir is susceptible to pollution caused by vehicles, industrial activities, and improper agricultural activities. Especially when soil erosion is strong due to fertilizer pollution or runoff erosion, rainwater can bring these

pollutants into the reservoir (Zhao and Yu, 2021). With the completion of large-scale water diversion and storage projects like the South-to-North Water Diversion Project in China, reservoirs have become vital intermediate regulating reservoirs for water resource allocation. This project places higher demands on the protection of reservoir water quality and water environment management (Li M. H., 2019).

4 Optimization of BMPs for cost-benefit analysis

BMPs are widely recognized as effective tools for reducing non-point source pollution (Leng et al., 2022). Achieving efficient and cost-effective BMPs at the watershed level remains an ongoing challenge. It is crucial to consider the trade-offs between environmental and economic goals. The effectiveness of BMPs is influenced by the complex interactions among environmental factors and the limitations of local resources (Zhou and Wang, 2019; Jamshidi et al., 2020). To protect and improve the environment, it is necessary to further explore the impacts of BMPs and develop multi-objective combination measures. Conducting a effectiveness analysis can assist decision-makers in planning and providing the highest level of environmental protection with limited resources and funding. BMPs specifically refer to “measures, operational procedures, or methods that can prevent or reduce water resource pollution, primarily including engineering and non-engineering measures, as well as operational and maintenance procedures.” The research mainly focuses on simulating the ecological control effects of BMPs and evaluating their cost-benefit as the basis for selecting preferred solutions. The technical roadmap is shown in Figure 1.

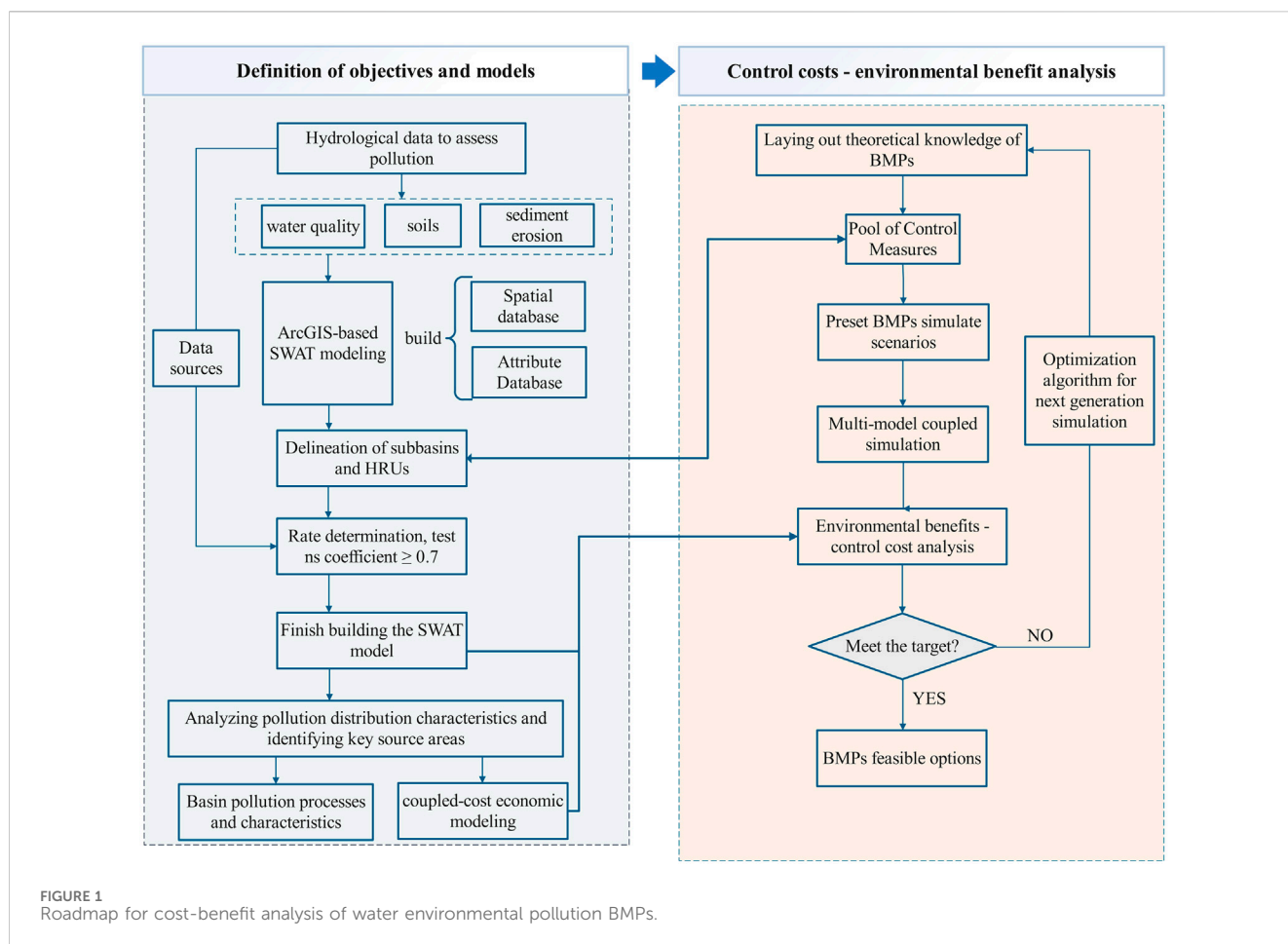
4.1 Main measures and effects of BMPs

Engineering measures refer to weaken the intensity of pollutant migration process by adjusting their runoff and sediment flow rates, increasing infiltration rates, and reducing flood peaks, also known as interception measures. Non-engineering measures mainly control the source of pollution, reduce the production of pollutants, and achieve the goal of controlling non-point source pollution. Non-engineering measures, also known as source control measures, are important component of agricultural non-point source pollution management measures (Yin, 2017; Xue et al., 2020).

4.1.1 Measures for controlling agricultural non-point source pollution

(1) Engineering measures

Due to the fact that the main carriers of agricultural non-point source pollutants are sediment and runoff, the amount of sediment and runoff pollutants entering the river can be greatly reduced through the implementation of engineering measures, thereby achieving the effect of river and lake management. Specific measures include vegetation buffer zones, grassy river channels,



sedimentation ponds, wetlands, slope farmland conversion to forests, afforestation, and terraced fields (O'Hogain and Mccarton, 2018).

