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A Bi-level optimization approach to reduce the pollution burden of lake water with ecological compensation

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ABSTRACT

Lake Ecological Compensation (LEC) mechanism is a localized approach of payment for ecosystem services to address the conflict between economic development and ecological conservation. However, how to motivate regional stakeholders to participate in water quality protection is a challenge. Based on the traditional Coase Theorem, vertical eco-compensation mechanism has been proposed to solve pollution of lake basin. The quantification of LEC is characterized by key water quality indicators (NH_3-N and COD) in this paper. Integrating LEC mechanism with the ecological-economic model, this paper proposes a bi-level optimization framework for the conservation of the lake water environment. Referring to Coase's theory, the leader's goal is to distribute waste load permits equally to sub-regions while followers aim to minimize environmental costs. The appropriate application of this method to Taihu Basin demonstrates its efficiency and practicality. The LEC mechanism with different scenarios is analyzed and suggestions for lake water quality are made. The results show that: (1) Considering equitable principle, the new COD allocation scheme has reduced the total amount of emissions by 17% compared to the data in 2020, and the total amount of NH_3-N has decreased by 16%. (2) With the cooperation of lake basin institutions, the LEC mechanism is proved to be an effective measure in promoting the conservation of the lake water environment. (3) The spillover effect of environmental and ecological policies in lake water indicates the need to upgrade industrial structure. This paper proposes to provide a more reliable the conservation of the lake water environment paradigm.

1. Introduction

Payment for Ecosystem Services (PES) has been proposed and operated as economic incentives for ecological conservation across different regions and countries for about two decades (Engel et al., 2008; Ouyang et al., 2016; Zhang et al., 2022; Wunder et al., 2008). Ecological conservation is a general behavior targeting the natural environment. The diversification of PES practice is an inevitable result of various environmental and institutional settings (Zeng et al., 2021). Forest Restoration Programs in the western US (Belavenutti et al., 2022), the Okavango River Basin in South Africa (Wang and Nuppenau, 2021), and the Lake Erie Watershed (Xu et al., 2018) are all successful applications of PES. How the PES mechanism adopted, comprehended and implemented by the Chinese local governments is noteworthy for ecological conservation. For the localization of PES into the Chinese ecological conservation, eco-compensation is conceptualized as a national environmental protection policy in China (Feng et al., 2018).

Watershed PES (US$24.7 billion in 62 countries in 2015) (Salzman et al., 2018), also known as watershed ecological compensation, mainly restricts the behavior of polluters through the design of a reward and punishment mechanism. The ecological compensation mechanism, as an effective environmental policy, that uses economic instruments to coordinate the interests of stakeholders has been the focus of many scholars (Connor et al., 2022; Jiang et al., 2019). However, few of them synergize the institutional structure of lake basins with ecological compensation mechanisms. Existing studies have paid little attention to lake ecological compensation (LEC) for the conservation of the lake water environment, which means specific behavior targeting water quality.

Lake basin, as integrated place to accommodate water bodies, plays vital ecological roles such as flood regulation and storage, water diversion for irrigation, drinking water sources, aquaculture, and tourism

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(Watson et al., 2016; Woolway et al., 2021). However, the continuous deterioration of lake ecological environment has become an impediment to the sustainable development of social economy. The increasing nutrients in lakes has put water quality at risk worldwide. Varying degrees of water eutrophication and water quality degradation have been discovered in the North American Great Lakes (Ricciardi and MacIsaac, 2000), Lake Biwa in Japan (Ma et al., 2022), Lake Bolsena and Lake Chiusi in central Italy (Fischer et al., 2016), and Lake Erhai in China (Lin et al., 2021). According to the United Nations' Sustainable Development Goals (SDGs) (Pereira and Marques, 2021; Wang et al., 2022), clean water for SDGs 6 and 4 is urgently needed for the whole world. Based on water quality monitoring and combined with modelling studies (Vörösmarty et al., 2010), reviews of global water pollution indicate effective measures need to be taken to control the ecosystem pollution of lake waters.

LEC mechanism is one of the sensible economic means for water pollution control and ecological conservation (Shen et al. 2021). It seeks to internalize the externalities related to human behaviors and creates incentives for sub-regions to ensure ecological service provision. To clarify that, the dominant papers of PES researches are summarized in Table 1.

The quantification of compensation is a key link in the implementation of ecological compensation for water quality pollution. Nash equilibrium model (Nimubona and Pereau), optimal model (Zhao et al., 2013), Stackelberg game (Fernandez, 2013), and the evolutionary game (Gao et al., 2019) are typical methodologies used in previous research. Water quality requirements of the lake and discharge standards are the aim of pollution planning and the key indicators for decision-making.

To the best of the authors' knowledge, existing literature lacks comprehensive studies that combine mathematical models for lake water environmental ecology and waste load allocation to quantify the lake ecological compensation mechanism. What's more, in the institutional structure system, two levels of decision-makers are included which are the Lake Environment Committee and sub-regional authorities. The Lake Environment Committee is the priority decision-maker that makes it necessary to allocate the waste load permits effectively. The sub-regional authorities, as the lower-level decision makers, try to minimize the environmental costs under the LEC mechanism.

This paper makes significant contributions in three aspects. Firstly, it refines an analytical framework to quantify lake ecological compensation, which helps to resolve the conflict between economic development and the conservation of the lake water environment. Secondly, a bi-level optimization model is proposed based on the Coase Theorem, which enables equitable waste load allocation and reasonable annual planning for water quality control. Thirdly, various scenarios for joint governance of the lake water ecosystem in Taihu Basin are discussed, providing support for its sustainable development.

2. Key problem statement

The over-exploitation of water resources in lakes has aggravated the deterioration of water quality. Therefore, how to coordinate regional economic development with water environmental protection has attracted widespread attention. In this paper, two perspectives are considered which are waste load amount control and water pollution concentration control based on the governance system. Each perspective has multiple considerations. This research is conducted to shed light on the strategy of maintaining sustainable development of the lake water ecosystem.

2.1. Multi-stakeholder governance system

The formation and evolution of lakes are not only affected by the changes of natural factors in the basin but also influenced by human activities. Hence, lakes present different regional evolutionary characteristics and ecological problems.

