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Horizontal ecological compensation policy and water pollution governance: Evidence from cross-border cooperation in China

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A B S T R A C T

Cross-border cooperation can overcome the administrative boundaries of water pollution governance, and the two-way ecological compensation model emerges as a solution to transforming government-financed payments into locally-driven development initiatives. This study presents a tripartite evolutionary game model for two-way ecological compensation, incorporating city-level data, and employs time-varying difference-in-differences to estimate the incentive impact of China's cross-border horizontal ecological compensation policy on water pollution governance during 2006–2018. Furthermore, this study aligns state-controlled monitoring stations with their respective administrative districts and enhances water pollution indicators obtained from these stations for a more comprehensive policy assessment. The results show that horizontal ecological compensation effectively reduces the prevalence of industrial wastewater discharges and associated water pollution; this effect is more pronounced upstream (20.94%) compared to downstream (16.01%). However, it does not significantly impact urban sewage treatment, agricultural non-point source pollution, or lake water quality and eutropHication. In addition to promoting horizontal coordination between upstream and downstream regions, vertical central governmental inspections are crucial for effectively stimulating and guaranteeing horizontal collaborative governance between upstream and downstream local governments. These results provide strong empirical evidence in favor of expanding horizontal ecological compensation initiatives throughout the entire river basins, as well as in other countries or regions.

1. Introduction

The water resources management system in China integrates both watershed and administrative regional management (Li et al., 2020b). Ecological compensation can promote the idea that green mountains and clear waters are as valuable as gold and silver (Wan et al., 2022; Quan et al., 2023), which refers to the greening of transfer payments, known as the green gold way towards ecological civilization. Villarroya and Puig (2010) conclude that the concept of eco-compensation can appear in different ways in different countries. The diverse modes of eco-compensation include capital, technology, industry, talent, and projects, of which government-led ecological compensation is currently the predominant approach in China (Sheng et al., 2020). The Chinese central government provides support for projects and financial funds, which are raised and allocated through government-financed payments, thereby igniting local enthusiasm for ecological compensation efforts. Ecological compensation comprises both vertical and horizontal dimensions of distribution. Vertical ecological compensation involves transfer from higher to lower levels of government, while horizontal ecological compensation occurs between local governments (Sheng et al., 2020). Currently, the predominant form of compensation in China remains primarily as single vertical ecological compensation (Ni et al., 2021). Horizontal ecological compensation policies offer distinct advantages over vertical compensation methods. They help mitigate negative externalities (Wang et al., 2023), and promote fairness and efficiency across river basin regions (Zhang et al., 2023). Encouragingly, initial progress has been achieved in exploring horizontal ecological compensation, with river basins serving as effective models for its implementation in China (Ren et al., 2021; Zhang et al., 2021).

Recently, China has initiated pilot programs for horizontal ecological compensation within river basins. These programs have introduced mechanisms for cost-sharing, benefit-sharing, and cooperative co-governance, effectively addressing external conflicts and leading to a significant improvement in water quality in the transboundary regions

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covered by these initiatives. As of 2021, the Chinese central government had guided and coordinated 18 provinces and signed 13 cross-provincial horizontal ecological compensation agreements (data sourced from the Ministry of Ecology and Environment of China). While local implementations of horizontal ecological compensation practices have achieved positive outcomes (Wan et al., 2022), certain challenges persist. These include unclear delineation of rights and responsibilities related to ecological protection in river basins, ambiguity in pollution boundaries, and disparities between costs and benefits. There is an urgent need to modernize water environmental governance, transitioning from government-financed payments to locally-driven development. Nevertheless, the pilot programs for horizontal ecological compensation within transboundary river basins can provide a valuable scientific foundation and a strong reference point for the future comprehensive development of horizontal ecological compensation across river basins in China.

Historically, China's approach to ecological environmental protection has involved a dual governance system, with both central and local governments playing key roles (Jiang et al., 2019). Horizontal ecological compensation within a river basin is led by the central government. In this system, upstream and downstream regions collaborate to establish compensation funds, which are funded through contributions from provincial budgets, and municipal financial departments are responsible for withholding and transferring these funds. The allocation and distribution of these funds typically hinge on objective compensation criteria, primarily centered around water quality and quantity in transboundary areas. Importantly, the central government employs a system of rewards and penalties based on assessment outcomes, thus tying financial compensation to the results of water quality assessments. This approach ensures that the assessment standards are designed to be objective, authoritative, fair, and independent.

Combined with governmental management, this incentive environmental policy resembles the concept of payment for ecosystem services (PES) (Wang et al., 2016). Notably, Sheng et al. (2020) found that horizontal ecological compensation in China shares more similarities with the international concept of PES than vertical ecological compensation. Furthermore, Hu et al. (2022) stated that horizontal ecological compensation is more sustainable than vertical ecological compensation. Additionally, cross-border horizontal ecological compensation focuses on cultivated land (Ding and Yao, 2022) and river basins (Gao et al., 2019; Sheng et al., 2020; Ding et al., 2022), and it can be broadly categorized into two main types: government–enterprise cooperation (Ding et al., 2022) and government–government cooperation (Gao et al., 2019).

This study conducted a comprehensive examination of four aspects related to horizontal ecological compensation. First, with respect to theoretical analysis, previous research predominantly concentrated on one-way compensation, such as protecting upstream regions and subsidizing downstream areas (Ding et al., 2022; Gao et al., 2019) and, thus, lacked two-way ecological compensation in model construction. Second, research on horizontal ecological compensation has been limited to local or regional river basins, such as the Xin'an River basin (Zheng et al., 2021; Sheng and Han, 2022). Zheng et al. (2021) employed the difference-in-differences (DID) method to examine the impact of ecological compensation on the industrial structure upgrades in the Xin'an River Basin. Yang et al. (2022) argued that horizontal ecological compensation can promote the sustainable development of urban agglomeration. Chen et al. (2021a) used the Zhejiang province as an example to discuss the environmental effects of ecological compensation policy, which significantly improved the local environment. Using the Yellow River Basin as an example (Hu et al., 2022), Zhou et al. (2022) assessed the value of ecosystem services in 72 cities in 9 provinces, and the ecosystem service value was positively correlated with ecological compensation. However, due to current data limitations, few studies on ecological compensation policies have effectively evaluated (Cao et al., 2021). Third, much of the prior research on ecological compensation relied heavily on theoretical and qualitative analyses, with insufficient quantitative analysis. Wang et al. (2022), who examined and quantified previous literature on ecological compensation, encouraged quantitative research on ecological compensation over qualitative research. Additionally, some literature regarding water monitoring sites and environmental data at the enterprise level has been quantitatively analyzed. Liu and Mao (2020) analyzed data on 13 water quality variables at 40 monitoring stations in Xiangjiang, Hunan Province. Zhang et al. (2018) adopted a unique dataset of Chinese Environmental Statistics and evaluated the impact of central inspections on chemical oxygen demand of industrial emissions via the National Specially Monitored Firm program. Furthermore, central supervision greatly promotes environmental protection (Zhang et al., 2018; Gao et al., 2019), but the decentralization of environmental monitoring negatively impacts regional green development (Wu et al., 2020). Zhang et al. (2021) considered the Miyun Reservoir watershed, employing quantitative policy evaluation methods to estimate the ecological and economic effects of ecological compensation policies. However, collecting and sorting large amounts of monitoring data presents difficulties. Hence, although expanding the sample size improves the accuracy and stability of the results, quantitative analysis is often limited. Fourth, existing studies tended to focus on ecological compensation standards (Yang et al., 2022) rather than its effects and mechanisms. The current practice of ecological compensation is far from reaching the theoretical goal of “no net loss” or “net benefit” (Villarroya et al., 2014). Sonter et al. (2020) expressed uncertain attitudes towards the achievement of ecological compensation policy goals. Liu et al. (2023) noted that watershed ecological compensation policies are affected by the transformation of government functions (Chen et al., 2021a), compensation funds, and assessment intensity (Wan et al., 2022). Horizontal ecological compensation policies have certain deficiencies that can affect their effectiveness. These shortcomings are primarily concentrated in the short and medium term, a lack of long-term planning, and an over-reliance on financial subsidies (Liu et al., 2023; Yu et al., 2023). Additionally, Wang et al. (2023) concluded a study on the impact mechanisms of horizontal ecological compensation on technological progress. However, these mechanisms are often neglected when considering the behavior of multiple local governments, which can explain the improvements in horizontal ecological compensation governance efficiency within river basins under pluralistic collaborative governance.