Studies have been conducted to evaluate the effectiveness of grass-planted waterway measures in reducing non-point source pollution. For example, Zhang et al. (2014) used the Soil Water Assessment Tool (SWAT) model to assess the impact of grass-planted waterways on non-point source pollution in the Xiangxi River basin of the Three Gorges Reservoir area. The study indicated that grass planting waterways can effectively control agricultural non-point source pollution, particularly in reducing total phosphorus pollution. Furthermore, Shen et al. (2015) investigated the reduction effect of grass planting on surface source pollutants in river channels by simulating rainfall runoff. The results demonstrated that this measure had an interception effect of over 90% on sediment and a reduction rate of over 70% on nitrogen and phosphorus.

Vegetation buffer zones are an effective means of reducing source pollution. However, research has shown that the width of these buffer zones does not always directly correlate with the reduction rate of pollutants. In China, it is a common practice to use buffer zones as a measure for pollution control (Fu et al., 2019; Carolus et al., 2020). Buffer zones' effectiveness in pollutant removal depends on factors like surface type, vegetation, and slope. The width of the buffer zone does not have a linear relationship with

pollutant removal rate. Therefore, determining the appropriate width is crucial based on specific regional conditions. The effectiveness and scope of measures may not always correlate linearly. Some measures may become less effective as their intensity or width increases. These findings provide valuable guidance for policy-making and modeling. Decision-makers should consider achieving small changes on a larger scale and reducing fertilizer use for pollution control.

In addition to engineering measures such as grass-planted river channels and vegetation buffer zones, other methods like artificial wetlands, terracing projects, and afforestation have shown positive effects in controlling surface source pollution (Fang, 2014; Ruan et al., 2015; Liu et al., 2018; Li et al., 2022). Wan et al. (2012) found that artificial wetlands have the highest overall reduction of various pollutants and exhibit good stability in controlling non-point source pollution. Chen. (2015) conducted a study using the Hydrological Simulation Program Fortran (HSPF) model and integrated artificial wetland technology to analyze the reduction effect of different measures on nutrient pollution in a watershed. They found that canna and water hyacinth have strong tolerance to harmful components in agricultural wastewater and possess high absorption capacity for nitrate nitrogen. Liu et al. (2014) found that afforestation is particularly effective in reducing total phosphorus levels, based on the SWAT model.

(2) Non-engineering measures

Non-engineering measures play a crucial role in controlling agricultural non-point source pollution. These measures include various tillage management practices (such as contour tillage, vegetation coverage, conservation tillage, and rotation tillage), effective fertilizer and nutrient management, reduced pesticide use, and residue cover measures (Liang, 2013; Li, 2021; Huang et al., 2022).

Among these measures, fertilizer management is considered a top priority in pollution control (Liu et al., 2019). For instance, Xu et al. (2019) developed a cost-benefit optimization model for water environment management in the Xiaoqing River Basin. By minimizing costs while ensuring water quality compliance, they found that reducing fertilization by 2,900 tons could lead to a reduction of 2,916 tons of pollutants. Similarly, Shi et al. (2021) utilized the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) to simulate and optimize multiple objectives. They concluded that reduced fertilization and returning farmland to forest were suitable measures for the back slope and valley areas of the Zhongtianshe watershed, validating the effectiveness and rationality of these practices.

Tillage management measures are implemented through various cultivation techniques to weaken the conversion ability of non-point source pollutants at their source, reduce the loss of pollutants in rainfall runoff, and maintain soil fertility (Fang, 2014). Research by Liu et al. (2014) has shown that tillage management is particularly effective in reducing total nitrogen. By combining measures such as returning to the forest, no tillage, contour tillage, and reducing weight by 0.8 times, significant reductions in annual nitrogen and phosphorus loads can be achieved. Among different tillage methods, no tillage is considered more environmentally friendly, while contour tillage is more cost-benefit. Huang (2020) implemented stubble cover tillage and contour tillage measures in the Danjiang River Basin, resulting in reduction rates of 15.26% and 11.26% for total nitrogen, and reduction rates of 25.23% and 20.23% for total phosphorus, respectively. Yang et al. (2019) used the SWAT model to implement no tillage measures in the Guishui River, observing a reduction rate of around 10% for nitrogen and phosphorus.

In summary, both engineering and non-engineering measures have a certain effect in reducing agricultural non-point source pollution, although the effectiveness of individual measures is limited. Through the combination of different management measures, non-point source pollution can be reduced to a greater extent. Finding the optimal combination of management measures is a research hotspot, considering not only the reduction effect on non-point source pollution but also the cost-benefit of these measures. The economic cost of BMPs includes construction and maintenance costs, while environmental benefits mainly consider the reduction of non-point source pollution.

4.1.2 Urban non-point source pollution control measures

The 2014 “Technical Guidelines for Sponge City Construction” and the 2022 “Notice on Further Clarifying the Relevant Requirements for Sponge City Construction” of China, emphasized the need for cities to adopt a comprehensive planning and design approach to address pollution. This

approach involves controlling pollution at its source, reducing transmission processes, and enhancing end treatment. These measures not only help prevent waterlogging but also enable the efficient utilization of rainwater resources (Chen, 2013; Luo and Li, 2014; Li et al., 2020). To address the random and indirect discharge of urban non-point source pollution, a combination of engineering and non-engineering measures is primarily employed for centralized pollution source control (Table 1).

Engineering measures: engineering and technical measures for controlling urban non-point source pollution involve various infrastructure projects that combine green rainwater facilities with gray facilities. These measures aim to address urban non-point source pollution and include the construction of sedimentation tanks, leakage pits, porous roads, reservoirs, permeable paving, rainwater gardens, green roofs, grass planting ditches, and other drainage projects (Qiu et al., 2020). These measures can be categorized into three main aspects: 1) controlling pollution sources to minimize pollutants in rainwater runoff from the source: 2) Control the diffusion pathways of pollutants by studying the transport and diffusion patterns of pollutants in rainwater runoff, taking appropriate measures to reduce the amount of pollutants discharged into underground or surface water bodies: 3) Terminal governance involves the degradation of pollutants brought into water by runoff through natural ecological technology or artificial purification technology.

Non-engineering measures: non-engineering measures involve implementing various management strategies and practices to complement and support the technical measures in controlling urban non-point source pollution. These measures focus on utilizing and protecting ecological spaces within cities, leveraging the natural absorption and slow-release effects of built environments, and promoting the formation of an ecological and sustainable urban water circulation system.