Coase Theorem (Hahn, 2013), proposed by a Nobel Prize winner, is well-known in ecological conservation. Based on Coase Theorem, environmental externalities are turned into property right problems, as it uses a market mechanism to maximize the environmental and economic benefits based on clear property rights. Coase's theory also supports the quantification and equitable allocation of waste load permits. The conservation of the lake water environment is mainly manifested mainly in three aspects.

1. The rapid economic development of the lake areas, as the focus of local governments, will inevitably cause water quality degradation, for the pollutant-holding capacity of lakes is limited. The equitable allocation of limited waste load permits (WLP) is a feasible method for the conservation of the lake water environment.
2. The lack of an effective behavioral regulatory mechanism affects the sustainable development of lakes. If the local government conducts little intervention in local sewage discharge, the pollution of lakes will be disastrous.
3. The sustainability of the water ecosystem in the basin needs multi-index and multi-dimensional measures instead of simple evaluation. Multi-sectoral involvement, covering Lake Environment Committee and sub-regional authorities, is equally vital.

For the institutional structure of lake management, the Lake Environment Committee works as the upper-level decision maker (Leader) and sub-regional authorities of lakes are the lower-level decision makers (Followers). As the supervisor of the overall water quality in the lake basin, the Lake Environment Committee focuses on how to rationally allocate the total amount of WLP as it is limited. Furthermore, the Lake Environment Committee formulates the LEC mechanism and regulates regional behaviors by monitoring section data. Regional governments mainly work on the annual average concentration of pollutants within

Table 1
Practice and application of payment for ecosystem services.

Articles	Research object	Key problem and innovation	Eco-compensation Mechanism	Methods
Nimubona and pereau, 2022	Wetland	To analyze the economic efficiency between the beneficiaries and providers though novel payment schemes.	√	A Nash equilibrium model with three types of agents
Zhao et al., 2013	Lake	To compute the cost of minimized transfer tax rate along with the reduction quantities of individual regions.		A bi-level programming framework
Fernandez, 2009; 2013	Transnational river	To help stakeholders bear pollution abatement costs and share water monitoring responsibility.		A Stackelberg game and Nash Equilibrium
Gao et al., 2019	Transboundary river	To explore how ecological benefits are distributed between different governments.	√	An evolutionary game of multi-governments
Lu et al., 2020	Transboundary river	To build an econometric model of economic loss and calculate the amount of compensation for economic loss due to water pollution.		An econometric model to calculate the economic loss
Smith et al., 2019	Land	To design a land payment for ecosystem services mechanism and examine spatial coordination on the demand side of the market.	√	Spatial simulation modelling

the mechanism. The decision variables represent the actual discharge amount in the region from the leader part and the annual average water quality concentration of the monitoring section from the lower part. The goal is to find the balance between economic benefits and the sustainability of the water ecosystem.

2.2. Structuring incentive mechanism

A growing amount of research suggests that using the LEC mechanism as economic incentives to maintain water sustainability is a more direct approach to achieving the goal (Guan et al., 2021; Li et al., 2022). However, the existing quantitative analysis of lake eco-compensation is not sufficiently systematic and is somewhat defective. To fill these gaps, we explore the establishment of LEC mechanism based on water quality and the quantity of discharged contaminants. A tradeoff occurs when wastewater emission increases because of economy production and ecology value reduces accordingly . However, a synergy works when all sub-regions take the sustainability of lake water environment as their own mission.

The LEC mechanism is an embodiment of PES which refers to reward and punishment. Behaviors that protect the water environment are rewarded, while behaviors that cause damages are punished (Wu et al. 2018). In essence, the LEC is an environmental and economic incentive policy and it takes the form of fiscal funding between the Lake Environment Committee and individual sub-regions. Furthermore, as there is no strict division between upstream and downstream in the lake, how to judge the impact of sewage among different regions is also regarded as a tough assignment.

The control of pollutant concentration is the main indicator of the LEC mechanism. Through the data analysis of the monitoring section, the reward and punishment of sub-regions can be judged. The lake eco-compensation mechanism is expressed as the following function $g(y_{ij})$:

$$g(y_{ij}) = \begin{cases} -\alpha p_i \ , \ 0 < p_i \leqslant 1 \\ \beta p_i \ , \ p_i > 1 \end{cases} \alpha, \beta > 0 \tag{1}$$

$$P_i = \mu_0 \sum_{j=1}^{n} k_j \frac{y_{ij}}{Cijo} \tag{2}$$

where p is the compensation index of the monitoring section, i is the sub-region located at the same lake, and j presents different contaminants. μ_0 is the lake water quality stability coefficient which mainly considers the influence of natural conditions such as rainfall and runoff ; k_j is the indicator weight coefficient ; y_{ij} is the annual mean concentration value of the indicator ; C_{ij0} is the basic limit of the indicator, where the lower limit of the III class of water quality is used as the standard. The decision framework for lake water environment management is illustrated in Fig. 1.