Compared to previous studies, this research distinguishes itself in two key aspects. Firstly, it incorporates the two-way compensation model into both theoretical framework development and empirical analysis. Secondly, it places a special emphasis on the concept of vertical and horizontal integration, encompassing horizontal cooperation incentives between upstream and downstream parties and vertical regulatory constraints from central governments. Potential innovations in this study include:

To begin with, this study constructed a theoretical evolutionary game model, integrating the two-way ecological compensation model into horizontal ecological compensation. This underscores the significance of strict inspections by the central government within horizontal ecological compensation policies, building upon the existing vertical reward and punishment to realize the horizontal allocation of costs and benefits.

Secondly, the empirical data sample are controlled at the city levels, avoiding limitations due to insufficient data in local river basins and monitoring points. The sample range covers the entirety of China, spanning from 2006 to 2018. This addresses issues related to unstable estimation results stemming from localized samples. Furthermore, this study aligns administrative region data with state-controlled monitoring areas, rigorously examining weekly, quarterly, and annual water pollution indicators data compiled by us within city-level administrative divisions. This further validates the stability of the model through water pollution indicators.

Thirdly, this study explored various aspects, including domestic sewage treatment rates, agricultural non-point source pollution, lake transparency, and various watershed areas, thereby enriching the dataset with heterogeneity. Consequently, it provides valuable reference data and policy support for comprehensive promotion of horizontal ecological compensation in both upstream and downstream areas of each province (responsible entities at the city and county levels).

Lastly, the theoretical hypothesis is further verified by empirical data. When combined with the effective horizontal incentives and constraints of the two-way ecological compensation model, it is found that central environmental monitoring enhances the expected effect of policy. This highlights the necessity of appropriate central government intervention in environmental monitoring to fully realize policy impacts, emphasizing that incentive measures are pivotal for achieving ecological compensation in transboundary river basins (Ren et al., 2021).

The reminder of this study is organized as follows. Section 2 summarizes an overview of the practices of vertical and horizontal ecological compensation in China. Section 3 presents the evolutionary game model and hypotheses, and section 4 outlines the data and estimation approach. The empirical results are detailed in section 5. Section 6 are conclusions and policy recommendations.

2. Background

2.1. Vertical ecological compensation

Ecological compensation is divided into vertical and horizontal ecological compensation based on administrative affiliation (Sheng et al., 2020). Vertical ecological compensation mainly refers to governmental compensation via ecological transfer payments, including compensation from the central government to the local government, as well as compensation between higher and lower governments within provincial administrative jurisdictions.

In China, vertical ecological compensation can be classified into two situations: one is the ecological compensation from the central government to provincial governments, and the most vivid embodiment of vertical ecological compensation is that of national key ecological-function areas; the other is provincial government transfer payments to key ecological-function areas. Presently, China mainly provides vertical transfer payments via provincial finance. After Zhejiang Province implemented an ecological compensation pilot in 2005, Jiangsu, Anhui, and other provinces gradually explored provincial ecological compensation systems. Along with improvements in the transfer payment policy for key ecological-function areas, intra-province vertical transfer payments have gradually improved to further encourage municipal and county governments to strengthen environmental protections. Supplementary Table A.1 in appendix A presents relevant documents regarding the provincial ecological vertical transfer payments during 2008–2021, including the composition of the subsidy funds for each river basin. The composition of the compensation funds has gradually shifted from early subsidy or reward and punishment funds to zoning and incentive compensation implemented using the national ecological-functional areas as the standard, which highlights these areas. Regarding fund allocation, the early subsidy standards were mainly distributed according to the factor method or proportion, and the rewards were weighted according to various standards. Moreover, punitive measures were enacted if areas did not meet their standards. In addition to their basis on main functional areas, the later subsidy funds also encouraged the construction of major ecological projects through the establishment of guided subsidies.

2.2. Horizontal ecological compensation

Horizontal ecological compensation occurs between subjects at the same administrative level. Although local ecological compensation practices have achieved phased results, a sustainable mechanism for horizontal ecological compensation remains unestablished. Horizontal ecological compensation, which is based on provincial-level administrative regions, can be classified into three categories: inter-provincial horizontal ecological compensation, intra-provincial horizontal ecological compensation, and ecological compensation across key river basins.

2.2.1. Inter-provincial watersheds

China has enacted several pilot projects for horizontal ecological compensation in inter-provincial river basins, and the agreements signed between provincial administrative regions have included one, two, and three rounds of agreements based on implementation progress, as detailed in Supplementary Table A.2 in appendix A. Most agreements last three years per round. Additionally, the allocation of funds may change between rounds. Funding primarily includes financial subsidies from the central government and joint funding from the involved local governments. For example, for the third round of the Xin'an River pilot project, funds from the central government have been gradually withdrawn, and the contributions of the local governments have increased slightly. From the perspective of the source and distribution of subsidy funds, compensation funds have gradually changed from co-funded individual compensation to two-way ecological compensation and from fixed amounts to proportional distributions (such as for the Chishui River). Nevertheless, capital contributions from the central government are more flexible.