4.2 Cost-benefit of BMPs

In the cost-benefit analysis of environmental governance, the conversion of costs and environmental benefit into actual currencies is a crucial step in conducting a comprehensive cost-benefit assessment. Benefit mainly refers to environmental benefit, namely the reduction of pollutants and the improvement of water quality. The “cost of expenses” of BMPs usually mainly includes research costs, layout costs, and post maintenance costs.

4.2.1 Cost of expenses

The costs of controlling non-point source pollution can be categorized into two aspects: explicit costs, which are evident and fixed, and implicit costs, which are complex, difficult to quantify, and have hidden sources (Kurkalova, 2015). The variation in implicit costs is influenced by factors such as economic patterns, technological levels, and educational levels across different regions. Most countries use model-based approaches to calculate costs, leveraging comprehensive agricultural economic data and mature economic models associated with BMPs. However, due to the lack of relevant economic databases and models in our country, calculations are primarily based on expenditure experience (Jiang et al., 2013).

TABLE 1 Urban non-point source pollution control measures [Revised from Wu Y. (2022)].

Types	Measures	Regulatory mechanism	Functions
Point type	Artificial wetland	Retention, infiltration, evaporation, settlement and transformation	Capture upstream drainage at specific locations, manage flow and remove pollutants
	Infiltration tank		
	Ecological regulation pool		
	Sand filter (surface)		
	Rainwater buckets water tanks		
	Wet and dry ponds		
Line type	Grass planting ditch	Runoff filtration, nutrient absorption, river shading	The linear shape is convenient for connecting with the river, supporting benefits of providing wildlife habitats and aesthetic value
	Infiltration ditch		
	Vegetation filter strip		
	Sand filter (without surface)		
Facial type	Green roof	Impact on impermeable area, land cover and pollutant input	Mainly used for land management practice
	Permeable pavement		

TABLE 2 Benefit exchange methods [Revised from Gao (2013)].

Methods	Key points	Characteristics
Market value method	Evaluate economic benefits or losses based on changes in enterprise costs or profits caused by changes in environmental quality	Prone to minor errors and disputes, requires a large amount of data, high economic statistics skills
Opportunity cost method	Using the opportunity cost of environmental resources to measure the economic benefits or losses of changes in environmental quality	Presetting resource usage methods and quantifying real-world environmental costs and benefits through physical models
Usage of protective fees	Evaluate environmental value based on human willingness to pay to prevent or reduce adverse environmental impacts	Measuring environmental pollution losses, limited to complete recovery or compensation for losses after environmental damage
Recovery fee usage	Using the cost of restoring the damaged environment as the lowest estimate of environmental quality	
Shadow engineering method	Estimating environmental value through the cost of manually constructing new projects that can replace the original environmental functions	Simplify resource valuation and reduce computational complexity, environmental functions are difficult to replace, errors and controversies are significant
Survey and evaluation method	Determine environmental value by directly asking respondents' willingness to pay for environmental quality	The required amount of data is small and easy to obtain, errors and controversies are significant
Impact path method	Simulate changes in pollutant concentration through air quality models and evaluate health benefits based on epidemiology	Measure the monetary and health risks brought by environmental pollution, require precise epidemiological research data

4.2.2 Benefit exchange

To evaluate ecological benefits, it is necessary to convert the feedback from control measures into quantifiable indicators in order to optimize models and conduct cost-benefit analysis of BMPs in different scenarios. In order to enhance the scientific validity of cost-benefit analysis, various benefit exchange ideas have been developed (Table 2). While the market value method was widely used initially, it was found to have limited comprehensiveness as model accuracy and algorithms improved (Lewis et al., 2020). Methods such as the protection fee method, recovery fee method, shadow engineering method, investigation and evaluation method, and impact path method were also found unsuitable for comparative analysis of multiple scenarios. The opportunity cost method is the most commonly employed approach for converting ecological benefits

into actual currency. The way holds an advantage in multi-scenario comparative analysis and is widely utilized in environmental policy assessment (Wei, 2022).

4.3 BMPs configuration refinement and simulation evaluation

The spatial optimization configuration of BMPs within the watershed is of great significance for the decision-making of comprehensive watershed management. Fully considering the spatial configuration relationship between different BMPs and optimizing the BMPs spatial configuration units is the key to ensuring the effectiveness of the simulation.

TABLE 3 Characteristics of commonly used simulation non-point source pollution models.

Models	Types	Scales	Applicable features	Insufficient	References
SWAT	Process type; Distributed	Day/Basin	Simulate nutrient migration, transformation, soil erosion, plant growth, and management measures	High requirements for parameter quality, poor ability to characterize engineering measures	Azimi et al. (2020); George et al. (2021); Aloui et al. (2023)
HSPF			Engineering BMPs have high accuracy, flexible algorithms	Large data demand, weak evaluation ability of non-engineering BMPs	Liu X. P. et al. (2021); Lee et al. (2023); Salaudeen et al. (2023)
SPARROW		Period/Basin	Widely used in nonlinear watershed algorithms, more complete and advanced applications	Complex operation, applicability of the application still needs to be studied and verified	Chen et al. (2023); Ren et al. (2023)
SUSTAIN (SWMM)	Distributed	Secondary/ Runoff	Diverse functional integration, wide applicability, provided multiple optimization configuration algorithms	Insufficient system stability, low adaptability for domestic users	Gao et al. (2015a); Park et al. (2017); Qiu et al. (2020)
CREAMS	Centralized		Calculated runoff and runoff pollution load parameters for predicting individual rainfall events	Not considering unit differences, can only make rough estimates	Zhang (1995a); Zhang (1995b); Knisel and Douglas-Mankin (2012)
ECM	Centralized; Experiential type	Year/Basin	Simple structure, small data demand, simulate the spatial pattern of non-point source pollution	Unable to evaluate engineering BMPs	Tian et al. (2017); Bai et al. (2023); Zhang and Luo (2023)
PI		Year/Plot or sub basin		Weak quantitative evaluation ability for BMPs	Duan et al. (2010), Su and Li (2020)

4.3.1 BMPs spatial configuration unit

Sub-basins, hydrological response units, plots, farms, slope locations, etc. are often used as spatial configuration units for BMPs (Gao et al., 2018). Initially, plots were widely used as the units for dividing BMPs configurations. However, the excessive subdivision of plots can lead to computational burdens and hinder practical implementation (Gaddis et al., 2014). Wu et al. (2017) found that using plot units may limit the representation of the relationship between upstream and downstream processes on slope surfaces, thereby reducing the effectiveness of China's watershed management model. The idea of introducing slope morphology units to characterize the basic morphological characteristics of slope terrain has been proposed. In order to further improve the accuracy of configuration, a research approach of overlapping slope positions with land parcels has been formed (Rathjens et al., 2016). Studies conducted by Shi et al. (2021) and Liu et al. (2019) have demonstrated that using slope block units or configurations that incorporate stacked slopes and plots can yield higher pollution reduction effectiveness at similar or lower economic costs, resulting in more reasonable optimized schemes.