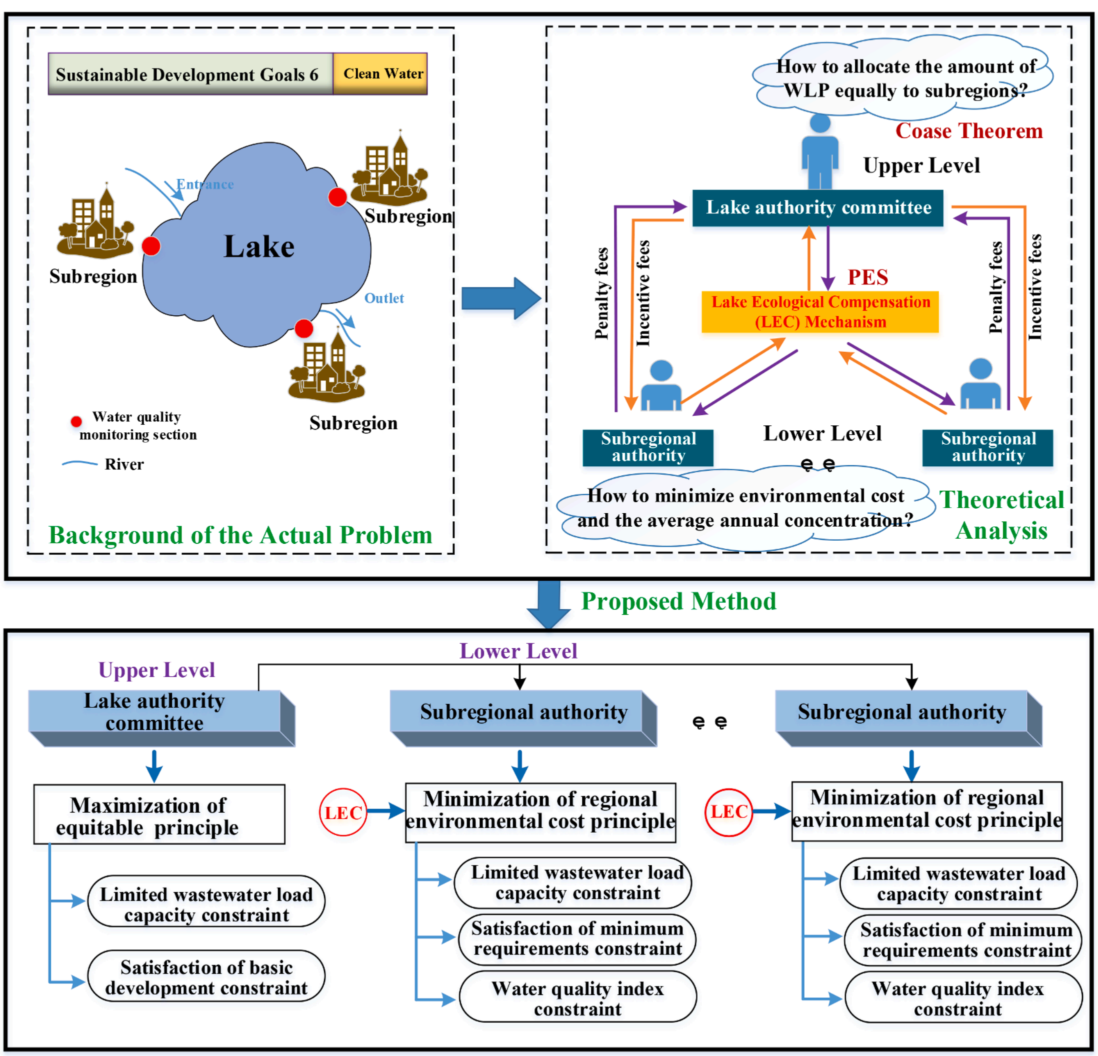

Fig. 1. Decision framework for lake water environment management in this paper.

3. Method

A bi-level optimization model has been developed for the lake eco-compensation mechanism of the watershed by analyzing the structure of the lake water environment management. The formulation process placed a strong emphasis on the model's feasibility and practicality, taking into account the real-world context of the problem.

3.1. Framework of the model

3.1.1. Assumption

The complete the conservation of the lake water environment requires the Lake Environment Committee to allocate waste load permits equally to sub-regional authorities. On the other hand, sub-regional authorities should control the average annual concentration of water contaminants within the LEC regulation framework. The implementation of the LEC mechanism has stimulated the protection of water quality in the region. Before establishing the basic model, four hypotheses are made as follows.

Assumption 1. *There is no obvious upstream or downstream relationship in the lake. Regional authorities share equal power in lake management, and the Lake Environment Committee has the priority right to supervise all of them.*

Assumption 2. *Each sub-region of the lake is willing to implement the lake ecological compensation mechanism.*

Assumption 3. *The planned interval is one year. The concentration of water contaminant as an indicator is based on the average value of the monitoring section in sub-regions.*

Assumption 4. *Regional authorities are responsible for water pollution abatement costs and take cost minimization as the objective function of decision-making.*

3.1.2. Upper-level optimization model

Equitable allocation of WLP is considered to be the main goal of the Lake Environment Committee based on the Coase Theorem. As the leader decision-maker, Lake Environment Committee concentrates on rationally allocating the annual amount of the sewage to sub-region.

Gini (Dalton, 1920) proposed the Gini coefficient to measure income inequality, and it also has been used to measure land inequality and water allocation inequality in recent years. The threshold for the Gini coefficient is 0 to 1, and the lower the value, the more equity it is. Specifically, the Gini coefficient can be constructed for waste load allocation in the watershed system (Hou et al., 2021). Equity is specifically expressed as the difference of in waste load permits per unit of economic benefit within sub-regions. This paper proposes that the smaller the difference, the more reasonable it is. The specific model is expressed in terms of the Gini coefficient. The first optimization objective can be written as:

$$MinG = \sum_{j=1}^{n} \frac{1}{2m\sum_{i=1}^{m}\frac{x_{ij}}{EB_i}} \sum_{l=1}^{m} \sum_{h=1}^{m} \left| \frac{x_{lj}}{EB_l} - \frac{x_{hj}}{EB_h} \right| \quad (3)$$

where x_{ij} is the decision variable, which means the amount of WLP allocated to subarea i for contaminant j. m is the region related to the same lake. EB_i is the annual average of economic benefits as an indicator of regional economic development. The constraints are formulated as follows.

(1) Limited wastewater load capacity constraint. The total environmental carrying capacity of the whole lake basin is limited. T_j is the total amount of WLP that can be allocated by the Lake Environment Committee under the condition of ensuring the sustainable development of the watershed.

$$\sum_{i=1}^{m} x_{ij} \leqslant T_j \quad (4)$$

(2) Satisfaction of basic development constraint. When making decisions, the upper level needs to consider that the actual emission rights of the region are greater than the actual amount of pollution emitted. The actual discharge of regional water pollutants should be lower than the allocated amount. ϕ_i presents the reduction rate of contaminant. Q_i represents the average annual wastewater flow. y_{ij} is the annual concentration of the monitoring section controlled by the sub-region authorities under the LEC mechanism.

$$\sum_{i=1}^{n} h1 + \phi_i)x_{ij} \geqslant \sum_{i=1}^{n} Q_i y_{ij} \quad (5)$$

3.1.3. Lower-level optimization model

Sub-regional authorities implement the tactic to achieve its optimal average annual concentration at the lowest environmental cost under the lake eco-compensation mechanism. For lake sub-regions, the Total Environmental Cost (*TEC*) contains two parts, covering pollution reduction cost and eco-compensation fee.

$$MinTEC_i = \sum_{j=1}^{n} \eta_{ij}\phi_i x_{ij} + g(y_{ij}) \quad (6)$$

where η_{ij} is the unit reduction cost of contaminant. $g(y_{ij})$ is the expression of the lake eco-compensation mechanism which is shown as Eq.(1). y_{ij} is the decision variable. The ecological compensation value can be positive or negative. A positive number represents an increase in the total environmental cost of penalties due to the high concentration of water discharged. Negative value is the opposite. The constraints are formulated as follows.