2.2.2. Intra-provincial watersheds

With the continuous advancement of transboundary horizontal ecological compensation pilot programs, Zhejiang, Hubei, Hunan, Shanxi, Guangxi, Guangdong, Inner Mongolia, Sichuan, Shandong, Chongqing, and Jiangsu have enacted horizontal ecological compensation between intra-provincial cities and counties. Among them, in 2018, Chongqing achieved full coverage of the key rivers in the city. In 2020, 60% of the listed counties in the Yangtze River Basin of Hubei province had horizontal ecological compensation mechanisms. In 2021, more than 80% of counties, cities, and districts in Jiangxi had established horizontal ecological compensation mechanisms of river basins. The gradual promotion of intra-provincial horizontal ecological compensation encourages independent consultation, collaborative governance, joint prevention, and increased cooperation regarding these policies.

2.2.3. Key watersheds

Horizontal ecological compensation throughout key river basins in China has gradually been examined and promoted. The most influential example is its establishment throughout the Yellow and Yangtze River basins. In 2020, China explored the establishment of horizontal ecological compensation for the entire Yellow River Basin, and in 2021, it further promoted the implementation plan of the horizontal ecological compensation mechanism in the Yangtze River Basin. The transformation of horizontal ecological compensation in key basins from guidance programs to implementation plans reflects the support for horizontal ecological compensation for entire river basins in China and demonstrates its effective promotion.

In summary, horizontal ecological compensation throughout river basins currently focuses on inter-provincial pilot policies, followed closely by intra-provincial horizontal ecological compensation, which is promoted accordingly. Furthermore, the development of horizontal ecological compensation in key river basins should enable future cooperation and collaborative governance across multiple administrative regions.

3. Evolutionary game model with two-way ecological compensation

Water pollution can exhibit spatial spillover and varying flow connectivity. Upstream regions have preemptive and active advantages regarding pollutant discharges, whereas downstream areas often occupy a passive, disregarded position. Based on their location within the river basin, the upstream and downstream responsible entities are divided into indemnitor and indemnitee. Thus, the asymmetric information and spatial distribution of the main strategy often aggravate governance issues and discord between upstream and downstream areas. Nevertheless, the central government, as coordinator and supervisor, can enhance the agreement stability by introducing incentives and constraints. Therefore, whether upstream and downstream entities will choose beggar-thy-neighbor or neighbor-partner policies should be investigated for both responsible parties under the fiscal constraints, incentives, and limitations of their alliance agreement.

Presently, horizontal ecological compensation is primarily based on government-led financial compensation but includes counterpart collaboration, personnel training, industrial transfer, joint park development, and in-kind subsidies, which can be classified into top-down compensation and bottom-up subsidies. Although China encourages market-oriented trading of emissions and water rights between upstream and downstream areas, this study focuses on horizontal ecological compensation policies that are primarily government-led and aimed at water environmental protection. The characteristics of horizontal ecological compensation in the river basin are that compared with the previous one-way compensation, it is transformed into two-way ecological compensation, which is reflected in vertical top-down incentives and bottom-up withholding, and also includes horizontal top-down compensation and bottom-up subsidies (Fig. 1). To this end, a three-party evolutionary game model under two-way compensation of horizontal ecological compensation between local upstream and downstream governments, guided by the central government, has been constructed, which contains both vertical transfer payments and horizontal transfer payment incentive scenarios, explaining the importance of vertical regulatory constraints and horizontal synergistic incentives in horizontal ecological compensation.

This model contains three parties, namely the central (principal: g), upstream (agent 1: u), and downstream (agent 2: d) governments. The three parties are all rationally bounded and maximizing their own comprehensive profits, and information is asymmetrical between them. The central government can choose a strategy of strict inspection or loose inspection, while the upstream and downstream governments may exhibit either proactive cooperation or passive cooperation. Hence, the probability of selecting a strategy actively supervised by the central government and actively executed by both the upstream and downstream governments is respectively $x(t)$, $y(t)$and $z(t)$, and satisfies $x(t)$, $y(t)$, and $z(t) \in [0,1]$.

In the case of strict inspection, the central government can earn R_g while supervising the governance of the upstream and downstream areas and must pay the cost C_g for the water environment. Regardless of the negative actions of the local governments, a bottom-up fine F needs to be paid. If there is active cooperation, the central government will reward it through vertical transfer payments; thus, the local governments can receive incentive quotas of W_u and W_d, respectively. Additionally, if the upstream government actively implements horizontal ecological compensation, the downstream government must provide a subsidy of T_d to the upstream government; otherwise, the compensation paid by the upstream government to the downstream is T_u.

If upstream and downstream governments actively implement horizontal ecological compensation policies, the corresponding benefits are R_u and R_d, respectively, and the costs of choosing active cooperation are C_u and C_d. In the case of opportunism, the benefits of passive enforcement by upstream and downstream governments are B_u and B_d, respectively.

If the central government chooses a loose inspection strategy, the benefits can be expressed as σR_g and $\sigma \in [0,1]$. Simultaneously, abandoning the incentives and penalties of vertical fiscal transfers will also affect the payment situation and capital flow of the horizontal transfer payments between the upstream and downstream governments.

Based on the model assumptions, the game payment matrix of the tripartite participants is shown in Table 1, and the detailed solution process can be found in Appendix B.

According to Lyapunov's stability judgment, the evolutionarily stable strategy (ESS) of the system can be found by adding constraints. When the eigenvalues of the Jacobian matrix are negative, $\lambda_{ij} < 0(i = 1,2,3,\ldots,12; j = 1,2,3,\ldots,12)$ and the local equilibrium point is the ESS. Table 2 indicates local stability in two cases.

Scenario 1: The benefits to the central government under strict inspection are greater than those under loose inspection, that is, $R_g - W_d - W_u - C_g > \sigma R_g$, $R_g + F_d - W_u - C_g > \sigma R_g$, $R_g + F_u - W_d - C_g > \sigma R_g$, or $R_g + F_u + F_d - C_g > \sigma R_g$. If the net benefit of active monitoring after deducting the monitoring and incentive costs remains greater than the net benefit of passive monitoring, this indicates that the loss caused by loose inspection includes a lack of information, risks caused by misjudgment during decision-making and implementation, and effects on policy evaluation. Under this condition, the equilibrium point E_8 is

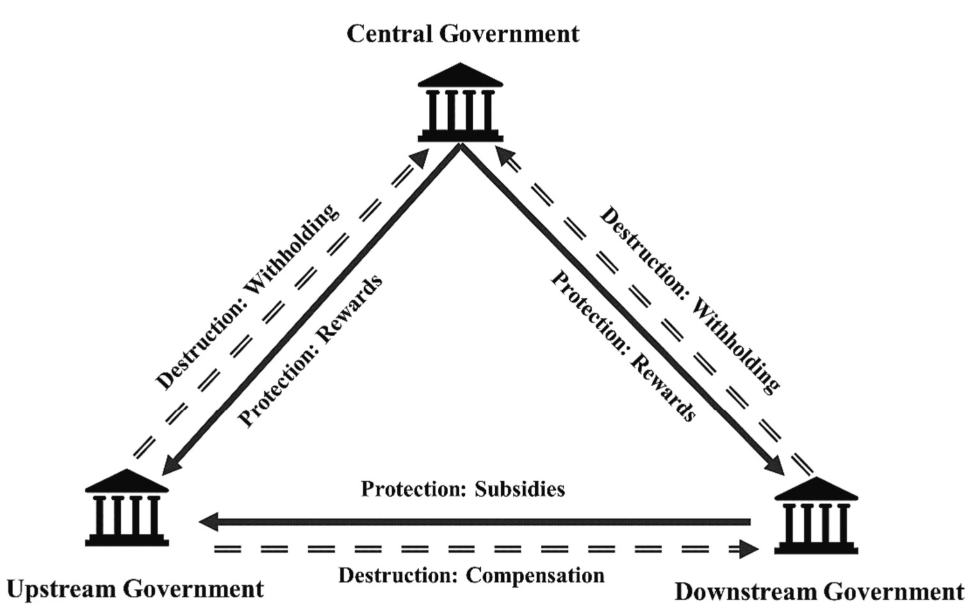

Fig. 1. Two-way ecological compensation model.