4.3.2 BMPs simulation evaluation optimization

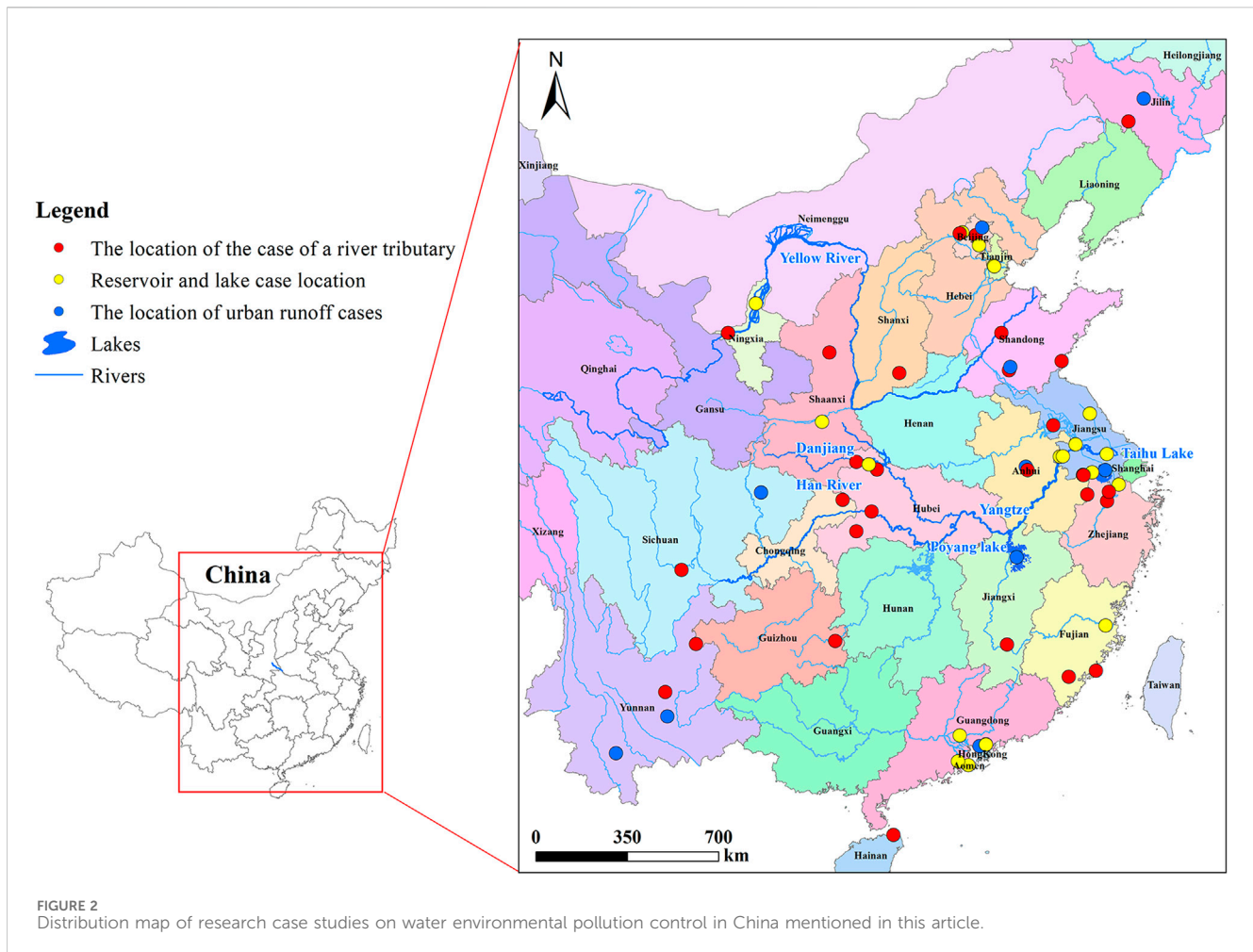
The evaluation and optimization research on BMPs primarily relies on the "hydrological model and optimization method" developed by American and Chinese scholars (Geng et al., 2019; Kim and Ryu, 2020). These researchers propose a multi-objective decision-making approach for BMPs, aiming to achieve the lowest cost, highest pollution reduction efficiency, and significant water quality improvement (Chaubey et al., 2010; Ratté-Fortin et al., 2019). To evaluate the effectiveness of BMPs, watershed agricultural non-point source pollution models are commonly used and considered essential for accurate and reliable assessments.

In the evaluation and optimization process, the model initially sets BMPs with ecological control effectiveness as a cost constraint.

Then, by employing various optimized algorithms like linear programming and NSGA-II, the search direction of the algorithm is guided through objective functions such as minimizing cost or maximizing pollution reduction. This approach provides a scientific solution for multi-objective evaluation and optimization. Finally, an implementation plan is adjusted and determined (Zhang et al., 2013; Wang, 2016; Chang et al., 2017). The algorithm-based optimization model simulates and selects BMPs with specific and targeted measures, ensuring that the optimal solution is not lost and resulting in the most cost-effective combination of measures (Zhang et al., 2019; Qi et al., 2020; Zhang et al., 2020; Zhang et al., 2022). Over time, as the model's modules and algorithms are continuously revised and optimized, the credibility of the simulation results increases significantly (Chang et al., 2017; Liu Z. B. et al., 2021; Wu Y., 2022). Table 3 presents an overview of the characteristics and limitations of commonly used models for simulating non-point source pollution.

Models such as SWAT, HSPF, and SUSTAIN have found numerous applications in simulating and predicting non-point source pollution, and they hold significant potential for future development. The SWAT model, for instance, integrates efficient economic modules and benefit algorithms to evaluate the optimization of BMPs in agricultural watersheds. It has become a valuable tool for in-depth research on agricultural non-point source pollution in watersheds, gaining recognition and widespread use among researchers in the same field (Briak et al., 2019; Chang et al., 2021).