(1) Limited wastewater load capacity constraint. For a sub-region of the lake, actual annual discharge amount should not exceed the allowable emission permits. The reduction of contaminants can increase the total amount of emission pollution. Q_i represents the average annual wastewater flow.

$$Q_i y_{ij} \leqslant h1 + \phi_i)x_{ij} \quad (7)$$

(2) Satisfaction of minimum requirement constraint. As pollution emission and economic development are closely related in some way. The right to pollution emission can be seen as the right to economic development. In order to ensure the basic development of economy, the total amount of pollutants has a minimum value.

$$Q_i y_{ij} \geqslant M_{ij}^{\min} \quad (8)$$

where $M_{ij}^{\min}$ is the basic emission requirement for regional economic development.

(3) Water quality index constraint. Pollutant concentration is a significant indicator in lake water environment management. The main function of the water quality monitoring section of the lake is to detect the pollution concentration.

$$y_{ij} \leqslant C_{j0}^{\max} \quad (9)$$

where $C_{j0}^{\max}$ is the upper limit of the concentration standard.

3.2. Global model

Interactive decision-making management between Lake Environment Committee and multiple sub-regional authorities in the lake is proposed in our model. Hierarchical decision process is considered as a Stackelberg game model (Fischetti et al., 2017). The objective function of the upper level is to maximize the equity of allocation, and the lower level is mainly to minimize the environmental costs.

$$MinG = \sum_{j=1}^{n} \frac{1}{2m\sum_{i=1}^{m}\frac{x_{ij}}{EB_i}} \sum_{l=1}^{m}\sum_{h=1}^{m}\left|\frac{x_{lj}}{EB_l} - \frac{x_{hj}}{EB_h}\right|$$

$$s.t\left\{\begin{array}{l} \sum_{i=1}^{m} x_{ij} \leqslant T_j \\ \sum_{i=1}^{n} h1+\phi_i)x_{ij} \geqslant \sum_{i=1}^{n} Q_i y_{ij} \\ x_{ij} \geqslant 0 \\ MinTEC_i = \sum_{j=1}^{n} \eta_{ij}\phi_i x_{ij} + g(y_{ij}) \\ s.t\left\{\begin{array}{l} g(y_{ij}) = \begin{cases} -\alpha p_i\ ,\ 0 < p_i \leqslant 1 \\ \beta p_i\ ,\ p_i > 1 \end{cases} \\ P_i = \mu_0 \sum_{j=1}^{n} k_j \frac{y_{ij}}{C_{ij0}} \\ Q_i y_{ij} \leqslant h1+\phi_i)x_{ij} \\ Q_i y_{ij} \geqslant M_{ij}^{\min} \\ y_{ij} \leqslant C_{j0}^{\max} \\ y_{ij} \geqslant 0 \\ \mu_0 > 0 \\ \alpha, \beta > 0 \end{array}\right. \end{array}\right. \tag{10}$$

4. Case study and results

4.1. Study area

Taihu Basin, spanning Jiangsu, Zhejiang and Shanghai, covers a total area of 31,800 km^2. As a major part of the Yangtze River Delta, the area witnesses a large population density, developed industrial and agricultural production, fast-growing GDP and high per capita income. In this case, Taihu Basin includes 4 cities in Jiangsu Province (Suzhou, Wuxi, Changzhou and Zhenjiang), 3 cities in Zhejiang Province (Huzhou, Jiaxing and Hangzhou), and 3 towns in Shanghai (Liantang, Jinze and Zhujiajiao). Fig. 2 displays the location of Taihu Basin and demonstrates the poor water quality in the basin. According to the change in the nutrient index in the Taihu Lake Health Status Report (2012–2018), the water body of Taihu Lake is in a moderately eutrophic state. Therefore, effective measures for the conservation of the lake water environment are necessary for the sustainable development of the lake.

4.2. Data collection

The data collected in this case is from the Overall Plan for Comprehensive Water Environment Management in Taihu Basin in 2013 and 2022 from the National Bureau of Statistics in China and the Department of Ecology and Environment of the three areas. According to the latest document, the main pollution indicators of the basin are COD and NH_3-N. Basic data of Taihu Basin in 2020 are shown in Table 2. As shown in the table, Jiangsu has the largest area in the basin while Shanghai has the smallest.

It can be seen from Table 2 that Jiangsu Province in Taihu Basin has the widest area and the largest amount of sewage. Only a small part of Shanghai is located in the Taihu Basin, so the index value is the smallest accordingly. As its pollution load into the lake is relatively large, Jiangsu is considered as a key area for the prevention and control of pollution loads.

For more detailed data, to calculate the optimal model, the initial assignment based on historical data is summarized in Table 3. In terms of location, Jiangsu and Zhejiang have more estuaries related to the lake, while Shanghai is close to the lower reach of Taihu. Therefore, Shanghai poses a relatively smaller impact on the lake. In the calculation value of the P_i, 15 mg/L was used as the basic limit for COD and 0.5 mg/L for NH_3-N.

4.3. Optimal results

After assigning the parameter values, the software is utilized to calculate the optimization model in this section. In addition, the characteristics of regional decision-making behavior in different scenarios are also discussed. Furthermore, it provides data support for the protection and sustainable development of the lake ecological environment. According to the above model construction, this is a linear bi-level optimization problem regarded as NP-hard. Bi-level programming is motivated by Stackelberg to solve the unbalanced economic market problems (Colson et al. 2005). Generally, Karush-Kuhn-Tucker (KKT) (Lu et al., 2006; Shi et al., 2005; Sinha and Sinha, 2002) transformation approach has been applied to multi-level decentralized optimization model.

This paper regards $P_i > 1$ as the base scenario. Three regions are chosen as the payers of ecological compensation for economic development. Environment Committee of Taihu Lake as the leader pursues the equitable allocation of WLP, and initial results are shown in Fig. 3. The value of the upper objective function is 0.58. Zhejiang has been allocated the largest amount, Jiangsu the second and Shanghai the least. Although Jiangsu has a larger area than Zhejiang, the decision maker gives Zhejiang more WLP. For the reason, economic development is one factor, and on the other hand, Zhejiang is willing to pay more compensation. The annual average pollutant concentration of monitoring points is used as the main indicator of reward and punishment, and is supervised by the upper level.