Table 1
Tripartite evolutionary game payment matrix under horizontal ecological compensation.

Players				Central Government	
				Strict Inspection (z)	Loose Inspection ($1-z$)
Upstream Government	Positive Cooperation (x)	Downstream Government	Positive Cooperation (y)	$(R_u+W_u+T_d-C_u, R_d+W_d-T_d-C_d, R_g-W_d-W_u-C_g)$	$(R_u-C_u, R_d-C_d, \sigma R_g)$
			Passive Cooperation ($1-y$)	$(R_u+W_u+T_d-C_u, B_d-F_d-T_d, R_g+F_d-W_u-C_g)$	$(R_u-C_u, B_d, \sigma R_g)$
	Passive Cooperation ($1-x$)	Downstream Government	Positive Cooperation (y)	$(B_u-F_u-T_u, R_d+W_d+T_u-C_d, R_g+F_u-W_d-C_g)$	$(B_u, R_d-C_d, \sigma R_g)$
			Passive Cooperation ($1-y$)	$(B_u-F_u-T_u, B_d-F_d+T_u, R_g+F_u+F_d-C_g)$	$(B_u, B_d, 0)$

Table 2
Local stability at the equilibrium points.

Equilibrium Point	Scenario 1			Stability	Scenario 2			Stability
	Eigenvalue λ_1	Eigenvalue λ_2	Eigenvalue λ_3		Eigenvalue λ_1	Eigenvalue λ_2	Eigenvalue λ_3	
E_1 (0,0,0)	+	+	+	Saddle point	+	+	–	Unstable point
E_2 (0,1,0)	–	+	+	Unstable point	–	+	–	Unstable point
E_3 (0,0,1)	–	+	+	Unstable point	+	+	+	Saddle point
E_4 (0,1,1)	–	–	+	Unstable point	+	–	+	Unstable point
E_5 (1,0,0)	–	+	+	Unstable point	–	+	–	Unstable point
E_6 (1,1,0)	–	–	+	Unstable point	–	–	–	ESS
E_7 (1,0,1)	–	+	–	Unstable point	+	+	–	Unstable point
E_8 (1,1,1)	–	–	–	ESS	+	–	–	Unstable point

the ESS, and the corresponding strategies are active cooperation, active cooperation, and strict inspection.

Scenario 2: The benefits to the central government under active monitoring are less than those of passive monitoring. If the net income after deducting monitoring costs and incentive costs is less than the net benefit of loose inspection, this indicates that the loss caused by loose inspection can cover the net benefit brought by strict inspection. The equilibrium point E_6 is the ESS, and the corresponding strategies are active cooperation, active cooperation, and loose inspection. In this case, the central government will choose loose inspection, but this seldom actually occurs.

Previous environmental protection disputes mainly occurred due to unclear rights and responsibilities; thus, joint prevention and co-governance provides effective prevention for transboundary water pollution emergencies (Lu et al., 2022), and is a long-term mechanism to achieve horizontal ecological compensation. Transboundary horizontal ecological compensation for river basins can break through the shackles of the administrative hierarchy of traditional vertical financial subsidy methods (Li and Lu, 2022), and different administrative entities can achieve cross-level collaboration and interaction, which emphasizes fairness and increases the enthusiasm of local governments for water pollution prevention and control. Therefore, horizontal ecological compensation policies have an incentive effect on water pollution prevention and control (Li et al., 2022).

Hypothesis 1. Horizontal ecological compensation policy under the two-way ecological compensation can effectively motivate upstream and downstream governments to coordinate their management of the water ecological environment and reduce water pollutant discharges.

In addition to the effective constraints of the two-way ecological compensation, it also includes vertical central supervision (Zeng et al., 2023). In terms of environmental water monitoring, the central government determines who assesses and monitors, strengthens the inspection of transboundary river basins through ecological and environmental accountability, and promotes water pollution prevention and control. Their inspections provide warnings to effectively promote the rectification of problems (Lin et al., 2021). Therefore, responsible upstream and downstream entities are motivated to invest in water pollution prevention and control, which will produce significant policy effects. This is called the incentive effect. Therefore, this study proposed hypothesis 2.

Hypothesis 2. Under the strict inspection constraints of central rewards and punishments and upstream and downstream bilateral agreements, the central government can effectively avoid improper interference and free-rider behavior from local governments in environmental monitoring through ecological and environmental accountability (Yu et al., 2022), and coordinate governance between upstream and downstream entities.

For further verification, this study examined these theoretical inferences through empirical data.

4. Data and estimation methods

4.1. Data and descriptions

Horizontal ecological compensation is primarily based on agreements between two provinces or municipalities directly under the central government. When an agreement is signed between two provinces, the responsible cities (or prefectures) involved include not only the parties to the contract, but also the beneficiaries. Therefore, when selecting the responsible entities, this study included the administrative regions involved in the transboundary section and the responsible subject involved in ecological compensation in the river basin. Although pilot cases are, in practice, often funded by provinces, the allocation of funds is implemented in cities, districts, and counties. Therefore, the research objects in this study were cities that implemented pilot transboundary horizontal ecological compensation in a river basin, totaling 283 cities in 31 regions (provinces, autonomous regions, and municipalities) in China, including 279 prefecture-level cities and 4 municipalities. Among these, 283 cities include both the treatment group (cities implementing the policy) and the control group (cities not participating in policy implementation). The sample period was 2006–2018.

In this study, the data was obtained from the National Bureau of

Statistics in China, Chinese Research Data Service Platform (CRDSP), China Stock Market & Accounting Research Database, CEIC Premium Database for China, Chinese Environmental Knowledge Service System (CEKSS), China National Environmental Monitoring Centre (CNEMC), China City Statistical Yearbook, China Urban Construction Statistical Yearbook, and others. Additionally, this study used manually collected data, such as data on establishment of a system of river chief, transboundary horizontal ecological compensation, and breakpoint water contaminant concentrations. The manually collated data was cross-verified to ensure reliability and accuracy; cross-verification was performed manually by multiple individuals through a comparison, gap filling (interpolation), and verification procedure, thereby ensuring the completeness and accuracy of the data. Data on water pollutant indicators from 2006 to 2010 came from the automatic water quality monitoring weekly report of the CNEMC. These data were extracted using crawlers and obtained via post-processing. For the period spanning 2012 to 2017, the data originated from the CRDSP, while the data for 2011 and 2018 were obtained from the CEKSS. Data for 2019 and subsequent years are not available. The Descriptions of variables are detailed in Table 3.