The HSPF model possesses two key advantages: comprehensiveness and flexibility. These attributes contribute to achieving high computational accuracy and make it suitable for large-scale agricultural watersheds, intricate urban watersheds, and specific rainfall scenarios (Xie et al., 2022). Due to the model reliance on older data manipulation platforms (BASINS) to obtain comprehensive data, its performance may be compromised, particularly in areas with urbanization and limited data



availability. Consequently, the combination of HSPF with BMPs' effectiveness has been less extensively applied (Chen, 2015; Her et al., 2017).

SUSTAIN has developed a comprehensive system model for urban stormwater treatment and analysis based on the combination of the well-established stormwater management model SWMM. SUSTAIN takes into account the simulation of various BMP types and possesses robust internal simulation capabilities for transporting runoff and associated pollutants. The SUSTAIN model, which combines the NSGA-II algorithm, is widely used and can provide cost-benefit curves for measures under limited objectives and cost conditions. These curves facilitate the analysis and selection of the optimal BMPs scheme. (Chung, 2010; Li X. G., 2019; Ling and Dai, 2019; Taghizadeh et al., 2021).

5 Research on non-point source pollution control and application analysis of cost-benefit methods

The distribution of sampling sites for the research case studies on water environmental pollution control in China mentioned in this article is shown in Figure 2. This chapter primarily focuses on the application of multi-attribute decision-making methods in cost-

benefit analysis for non-point source pollution control. In agricultural non-point source pollution control, research has found that the combination of information entropy and multi-attribute decision-making methods for cost-benefit evaluation balances the influence of different constraint factors, and can more accurately simulate the effectiveness and cost of single or combination pollution control measures in the watershed. Urban non-point source pollution, as an important pollution control direction at present, has different measures and cost-benefit analysis methods, but the simulation effect of control measures is somewhat similar to the former.

5.1 Analysis of pollution control measures for agricultural non-point sources mainly receiving water

5.1.1 Rivers and tributaries

Traditional research on BMPs for agricultural non-point source pollution has primarily focused on rivers, tributaries, and lakes. Among the most commonly used cost-benefit analysis methods in this context are the Net Present Value (NPV) method and the Cost-Benefit Ratio (CBR) method. For example, Xu et al. (2013) utilized the SWAT model to estimate non-point source loads in the Weinan

TABLE 4 Cases of agricultural non-point source pollution control.

Pollutants	Simulation/ Research methods	Basins	Preferred BMPs	Cost-benefit feasibility	References
N, P	SUSTAIN	Huaijiu river	Tandem green roof, rainwater tank, biological retention tank, permeable pavement (farmers), tandem green roof, biological detention tank, permeable pavement, wet detention tank (community), tandem biological detention tank, wet detention tank, infiltration ditch (basin)	Both the net present value method and cost-benefit ratio is feasible	Geng (2012)
		Zhangweinan canal	Riverside buffer zone, contour planting, vegetation type ditches, terraced planting, reducing fertilizer usage	The net present value method, feasible	Xu et al. (2013)
	SWAT	Guishui river	Domestic sewage treatment and livestock and poultry prohibition and 20% reduction in fertilizer application measures (source), vegetation filter belt and grass planting waterway (process), water source protection (terminal)	Cost-benefit ratio, feasible	Wang (2022)
		Gongjiang	20% reduction in fertilizer, residue coverage, vegetation buffer zone		Wu (2022b)
		Zhuxi river	Engineering measures (vegetation buffer zones, grassed river channels), combination of non-engineering measures (20% reduction in fertilizer, no tillage, vegetation buffer zone)		Zhang et al. (2022)
		Jinjiang xixi	Terraced fields, contour cultivation, surface covering measures		Rong et al. (2019)
NPS	Survey and observation	Niulan river	Construction of sewage treatment plants, construction of supporting pipeline networks, industrial wastewater treatment (point source), balanced fertilization, resource utilization of livestock and poultry breeding waste, sanitary toilets (non-point source), buffer zone, river channel dredging (river channel)		Huang et al. (2007)
		Yangtze river	Urban industrial pollution prevention and ecological protection and restoration projects with the main goal of water pollution prevention and water resource protection		Zhou et al. (2019)
		Guanliao river	Straw coverage, firewood forest planting, artificial forest transformation, firewood saving stoves, hedge construction, landslide control	The net present value method, feasible	Shao (2013)
		Tai lake	Planting water hyacinth, Yangwan station project of the Tai Lake blue algae water station in Wuxi city, Gonghuwan wetland returning fishing to lake demonstration project		Kang and Liu (2015)
			Soil testing formula, construction of medium-sized biogas digesters, construction of household biogas digesters, construction of ecological ditches and ponds, construction of shore buffer zones	Both the net present value method and cost-benefit ratio are feasible	Yang (2011)

Canal Basin under different hydrological conditions (high, flat, and dry). They analyzed the spatial distribution characteristics of these loads and compared 47 different BMPs through simulation. And then, they identified the most effective measures for reducing total nitrogen and total phosphorus pollutants, which were the construction of vegetation type ditches. The authors also determined the unit reduction costs for these pollutants. Geng (2012) employed “3S” technology to divide the Huaijiu River into three spatial levels. They used the NSGA-II optimization module in the SUSTAIN system to optimize the cost-benefit of different combinations of BMPs at each level. Their findings revealed that the comprehensive reduction rate of annual pollution load for the

two pollutants could reach 65%. Huang et al. (2007) integrated fuzzy comprehensive evaluation and the Pearl growth curve method to develop an ecological benefit analysis method for water pollution control in watersheds. Their approach considered measures targeting point sources, non-point sources, and river pollution. They discounted all economic benefits and costs and arrived at a feasible cost-benefit ratio of 3.68. Shao (2013) conducted on-site research and collected data to analyze the unit investment and return rate of various ecological control project measures. They found that the measures with the highest return rate were landslide control, hedge construction, firewood saving stoves, artificial forest transformation, and fuel forest, in descending order. Among soil and

water conservation measures, straw coverage showed the highest return rate. Wang (2021) discovered a correlation between the magnitude of non-point source pollution load in the sub-basin of the Guishui River and the proportion of arable land, forest land, urban and rural construction land, and the distribution of elevation within the sub-basin. Zhang (2021) used the SWAT model to evaluate the effectiveness of engineering measures, such as vegetation buffer zones, in reducing pollutants. They found that these measures achieved a reduction rate of 50%–70%. The researchers also employed cost-benefit ratios to evaluate various BMPs and concluded that engineering measures often provide better environmental and economic benefits.