The new COD allocation scheme has reduced the total amount of emissions by 17% compared to the 2020 data, and the total amount of NH_3-N has decreased by 16%. The red monitoring points in Fig. 3 are not actual monitoring points, but only represent the phenomenon of water quality detection, which is normal in reality. There are many actual monitoring points for national and provincial levels. With these water quality data, managers can prevent excessive water pollution, and local government can adjust policy directives through the concentration data.

The initial calculation results of lower level are shown in Table 4, which contain the annual average concentration of pollutants, total environmental costs and ecological compensation values. The eco-compensation values are all positive, meaning that all three regions have opted to pay pollution fines. Zhejiang has the largest ecological compensation value. It is demonstrated that in this case, in order to develop the economy, Zhejiang would like to pay for water pollution.

5. Discussion

5.1. Scenario analysis

Under the ecological compensation mechanism, each region has two

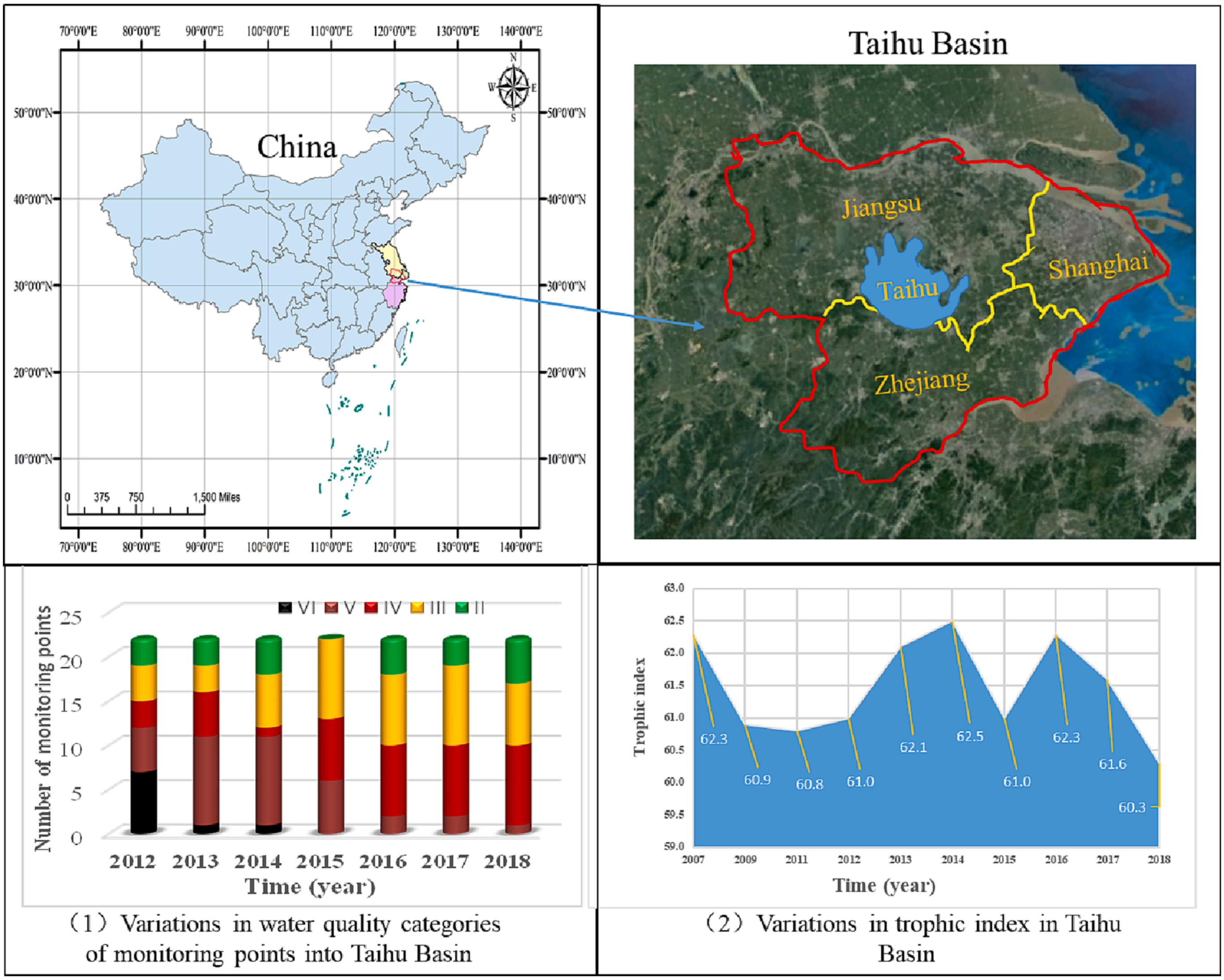

Fig. 2. Location map and water quality situation of Taihu Basin.

options: either be penalized for a large amount of pollutant discharge or be rewarded for reducing emissions. As the different choices of subregions will affect the allocation made by upper-level decision-makers. The Taihu Basin is divided into three regions, resulting in a total of eight scenarios. Fig. 4 presents a scenario analysis, which mainly reflects the regional governments' priorities regarding environmental protection.

P_i represents the willingness of local government to participate in environmental protection. $P_i > 1$ means that the region chooses to pay the compensation value, thereby expanding the amount of sewage. $0 < P_i \leq 1$ means to be rewarded with ecological compensation for controlling pollutant discharge. P1 represents Jiangsu, P2 presents Zhejiang and P3 presents Shanghai. As can be seen in Fig. 4, three regions choose to be punished in scenario 1. Jiangsu chooses to be rewarded and Zhejiang and Shanghai choose to be punished in scenario 2. Zhejiang chooses to be rewarded and Jiangsu and Shanghai choose to be punished in scenario 3. Shanghai chooses to be rewarded and Jiangsu and Zhejiang choose to be punished in scenario 4. Shanghai chooses to be punished and Jiangsu and Zhejiang chooses to be rewarded in scenario 5. Zhejiang choose to be punished and Jiangsu and Shanghai chooses to be rewarded in scenario 6. Jiangsu chooses to be punished and Zhejiang and Shanghai chooses to be rewarded in scenario 7. Three regions choose to be rewarded in scenario 8.