In this study, the explained variable was water pollution prevention and control, which was quantified through the measurement of the total amount, intensity, density, and per capita discharge of industrial wastewater (Jing and Zhang, 2018; Li et al., 2020a; Liu et al., 2021) and various water pollution indicators. The sources of pollution in Chinese rivers include industrial, domestic, and rural pollution (Shao et al., 2021). Industrial pollution is a point source; thus, it is easily controlled and monitored. Additionally, the domestic sewage treatment rate is calculated from centralized sewage treatment plants. In contrast, rural non-point source pollution is difficult to monitor. Therefore, the primary explained variables were the total industrial wastewater discharge (*IWD*) and its intensity (*IWDI*) (Ma et al., 2020). Extended explained variables included total industrial wastewater discharge per capita (*PCIWD*), industrial wastewater discharge density (*IWDD*), urban domestic sewage treatment rate (*DST*), and nitrogen fertilizer (*NF*) and phosphate fertilizer (*PF*) from agricultural non-point source pollution. Additionally, to verify the robustness of the regression results, pollution severity indicator data from state-controlled water monitoring points was used to measure water pollution prevention and control, including pH (*PH*), dissolved oxygen (*DO*), aqueous ammonia nitrogen concentration (NH_3-N), and chemical oxygen demand of potassium permanganate (*COD*, the amount of dissolved oxygen necessary to oxidize all material in the sample). The lower the DO, the lower the water quality. Conversely, the higher the COD and NH_3-N, the lower the water quality. Furthermore, the lake reservoir transparency (*FUI*) indicator was added to evaluate the clarity and water quality (or eutrophication) of lakes and reservoirs. A higher value indicates lower transparency, and vice versa. Northern Hemisphere lakes will freeze during winter; hence, the *FUI* used data from Wang et al. (2020,2021), which were calculated from boreal May to October yearly. The present study used the annual mean to measure lake water quality. In addition, the explained variables economic development scale (*GDP*) and economic growth rate (*GDPR*) are the real GDP and GDP growth rate, respectively, and the impact of price changes has been excluded. The variable *CEPI* reflects the central environmental protection inspection.

Table 3
Descriptions of variables.

Variables	Description
IWD	The logarithm of the total amount of industrial wastewater discharge
IWDI	Industrial wastewater discharge intensity
PCIWD	Per capita industrial wastewater discharge
IWDD	Industrial wastewater discharge density
DST	Domestic sewage treatment rate
GDP	Scale of economic development
GDPR	Economic growth rate
NF	Nitrogen fertilizer
PF	Phosphate fertilizer
PH	PH
DO	Dissolved oxygen
COD	Chemical oxygen demand
NH_3-N	Ammonia nitrogen
FUI	Lake transparency
HEC	Horizontal ecological compensation
Fissuffi	Fiscal self-sufficiency rate
GDP2	Secondary industry structure
Popdensity	Population density
Indusenter	Logarithm of the number of industrial enterprises
FDI	Logarithm of foreign direct investment
Watersupply	Logarithm of water supply
Pipelength	Logarithm of the length of the drainage pipe
Plant	Logarithm of the total number of sewage treatment plants
Riverchief	Establishment of a system of river chiefs
Greenarea	Logarithm of the green area
Precipitation	Logarithm of precipitation
Weather	Temperature
RH	Relative humidity
Nature	Nature reserve
Waterten	Ten Water rule of China
Basin	Belongs to the river basin
Lakearea	Area of lakes in the jurisdiction
Freezing	Freezing of the lake
CEPI	Central environmental protection inspection

The selection of control variables considered indicators related to life, production activities, and geography. To extract the respective basin for each city, vector data on the nine major river basins in China and the administrative divisions of prefecture-level cities were jointly processed using ArcGIS software to calculate the watershed sections belonging to each city. Cases involving multiple watersheds, such as watershed junctions and intersections, were classified according to the combined watersheds, and same the combined watershed names and numbers were classified as the same category, for a total of 35 categories (see Table A.3 in appendix). To alleviate possible heteroscedasticity, some variables were calculated logarithmically. Table 3 describes the variables, and Supplementary Table A.4 in appendix A provides statistical details.

4.2. Monitoring points for state-controlled sections of river basins

To further introduce the state-controlled river monitoring points, Fig. 2–4 depict the distribution of monitoring points in the nine major river basins in China during the Eleventh, Twelfth, and Thirteenth Five-Year Plans, respectively. The study data covers 2006–2018, and changes in the distribution of the monitoring points can be observed in the figures. Fig. 2 shows that the points were initially predominantly concentrated in the Yangtze, Yellow, Huaihe, and Haihe River basins, and no monitoring points were located in the inland and southwest basins. Fig. 3 shows that during the Twelfth Five-Year Plan, more monitoring points were established in the Songhua and Liao River basins, and the Hainan, Xinjiang, and Tibet provinces. The state-controlled monitoring points added during the 13th Five-Year Plan period were mainly located in areas with river basins as administrative boundaries (Fig. 4).

4.3. Model settings

Transboundary horizontal ecological compensation policies in river basins can be viewed as a quasi-natural experiment among administrative regions. The cities covered by horizontal ecological compensation agreements were considered the treatment group, and areas that had not signed such agreements were the control group. Due to inconsistent pilot starting times in various regions, a one-size-fits-all approach cannot be used to identify their effects on governance. Therefore, this study used time-varying DID to identify the effects of horizontal ecological compensation policies on water pollution prevention and control, because it enables various policy implementation times (Callaway, and Sant'Anna, P. H. C., 2021). The model is as follows:

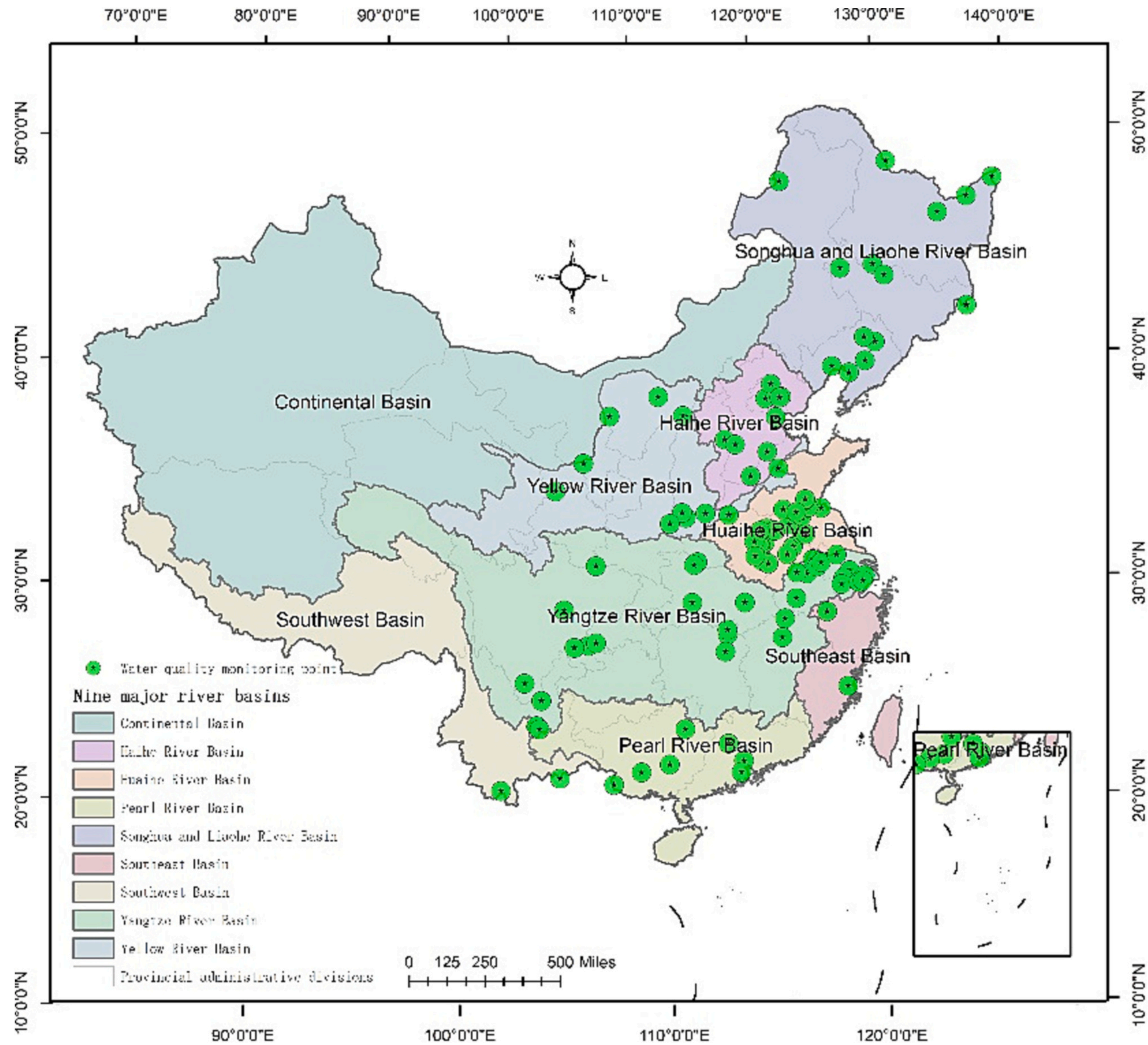

Fig. 2. Distribution of state-controlled water quality monitoring sites in China during the 11th Five-Year Plan (2006–2010).

$$Y_{it} = \gamma_0 + \gamma_1 HEC_{it} + \mathbf{Controls}_{\mathbf{it}}^{'}\boldsymbol{\beta} + \mu_i + \eta_t + \nu_{Basin} + \varepsilon_{it} \tag{1}$$

where Y_{it} represents the explained variable, which signifies the pollution prevention and control (industrial wastewater discharge, water pollution indicators, etc.) of city i during t year. The value range for the city was $i = \{1, 2, 3, \ldots, 283\}$and for the year was $t = \{2006, 2007, \ldots, 2018\}$. The variable HEC_{it} reflects the horizontal ecological compensation policy implementation of city i in year t in the form of dummy variable, where an assigned value of 1 indicates the degree of policy influence received by city i in year t and subsequent years, and vice versa is 0. The coefficient γ_1 represents the average treatment effect of the treatment group, which reflects the impacts of horizontal ecological compensation pilots on water pollution prevention and control in the basin in comparison to non-pilot regions. If $\gamma_1 > 0$, the horizontal ecological compensation has a laissez-faire effect on the prevention and control of water pollution. If $\gamma_1 < 0$, the horizontal ecological compensation has a restraining effect on the prevention and control of water pollution. The vector of $\mathbf{Controls}_{\mathbf{it}}$ refers to the $k \times 1$ control variables of city i during year t, which contains indicators related to life, production activities, and geography, where $k = \{1, 2, 3, \ldots, K\}$. $\boldsymbol{\beta} = (\beta_1, \ldots, \beta_k)^T$ is $k \times 1$ column vector of coefficients. Additionally, the coefficient γ_0 is a constant; μ_i represents the city fixed effect, which can control the inherent differences among cities; η_t represents the fixed effect of the year, which can control the influencing factors over time; ν_{Basin} represents the fixed effect of the watershed, which can influence the watershed distribution; and ε_{it} represents the estimated error.

5. Results

5.1. Benchmark regression results

Table 4 presents the results of the regression analysis on the effect of horizontal ecological compensation on water pollution prevention in the full sample and upstream and downstream. These results show that the implementation of transboundary horizontal ecological compensation policies significantly reduced the scale of water pollution in terms of industrial sewage discharge. The results in columns 3–5 show that the impact of horizontal ecological compensation on regional discharge intensity was significantly negative under the robust standard error and different cluster dimensions. Additionally, the influence coefficient of