The analysis of water environment cost-benefit can vary based on the scale of the research basin. Different research methods and techniques can be employed (Table 4). Several key findings have emerged from numerous studies: 1) Combined measures exhibit a stronger reduction effect on water pollution compared to individual measures. 2) Engineering measures, as a whole, have a better overall reduction effect on total phosphorus and total nitrogen pollution loads in watersheds. 3) Process interception shows higher cost-benefit than source control in reducing water pollution. 4) Engineering measures generally have higher cost-benefit compared to non-engineering measures. Among engineering measures, grassy waterways demonstrate the best cost-benefit, while terrace engineering exhibits the worst cost-benefit. Based on these findings, river basin managers can refer to the methods and technologies discussed to develop water pollutant control strategies. These strategies should be tailored to the specific scale and conditions of the research basin, aiming to strike a balance between environmental and economic benefits.

5.1.2 Reservoir pollution

Research by Zhang (2010) evaluated the effectiveness of BMPs (wetland and detention pond and grass ditch) and LID measures (vegetation and vegetation retention troughs) in reducing pollution in the Qiankeng Reservoir catchment area. They found that the pollutant removal efficiency of these measures decreases under larger runoff scenarios. It is suggested to employ the NPV method and cost-benefit analysis for preliminary engineering and cost analysis. Wang et al. (2009) conducted a comparative analysis of various pollution control measures. They found that converting farmland into orchards in the Miyun Reservoir catchment area had significant economic benefits. However, changing land use methods required substantial investment and the environmental benefits took time to manifest. Rural household biogas digesters were suitable for long-term pollution control. Riparian vegetation buffer zones had significant environmental benefits and were suitable for areas with scattered pollution sources. Returning farmland to forests, as a fundamental measure for soil erosion control, carried a higher economic benefit risk but was more effective when combined with other measures. These findings highlight the importance of considering runoff conditions and cost-benefit when selecting pollution control measures. Converting farmland into orchards, implementing biogas digesters, and using riparian vegetation buffer zones are recommended strategies for pollution control. Xie (2012) developed corresponding BMPs for farmland (implementing returning farmland to forest, setting contour hedges, implementing less or no tillage practices, and controlling

nitrogen fertilizer application), grassland (implementing returning grassland to forest), and rural residents (promoting Guangnong Village biogas digesters) based on the sensitive parameters of the ReNuMa model and the planned annual water quality goals of the watershed. Sun et al. (2017) proposed a comprehensive plan to address the challenges of monitoring and managing non-point source pollution in the Three Gorges Reservoir area. This plan combines source control, migration path interception, and end treatment strategies to effectively control non-point source pollution. The “slope to ladder” or “large cross slope and small slope” limited slope cultivation technology model is recommended due to its suitability in terms of engineering quantity and cost for managing pollution in slope farmland.

Reservoir pollution in the Three Gorges area is influenced by different factors compared to urban areas, and therefore, pollution control measures differ as well. Instead of using LID-BMPs, control measures focus on agricultural non-point source pollution. Implementing land conversion from farmland to forest, practicing less or no tillage, controlling nitrogen fertilizer application, and promoting rural biogas digesters are effective choices. Considering the specific conditions of the reservoir area, pollution control measures are often developed based on dividing pollution stages or areas. Smaller reservoir areas near residential, agricultural, and industrial areas can utilize non-engineering measures, such as land use planning, pollution source management, and agricultural and forestry land management. Engineering measures, such as biological retention ponds, wetland systems, grass ditches, buffer grass belts, grass belt systems, and erosion control blankets, can be employed for effective control.

5.2 Cost-benefit analysis of agricultural non-point source pollution based on multi-attribute decision-making method: taking danjiang as an example

In the context of cost-benefit analysis for environmental control, accurately evaluating the effectiveness of combined measures is often challenging for decision-makers. This difficulty arises from the limited cognitive ability of humans to accurately quantify the weights of influencing factors, as well as the complexity and uncertainty inherent in objective phenomena (Li et al., 2022). To address this issue, researchers have developed a comprehensive evaluation model based on information entropy multi-attribute decision-making. This model incorporates multiple steps to enhance the decision-making process. Firstly, the improved Analytic Hierarchy Process is utilized to determine the subjective weights assigned by decision-makers to each indicator. Then, information entropy theory is employed to determine the objective weights for each indicator. Finally, the subjective and objective weights are combined to obtain comprehensive weights for the final evaluation. By incorporating both subjective and objective weights, this model provides a more accurate evaluation of the effectiveness of decision-making methods. The resulting comprehensive attribute values consider the realistic weights assigned by decision-makers and utilize data as the basis for evaluation. Larger comprehensive attribute values indicate better effectiveness and are suitable for controlling and managing non-point source pollution in larger watersheds (Fu et al., 2015).

In the study conducted by Huang (2020), the researchers focused on the Danjiang River Basin and utilized the multi-attribute decision-making method based on information entropy to evaluate the cost-benefit of various management measures. The findings indicated that the combined BMPs exhibited a higher pollution reduction rate compared to individual measures, suggesting that their implementation should be prioritized. As an individual measure, returning farmland to forests showed a relatively high comprehensive attribute value (0.62), making it suitable for controlling small-scale agricultural non-point source pollution. However, for larger-scale situations, a more effective approach was found to be the combination of terracing engineering, stubble cover cultivation, and grassland waterway BMPs. Building upon Huang Kang's research, Li et al. (2022) discovered that non-engineering measures had relatively high comprehensive attribute values. Combined BMPs involving stubble cover, terrace engineering, and returning farmland to forest demonstrated the highest comprehensive attribute value (0.86), indicating the best decontamination effect. Regarding the research on pollution areas covering slopes, Wang et al. (2013) considered various factors such as the cost of measures, the extent of farmland occupation, and the control effect. They used the multi-attribute decision-making method based on information entropy to comprehensively evaluate and optimize measures in different slope areas surrounding the Danjiang River Basin. Different measures were proposed for different slope areas, although no further cost accounting verification was conducted. In another study by Yin (2017), the focus was on the impact of measures on pollution reduction and economic costs. The multi-attribute decision-making cost-benefit analysis method based on information entropy provided suggestions based on the scale of the governance area and the slope conditions.