As can be seen in Fig. 4, when a region chooses to receive ecological compensation incentives, the annual average concentration of pollutants will decrease. The main objective of the lower level is to minimize the environmental costs that are affected by the governance cost and ecological compensation value. The index that affects LEC value is the concentration of pollutants. Regional governments can control the total environmental costs through the annual concentration of pollutants.

As shown in Fig. 3, there are many water quality monitoring points, and this paper uses the annual average concentration of water quality monitoring points to represent the value. According to Eq. (1), different concentration values will affect the ecological compensation value. The

Table 2
Basic data of Taihu Basin in 2020.

Subregion	Areas located at the basin	Area data		GDP (10^9 yuan)	Main water quality indicators (t)	
		Basin area (km^2)	Proportion		COD	NH_3-N
Jiangsu	4 cities	16,854	53.0%	4366	327,690	22,000
Zhejiang	3 cities	10,621	33.4%	2482	156,897	11,894
Shanghai	3 towns	4325	13.6%	277	5257	538
Taihu Basin	—	31,800	100%	7125	489,844	34,432

Table 3
Initial assignment of main parameters for model calculation.

Subregion	Quantity of wastewater (Q_i, 10^6 m^3)	Reduction rate (ϕ_i,%)	Demand limit (M_{ij}, t)		Adjustment coefficient (μ_0)	Concentration upper limit (C_{j0}^{max}, mg/L)		Compensation coefficient (yuan)	
			COD	NH_3-N		COD	NH_3-N	α	β
Jiangsu	3120	85	158,978	16,800	0.75	30	1.5	10^6	10^7
Zhejiang	1575	80	139,259	8490	0.8	30	1.5	10^6	10^7
Shanghai	840	70	5157	416	0.85	30	1.5	10^6	10^7

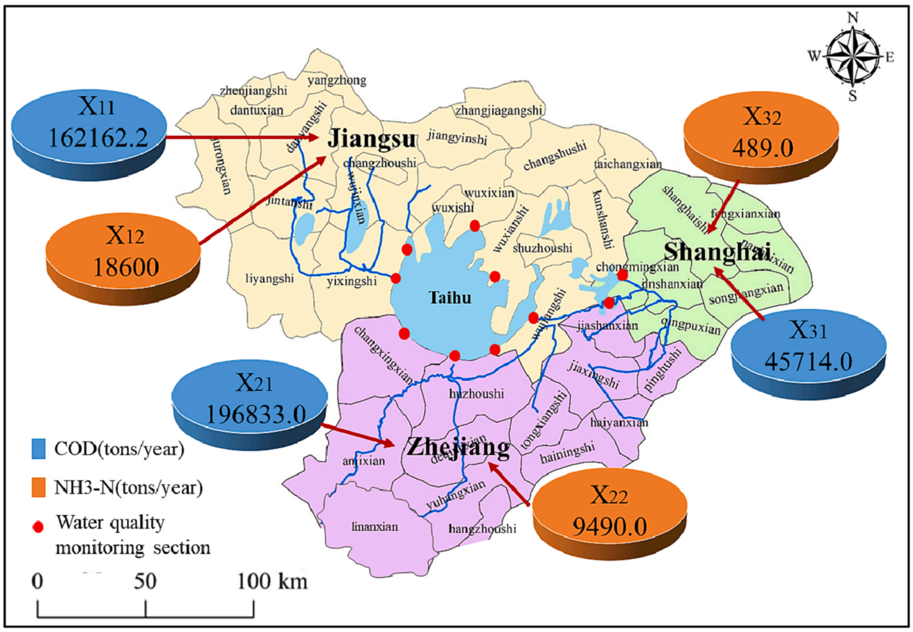

Fig. 3. The calculation results of upper level at initial parameter value.

optimal concentration is in scenario 8, where each region chooses to control water pollution discharge, and thus receives a reward.

As can be seen in Fig. 4, the willingness of local governments to participate in water ecological environment protection will directly affect the local water quality concentration. When local governments are willing to make efforts to protect water quality, the concentration of pollutants will be lower. Economic incentive policies have a certain degree of influence on ecological and environmental protection, but the attitude of local governments is also very important. On the one hand, local governments should follow the central environmental policy. On the other hand, it should adjust the environmental protection strategy according to local realities.

5.2. LEC sensitivity analysis

How do changes to the reward and punishment settings of the LEC mechanism impact the concentrations of pollutants? The establishment and implementation of a credible scientific LEC mechanism has become an effective governance measure to coordinate the relationship between profit and loss within a river basin, and also an important guarantee to promote equitable development among regions. This part discusses the sensitivity of LEC in eight scenarios from 1 to 8. Positive numbers of eo-compensation mean being punished, and negative numbers mean being rewarded.

Environmental policy is an important measure to promote the sustainable and coordinated development of both the economy and the environment. The environmental policy could be divided into three types: command-control environmental policy, market-based environmental policy and public participation environmental policy. Environmental policy is mainly through the design of environmental mechanisms to reduce pollution emissions. Market-based environmental policy is regarded as an incentive-based regulation approach which relies on market incentives to reduce pollution and minimize pollution control costs.

According to Fig. 5, when the punishment is increased, the concentration will decrease. The maximum punishment of LEC can reach 180.90 million yuan and the maximum reward can reach 89.4 million yuan. High payment costs drive regions to control the concentration of pollutants. For Jiangsu, the LEC values for scenarios 2, 5, 6, and 8 are positive, which means that Jiangsu chose to pay the penalty fee. In scenarios 1, 3, 4, and 7, Jiangsu chose to be rewarded. Zhejiang is punished in scenarios 1, 2, 4, and 6, and rewarded in scenarios 3, 5, 7, and 8. Shanghai chose to be punished in scenarios 1, 2, 3, and 5, and rewarded in scenarios 4, 6, 7, and 8. Different regions have different sensitivities to environmental policies. Jiangsu is the most sensitive one to policies, indicating that its regional development is closely related to policies. Shanghai is less affected by policies due to its smaller area.

Table 4
The initial results of lower decision variables and objective function.