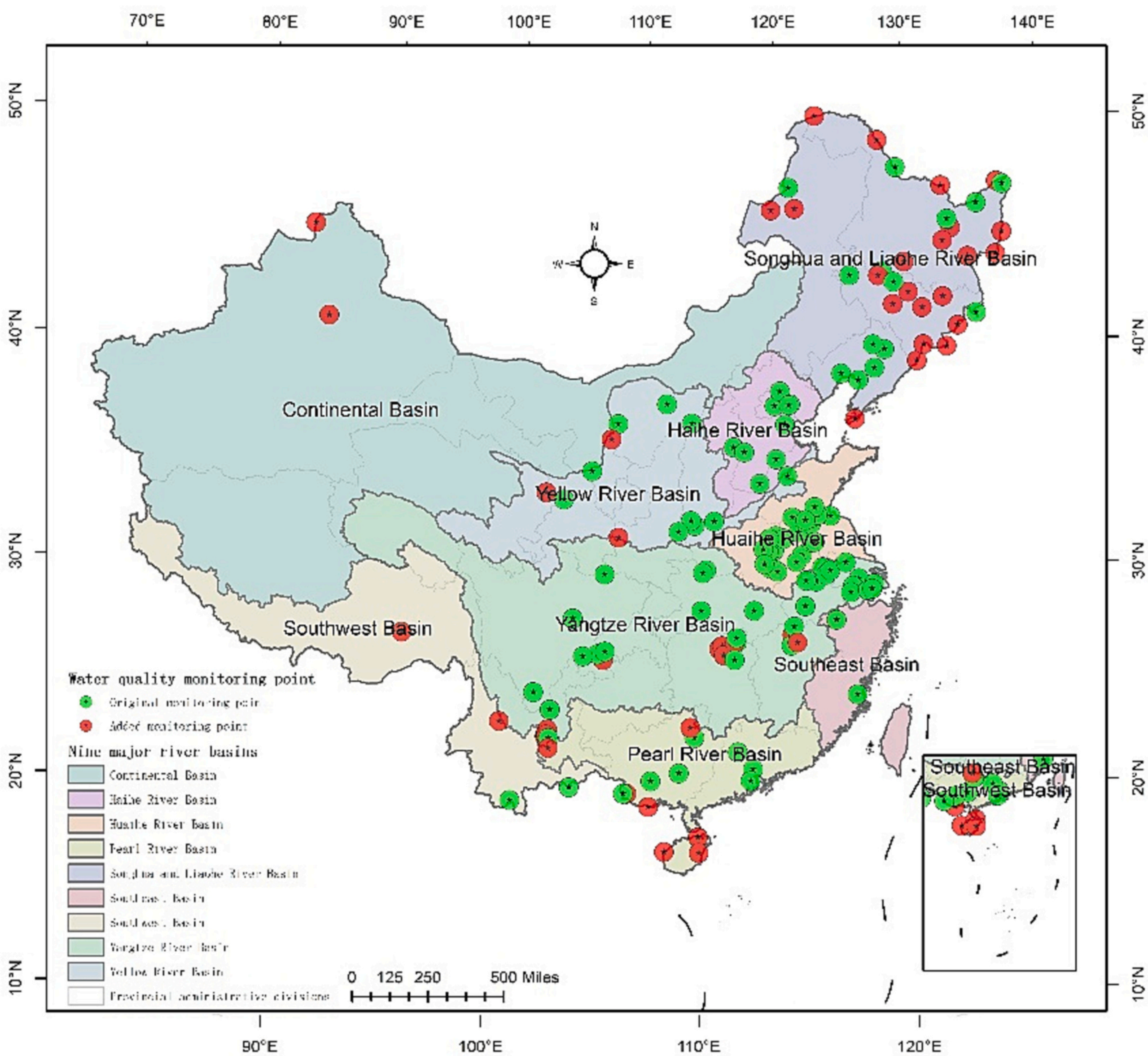

Fig. 3. Distribution of state-controlled water quality monitoring sites in China during the 12th Five-Year Plan (2011–2015).

the variable *Popdensity* was significantly positive, indicating that, the higher the population density, the more serious the water pollution (Dugan, 2012). In contrast, the influence coefficient of the variable *Pipelength* was significantly negative, reflecting that the more complete the sewage treatment infrastructure, the more difficult sewage treatment becomes. Notably, R^2 improved after controlling for fixed city, year, and watershed effects. Overall, these results indicate that horizontal ecological compensation policies can significantly reduce the total discharge volume and intensity of industrial wastewater. Moreover, transboundary horizontal ecological compensation provided an effective incentive for water pollution control.

Furthermore, the results in columns 6 and 7 demonstrate that the policies significantly reduced the scale of industrial wastewater discharge, regardless of the location of the cities within the basin. Nevertheless, the incentive effect was significantly higher in upstream areas than that in downstream areas. Therefore, the responsible entities upstream have increased their efforts regarding pollution control. Moreover, both upstream and downstream entities have coordinated governance and do not consider their neighbors as a barrier, which has mitigated free-riding behavior. Therefore, these results indicate that Hypothesis 1 is correct.

5.2. *Dynamics of horizontal ecological compensation and industrial wastewater discharge*

Beck et al. (2010) and Wing et al. (2018), divided the implementation of ecological compensation into phase-in effects, immediate effects, and anticipated effects through an event research method. Similarly, the dynamic impacts of horizontal ecological compensation policies on water pollution prevention can be analyzed according to these stages. Using the difference between the interval before and after the event and the time point of the policy, this study dynamically analyzed the 12 years before and 7 years after each event. The dynamic model is as follows:

$$Y_{it} = \beta_0 + \sum_{s=1}^{S} HEC_{it-s}\theta_s + HEC_{it}\delta + \sum_{m=1}^{M} HEC_{it+m}\phi_m + \mathbf{Controls}_{it}^{'}\boldsymbol{\beta} + \mu_i + \eta_t + \nu_{Basin} + \varepsilon_{it} \quad (2)$$