Based on the research findings, the following management measures are recommended for addressing non-point source pollution: 1) The best management measure is to return farmland, grasslands, and forests above 15°C. This approach helps to reduce surface source pollution and is cost-effective. 2) Contour tillage is the most effective method for reducing sediment loss. Stubble cover tillage is effective in reducing the loss of total nitrogen and phosphorus. A combination of contour tillage as the primary method, supplemented by residual stubble cover tillage, is recommended in areas ranging from 15° to 25° slope. 3) In areas with smaller slopes, prioritize the use of low-cost measures. These measures can be cost-effective while still reducing non-point source pollution. 4) In areas with slightly higher slopes, engineering measures primarily based on terracing should be prioritized. Terracing helps to control soil erosion and reduce the movement of pollutants. 5) In areas with large slopes, the main measure is to return farmland to forests. This approach helps to stabilize the soil, control erosion, and reduce non-point source pollution.

5.3 Urban non-point source pollution

In China, the urban non-point source pollution control plan, particularly on campuses, differs from typical watershed control measures and often incorporates LID-BMPs. Despite being

introduced relatively late, LID technology has been widely promoted and has achieved significant results nationwide. For instance, Wen (2022) proposed a plant configuration and rainwater treatment model for Hengqin New Area in Zhuhai. They implemented technical facilities like permeable pavement, grass planting ditches, sunken green spaces, and rainwater gardens in the road drainage system. These measures effectively addressed issues related to the quantity, peak flow, and pollution of rainwater runoff. As a result, urban rainwater management capabilities were improved, and the recreational needs of citizens were met. Zhou et al. (2018) analyzed the runoff situation in the old urban area of Zhangjiagang City under different return periods, considering the layout of permeable pavement, rainwater buckets, and sunken green spaces. They found that the combined layout of various LID measures did not simply have a superposition effect on reducing runoff. Permeable pavement had the most significant effect on reducing the runoff coefficient, while rainwater buckets and sunken green spaces had similar effects. Li et al. (2017) established biological detention zones and permeable paving in Tianjin's central urban area and surrounding districts to control flood peaks and total runoff. The results indicated that LID measures effectively controlled runoff. However, as the design recurrence period increased, the drainage capacity of urban drainage networks decreased. Therefore, optimizing the drainage pipe network and increasing the drainage capacity of river channels were deemed necessary. Chen and Long (2022) evaluated the comprehensive benefits of different spatial layout schemes in a residential area in Beijing. They used a multi-objective function simulation method combining the SUSTAIN model and NSGA-II. Two optimization schemes for LID facility spatial layout, namely permeable pavement and sunken green space, were selected and evaluated for their effectiveness.

The main trend of research on urban non-point source pollution in China is to transform the development of BMPs combined with LID from a single LID measure to a combination measure or a combination with green infrastructure; The research objective has shifted from only considering controlling rainwater and reducing pollutants to comprehensively considering social, economic, and ecological benefits; The evaluation method has changed from a single model to a multidisciplinary comprehensive application. With the gradual development of the national concept of ecological campus construction, the construction of sponge campuses in universities guided by sponge cities can become a good example of testing the effectiveness of sponge cities and an important means of promoting the construction of campus ecological civilization (Wang, 2020). The urban non-point source pollution BMPs in China should be based on their adaptability, with the goal of protecting and restoring the water ecological environment, and promoted by economic preferential policies. Based on the advantages and disadvantages of LID transformation conditions for different land types, different runoff control goals should be set to achieve the goals of ecological restoration and water system governance.

5.4 Cost-benefit analysis of urban non-point source pollution control based on cost-benefit curve

The cost-benefit analysis curve is derived from simulations and calculations using the SUSTAIN model. It represents the relationship between costs and ecological governance for LID-

TABLE 5 Research cases of urban non-point source pollution.

Regions	Runoff pollutants	Models	BMPs	Cost-benefit evaluation	References
A residential area in Yanqing county	TSS, COD, TN, TP	SUSTAIN (NSGA-II)	Green roof, permeable pavement, biological retention pool, grass planting ditch	The net present value method, due to the large proportion of green roofs, they can be constructed in stages in actual construction	Gao et al. (2015b)
A residential area in Jiaxing city		SUSTAIN (NSGA-II)	Permeable pavement, green roofs, drought and heat resistant plants	According to the cost benefit curve tangent, the engineering cost is approximately 2.15 million yuan	Chen et al. (2016)
Gulou district, Nanjing city		SUSTAIN (NSGA-II)	Green roofs, permeable paving, biological retention ponds, grass planting ditches	The cost-benefit curve tangent shows that the optimal investment plan can achieve an overall annual runoff reduction rate of up to 75%	Li (2019b)
Jinfeng district, Yinchuan city		SWMM (NSGA-II) SUSTAIN	A combination plan combining lid's permeable pavement, green roof, and rainwater garden	The cost-benefit ratio method shows that the optimized lid scheme has the highest cost-benefit, and the cost of the rainwater garden has significantly decreased after optimization	Sun (2020)
Yancheng drainage Area	TSS, TN	SUSTAIN	Biological retention facilities, reservoirs, grassed ditches, green roofs, infiltration depressions, infiltration channels	Obtain the optimal combination of annual runoff, annual total suspended solids output, and annual total nitrogen output reduction rate and cost based on the cost-benefit curve tangent	Yang (2017)
Shiyan city	COD, TN	SWMM	Building ecological rivers and low impact development facilities, standardize sewage reuse and discharge from sewage treatment plants	The net present value method can save 1.7 billion yuan and be sufficient for the construction of lid	Chen (2022)
Fujian Agricultural and Forestry university	SS	SUSTAIN (NSGA-II)	Renovation of building roofs and green spaces, addition of rainwater tanks in local areas, use of grass ditches for rainwater transportation, installation of wet retention ponds	The optimal investment cost for the cost benefit curve tangent is 18.44 million yuan	Lin (2016)
Chang'an university		SUSTAIN (NSGA-II)	Rainwater gardens, permeable paving, green roof (high decontamination efficiency), sunken green spaces, grass planting ditches, rainwater buckets (more economical)	The tangent of the cost-benefit curve resulted in a total runoff reduction rate of 21.07%, with a total cost of 4.2193 million yuan	Wu Y. (2022)

BMPs. Each point on the curve corresponds to a potential solution for the construction and configuration of these measures. The ratio of benefits to costs, indicated by the vertical and horizontal coordinates of each point, determines the cost-benefit of the solution. A smaller ratio signifies a more cost-effective option (Zeng et al., 2020; Azari and Tabesh, 2022). The horizontal axis represents the construction cost for different LID-BMPs configurations, while the vertical axis represents the percentage of pollution reduction achievable by each scheme.