Subregion	Decision variables of the lower level (mg/L)		Objective function value of the lower level (TEC*i*,10^8yuan)	Lake ecological compensation value (g (y), 10^8yuan)
	Y*i*1	Y*i*2		
Jiangsu	12.82	0.85	2.3	3.4
Zhejiang	16.93	0.95	2.8	4.2
Shanghai	9.52	0.74	1.4	2.7

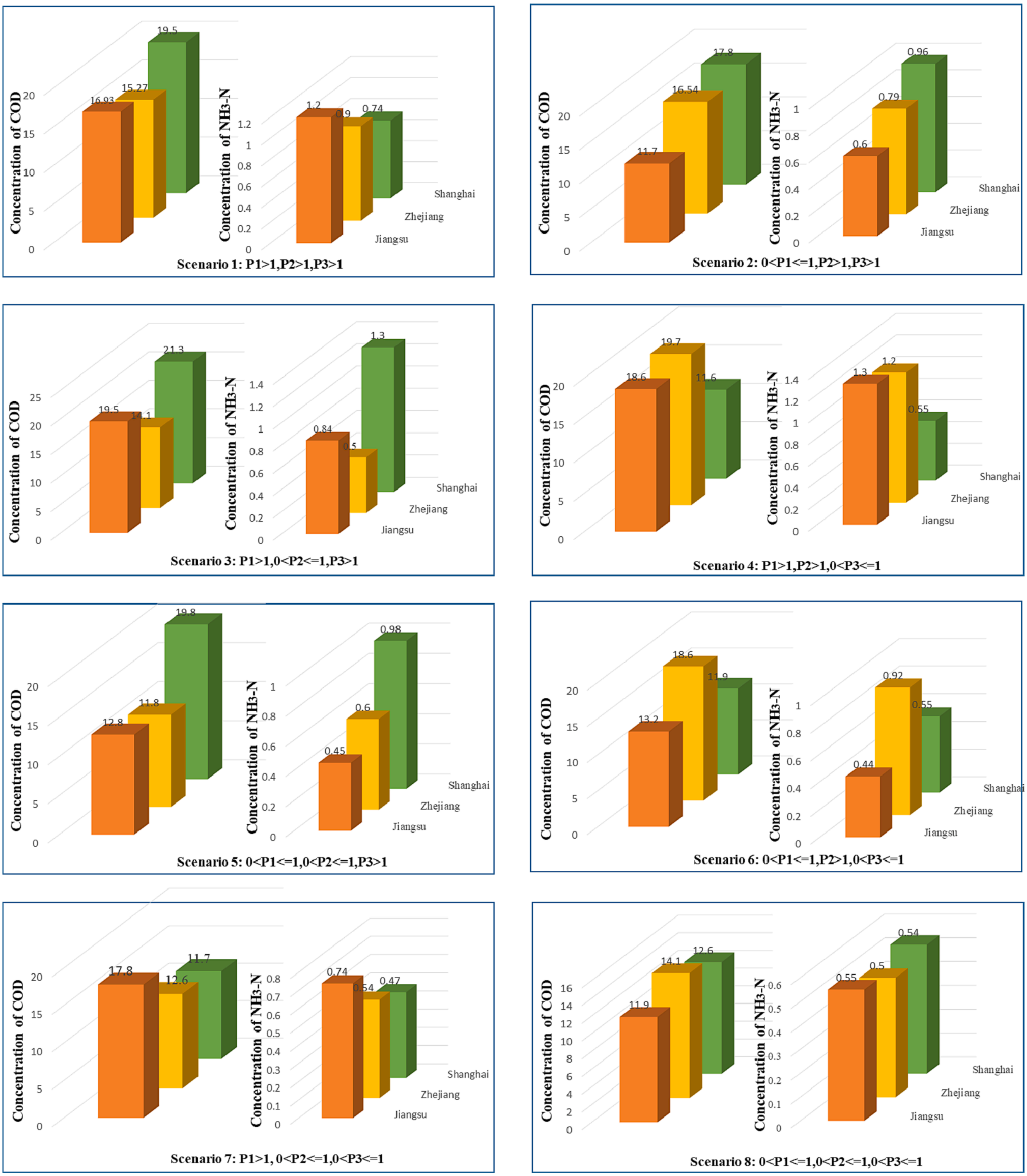

Fig. 4. Optimal concentration of COD and NH_3-N under eight scenarios.

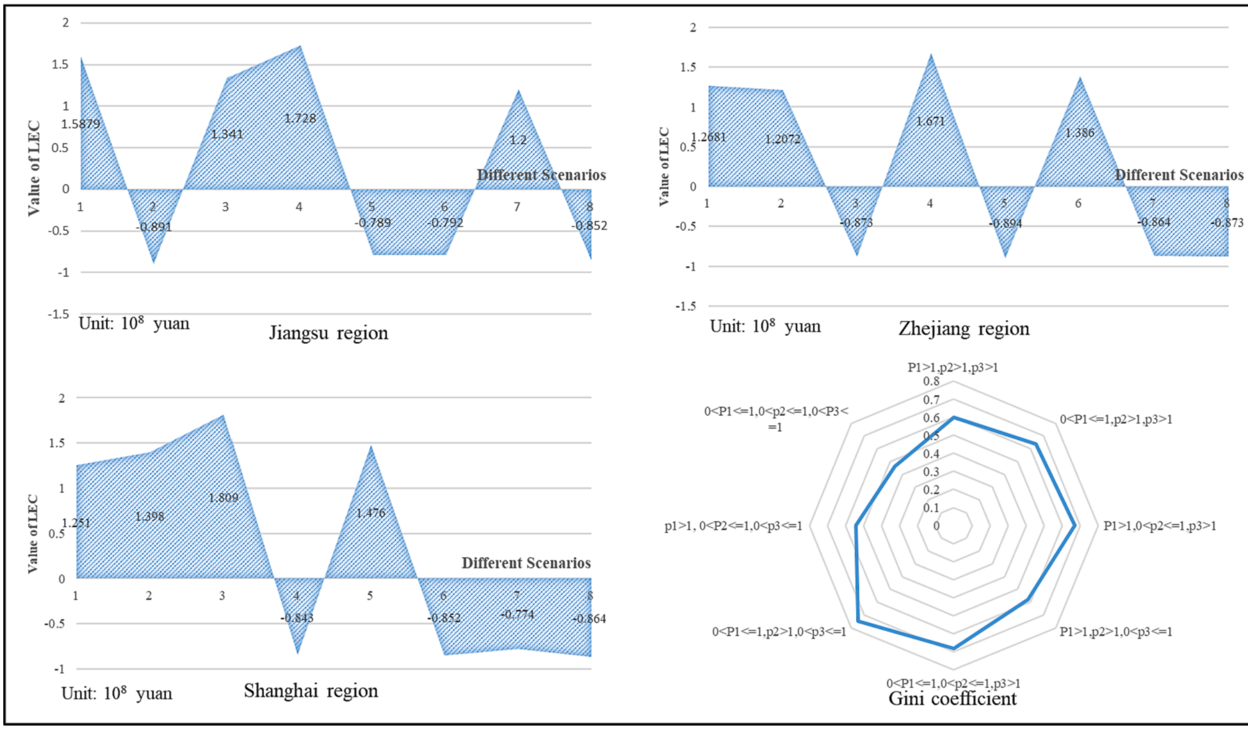

Fig. 5. The value of LEC and Gini coefficient under different scenarios.