Recent research cases have shown that decision-makers prioritize economic benefits in smaller functional areas like university campuses and residential areas, considering pollution control budgets. In contrast, in larger urban areas, practitioners tend to focus on control plans that offer environmental benefits (Table 5). Yang (2017) used the SUSTAIN model to determine the optimal combination of runoff reduction rates, total suspended solids output, and total nitrogen output reduction rates based on the tangent of the cost-benefit curve. Other researchers, such as Lin (2016) and Wu Z. J. (2022), utilized the Analytic Hierarchy Process and SUSTAIN to establish a urban non-point source pollution control measure comparison and selection system. They optimized the NSGA-II algorithm to meet environmental control objectives and determine the most cost-effective planning lid plan. Li

M. H. (2019) incorporated built-in and customized constraints into the model to obtain suitable spatial configurations for LID-BMPs. Their research showed that the series connection mode of LID-BMPs is more cost-effective than parallel and hybrid connection modes. They also found that there is a cumulative effect of LID on the cost-benefit of BMPs, and once the scale and cost of LID exceed a certain threshold, the runoff reduction rate stabilizes.

The cost-benefit curve provides a comprehensive qualitative and quantitative analysis of different LID-BMPs configuration schemes. Each point on the curve represents a specific combination of measures, allowing for accurate selection of schemes. This curve is unique in its ability to evaluate the cost-benefit of a single measure before and after optimization, which is not possible with other methods. The line connecting the leftmost points in the graph often represents the most cost-effective focus when considering the scope of the scheme, particularly at the inflection point where the curve transitions from steep to gentle. By selecting the most cost-effective solution from the cost-benefit curve, it is possible to achieve optimal environmental control goals while saving on initial investment costs. This approach creates a win-win situation for both economic and environmental benefits in urban non-point source pollution control. However, it is worth noting that the advantages of cost-benefit analysis using the SUSTAIN model for urban non-point source

pollution control have not yet been widely applied to other types of pollution control.

6 Summary and outlook

6.1 Characteristics and optimization direction of BMPs ecological assessment

Currently, BMPs configuration focuses on multi-objective optimization using a “hydrological model optimization algorithm” to evaluate and optimize BMP schemes at the plot or watershed scale. Evaluation methods and characterization indicators are becoming more comprehensive. However, there are several limitations to consider. Firstly, as research scale increases, hydrological and soil erosion processes in river basins are often simplified, leading to incomplete characterization of pollution from small-scale sources. Additionally, the impact of changes in transmission processes on pollutant reduction is not adequately considered. This limits the optimization of BMPs primarily controlled by transmission mechanisms, such as planting and feeding activities. Furthermore, most evaluations are qualitative and lack effective quantification of results. In terms of model research, the integration with actual monitoring data is insufficient. In China, inadequate database construction hinders obtaining optimal solutions for large-scale watersheds, often requiring adjustments based on the actual situation.

Future research should focus on auxiliary verification and validation through actual monitoring to enhance credibility. It is also important to establish a nonlinear relationship between pollutant load reduction in watersheds and water quality improvement. This involves developing and verifying the effectiveness of BMP schemes that combine multiple measures. Building upon this, a multi-objective decision support system can be constructed by integrating measure scheme databases, cost databases, and optimization configuration schemes based on evolutionary algorithms. This system aims to optimize the spatial configuration of BMPs and implement scientifically and efficiently controlled measures. In summary, future research should address these limitations by integrating actual monitoring data, establishing nonlinear response relationships, and developing comprehensive decision support systems to improve the accuracy and feasibility of BMPs configuration.

6.2 Cost-benefit analysis and development strategies for water environmental pollution control

The current cost-benefit analysis methods for water environment pollution control in China mainly include the following four types. The CBR and NPV methods are more accurate for analyzing the cost-benefit of individual control measures. The CBR compares the cost of implementing control measures with the achieved benefits, allowing for direct comparison between different measures. The NPV method takes into account the time value of money by discounting future costs and benefits, providing a more accurate long-term cost-benefit evaluation. The comprehensive attribute value method aims to

establish a comprehensive relationship between various ecological indicators and costs. The method considers multiple indicators and their impact on benefits, effectively balancing the influence of different indicators on cost-benefit. However, the cost-benefit curve method requires extensive data on the reduction of different pollution indicators and the cost of investment measures. It also relies on complex system model algorithms. While this method can provide valuable insights, there are limitations in terms of the accuracy of data detection and model simulation compared to real-world conditions.

In summary, although these methods have contributed to the cost-benefit analysis of water environmental pollution control, they still heavily depend on foreign models and databases. It is necessary to continue efforts in developing and improving domestic models and databases to enhance the accuracy and applicability of these analysis methods in the Chinese context. Several researches in China should be carried out: 1) Establish environmental cost-benefit assessment models for various scale standards in the environmental management system should be prioritized. It is crucial to achieve coupling and linkage of different scale models to ensure comprehensive and efficient evaluation. 2) Conduct comprehensive cost-benefit analysis and evaluation is essential to establish a rapid and dynamic feedback mechanism for changes in environmental policy conditions. This will enable timely adjustments and improvements in environmental management strategies. 3) Emphasize the development of computer technology is vital to enhance the efficiency and accuracy of cost-benefit analysis and optimization of BMPs. This will improve the feasibility of cost-benefit analysis methods in practical applications and enable the attainment of multi-objective cost-benefit optimal solutions.

6.3 Macroscopic supervision and control of water environment pollution

The current water pollution control process in China has drawbacks, such as local and departmental divisions. This closed governance model leads to a focus on pollution within specific administrative regions, neglecting overall water conditions and enabling the transfer of pollutants through local protectionism (Tong, 2017). Cost-benefit analysis primarily evaluates economic and engineering policies, but it should also consider regional development and native ecology. Although investment in river basin protection shows long-term benefits, efforts to control polluted river areas need to be increased. To address these issues, China should adopt integrated and collaborative approaches, transcending administrative boundaries and promoting cooperation among regions. This will enhance water pollution control and achieve more sustainable outcomes.

We urge the establishment of a collaborative governance model for water pollution management that considers the entire river basin. This should include an environmental cost-benefit assessment and cross-basin synergy to address agricultural non-point source pollution (Xu et al., 2022). It is important to prioritize emergency response capacity and upgrade industrial sectors while considering the ecological impact of the water environment. By balancing regional differences and promoting a win-win situation between the environment and economy, we can achieve effective water pollution control.

Author contributions

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