From the results of the environmental Gini coefficient in Fig. 5, it can be found that local behavior will affect the decision of upper-level decision-makers. When all three regions choose to protect the environment, the Gini coefficient is at its lowest at 0.46, indicating that the upper-level decision-makers are making the most equitable allocation.

5.3. Policy recommendations

Three policies for water quality management in the Taihu Basin are proposed from the perspectives of stakeholders, incentive mechanism, and extensibility, based on the computational results and analysis presented above.

5.3.1. Interactive hierarchical institutional structure is required

From the perspective of participating stakeholders, the interactive communication between different levels is of great help for water environment management within the basin. Collaborative governance of transboundary watersheds refers to the formation of a joint governance mechanism for transboundary environmental pollution management in accordance with the idea of division of labor, cost sharing, and benefit sharing. It highlights the joint protection of the ecological environment in Taihu Basin. The governance of Taihu Basin requires not only the management committee from the upper level, but also the active participation of local governments from the lower level. The upper-level government needs to decide the effective allocation of WLP according to the overall situation of the watershed and local behaviors. Meanwhile, Fig. 5 illustrates that local governments need to adjust their development strategies according to the upper policies. As shown in Fig. 1, the coupling management between multiple subjects makes the governance of the entire watershed even more effective.

5.3.2. LEC mechanism is an effective economic incentive policy

From the perspective of incentive mechanism, eco-compensation of lake can effectively motivate regional authorities to control pollution emissions, and if the punishment is increased, the effect will be more obvious as demonstrated in Fig. 4 and Fig. 5. LEC is an economic incentive means to effectively balance the relationship between watershed economic development and water quality protection. The establishment and implementation of a scientific and reasonable ecological compensation mechanism has become an effective governance measure to coordinate the relationship between profit and loss within lake basins. Based on the above analysis, a sound basin LEC mechanism should cover the following basic contents: basin management mechanism, compensation standards, compensation mode, and compensation subject and object. These interrelated contents work together to form the framework of LEC mechanism with an aim to achieve the goals of ecological green development, coordinated economic growth, and common social progress in the lake basin.

5.3.3. Spillover effect of lake environmental conservation policy deserves attention

From the perspective of extensibility, the spillover effect of lake water environmental policy deserves attention (Börner et al., 2017). The spillover effect of lake environmental policy means that when the government implements an environment management policy for the lake, it will not only prompt the adjustment of the emission of the total pollution as expected, but also has an impact on local industrial institutions (Feng et al., 2021). The adjustment of pollutant amounts forces the transformation of industrial structure. Taihu Basin, located in the Yangtze River Delta as shown in Fig. 2, is one of the regions with the most active economic development, the highest degree of openness and the strongest innovation capability in China. The governance of Taihu Basin water environment will inevitably promote the change of industrial structure in the Yangtze River Delta. Although this paper does not analyze the behaviors of enterprises, the management of the lake environment cannot be separated from the participation of local enterprises. The upgradation of industrial structure is surely conducive to its environment-friendly development.

6. Conclusion and future works

An analytical framework is refined to localize the PES to address the conflict between economy and the conservation of the lake water environment. According to Coase Theorem, a bi-level optimal model is proposed to realize the equitable allocation of waste load permits and reasonable annual planning of water quality control. Different scenarios are discussed to promote the joint governance of the lake water ecosystem in Taihu Basin, which provides a support for the sustainable development of the lake. Our study suggests that an integrated basin management should consider PES to encourage the conservation of the lake water environment. By focusing on the management of lake water environment, three aspects of research conclusions are contained in this paper.

Firstly, the maximum punishment of LEC can reach 180.90 million yuan and the maximum reward can reach 89.4 million yuan in Taihu lake. It puts forward a paradigm of lake water environment management and supervision. Lake eco-compensation mechanism based on water environment polity is constructed and quantified by a piecewise function mathematical model. Through the coupling study of water quality and waste load quantity, this paper constructs an optimal decision-making method.

Secondly, the new COD allocation scheme has reduced the total amount of emissions by 17% compared to the 2020 data, and the total amount of NH3-N has decreased by 16%. A bi-level optimal model is proposed to realize the equitable allocation of water contaminant and reasonable annual planning of water quality management. By controlling the total amount of carrying capacity, the goal of the leader is to rationalize the allocation of waste load permits to sub-regions, and followers aim to minimize environmental costs with environmental quality standards met.

Thirdly, when all three regions choose to protect the environment, the Gini coefficient is at its lowest at 0.46, indicating that the upper-level decision-makers are making the most equitable allocation. Taihu Basin is analyzed as a case to prove the effectiveness and practicability of the method, and to provide suggestions for the water environment management of the lake. Different scenarios are discussed for the joint governance of the water environment in Taihu Basin. Three proposals have been put forward that interactive hierarchical management is required, lake eco-compensation mechanism is effective and spillover effect of lake water environmental management policy deserves attention. This paper provides a support for the sustainable development of the lake.

One of the limitations of the paper is that the decision-making body is dominated by the government and enterprises are not mentioned as the main body of pollutant discharge, which is also important. Future researches on watershed water environment management can incorporate corporate behaviors into the evaluation.

CRediT authorship contribution statement

Linhuan He: Conceptualization, Data curation, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **Liming Yao:** Conceptualization, Funding acquisition, Methodology, Validation. **Petar Sabev Varbanov:** Funding acquisition, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data has been shared in this paper.

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