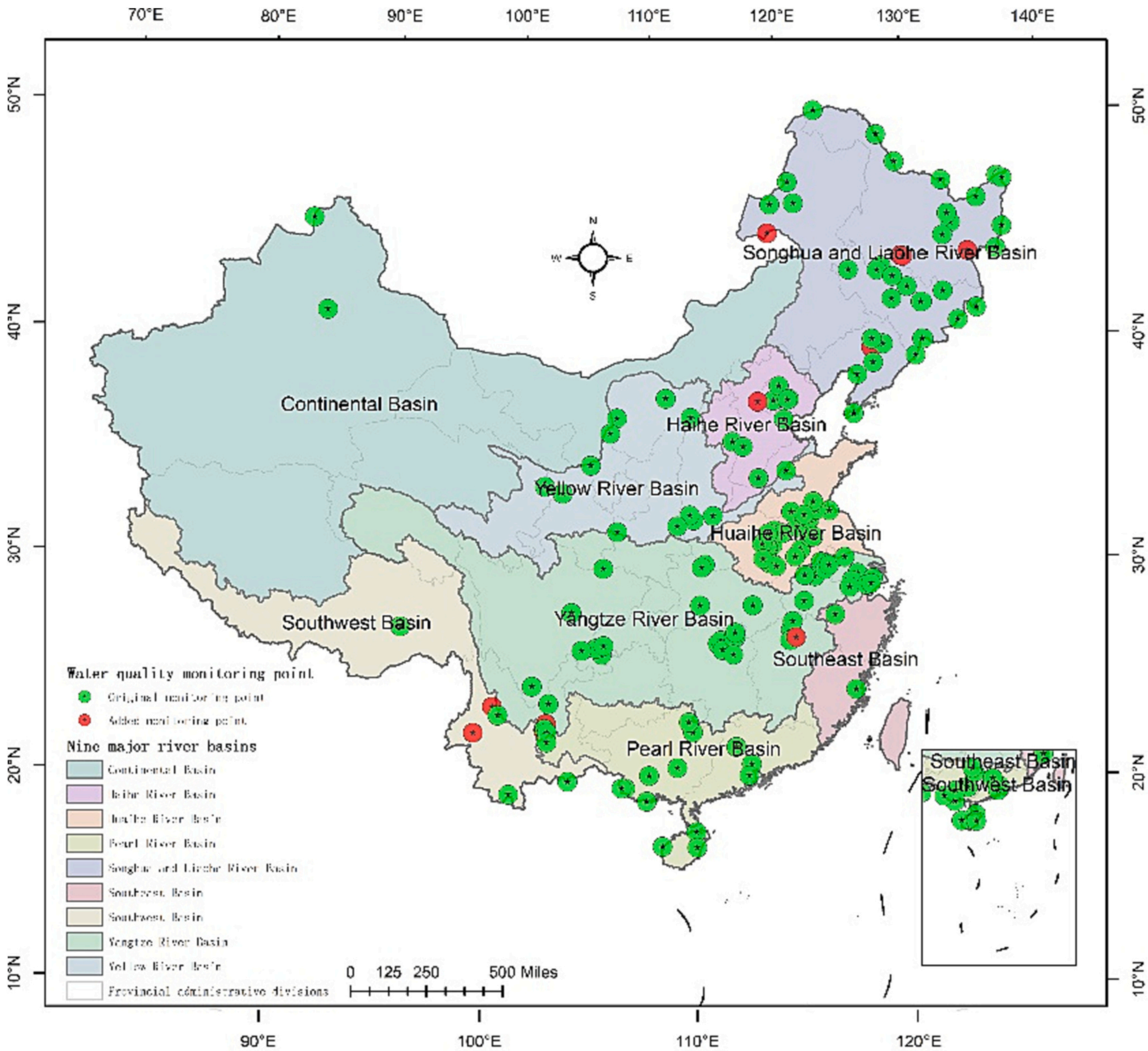

Fig. 4. Distribution of state-controlled water quality monitoring sites in China during the 13th Five-Year Plan (2016–2018).

where coefficient β_0 represents a constant term. In city *i* at *s* years before the event, the value of HEC_{it-s} is 1, and vice versa is 0, where the value range is$s = \{1, 2, \ldots, 12\}$. In city *i* at *m* years after the event, the value of HEC_{it+m} is 1 and vice versa is 0, where the value range is $m = \{1, 2\}$. Additionally, θ_s is the average phase-in effect coefficient of the advance *s* period, δ capture the coefficient of the average immediate effect, and ϕ_m is the average anticipated effect coefficient of the lag *m*period. If δ is negative, $\phi_m < 0$ indicates that the anticipated effect increases over time, and $\phi_m > 0$ indicates that the anticipated effect decreases over time (Wing et al., 2018).

Fig. 5 illustrates the mean treatment effect for industrial wastewater discharge relative to initial implementation of ecological compensation. The results show that most of the coefficients of the treatment effect prior to implementation were not significant at the 10% level, whereas those afterwards were significant. The specific results can be found in Supplementary Table A.5 in appendix A. Overall, the dynamic effect not only reflects a significant downward trend in industrial wastewater discharge after the implementation of the policies, but even supports the satisfaction of parallel trend assumptions.

Note: The line and circles show the dynamic coefficient of the treatment effect. It designates the first period as base period (Nunn and Qian, 2011), and the error bars indicate the 90% confidence interval.

5.3. Robustness

To measure the effectiveness of water pollution prevention and control from a multi-dimensional perspective and further enhance the robustness, this study further evaluated water pollution prevention and control through four aspects: per capita discharge, discharge density, and discharge intensity of industrial wastewater, and water pollutant indicators.

5.3.1. Emission intensity, per capita emissions, and emission density

Considering the impact of various factors such as differences in economic development, population sizes, and jurisdiction areas of various regions on the total industrial wastewater discharge, Table 5 presents the regression results for the industrial wastewater discharge intensity (*IWDI*), per capita industrial wastewater discharge (*PCIWD*), and industrial wastewater discharge density (*IWDD*), which were used as the explained variables. The negative regression result for discharge

Table 4
Regression results for the scale of industrial wastewater discharges.

Variables	Industrial wastewater discharge regression						
	Full sample					Upstream	Downstream
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
HEC	−0.3425***	−0.3288***	−0.1840***	−0.1840**	−0.1840**	−0.2094**	−0.1601
	(0.1236)	(0.0534)	(0.0537)	(0.0843)	(0.0789)	(0.1028)	(0.1174)
Fissuffi		0.7309***	0.1599	0.1599	0.1599	0.1665	0.0945
		(0.1299)	(0.1340)	(0.2272)	(0.2090)	(0.2127)	(0.2132)
GDP2		1.4442***	0.0310	0.0310	0.0310	−0.1325	0.1395
		(0.1994)	(0.2050)	(0.3830)	(0.3539)	(0.3579)	(0.3634)
Popdensity		0.3010***	0.2578***	0.2578*	0.2578	0.2683*	0.2397
		(0.0945)	(0.0913)	(0.1460)	(0.1571)	(0.1583)	(0.1575)
FDI		−0.0010	−0.0058	−0.0058	−0.0058	−0.0054	−0.0041
		(0.0094)	(0.0092)	(0.0119)	(0.0102)	(0.0106)	(0.0112)
Watersupply		−0.0211	0.0140	0.0140	0.0140	0.0208	0.0147
		(0.0247)	(0.0227)	(0.0321)	(0.0329)	(0.0345)	(0.0336)
Indusenter		−0.0702*	0.0183	0.0183	0.0183	0.0314	0.0047
		(0.0365)	(0.0400)	(0.0721)	(0.0666)	(0.0669)	(0.0698)
Plant		−0.0043	0.0025	0.0025	0.0025	0.0030	0.0043
		(0.0029)	(0.0032)	(0.0058)	(0.0055)	(0.0069)	(0.0055)
Pipelength		−0.1899***	−0.0479*	−0.0479	−0.0479	−0.0347	−0.0676
		(0.0253)	(0.0263)	(0.0395)	(0.0399)	(0.0420)	(0.0436)
Greenarea		−0.0399	0.0306	0.0306	0.0306	0.0245	0.0311
		(0.0274)	(0.0301)	(0.0530)	(0.0492)	(0.0520)	(0.0506)
Precipitation		−0.1504**	−0.0981	−0.0981	−0.0981	−0.0977	−0.0964
		(0.0646)	(0.0695)	(0.0829)	(0.0724)	(0.0773)	(0.0753)
Weather		−0.1164***	0.0002	0.0002	0.0002	0.0072	−0.0021
		(0.0174)	(0.0276)	(0.0298)	(0.0236)	(0.0241)	(0.0241)
RH		−0.0068	0.0021	0.0021	0.0021	0.0032	0.0013
		(0.0044)	(0.0050)	(0.0099)	(0.0069)	(0.0072)	(0.0072)
City FE	No	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	No	No	Yes	Yes	Yes	Yes	Yes
Watershed FE	No	No	Yes	Yes	Yes	Yes	Yes
Observations	3679	3679	3679	3679	3679	3471	3432
R^2	0.003	0.848	0.866	0.866	0.866	0.861	0.860

Note: *, **, and *** indicate a significance level of 10%, 5%, and 1%, respectively; column (3) is robust standard error in parentheses, robust standard error clustered at the province level in column (4), and robust standard error clustered at the city level in column (5). Upstream and downstream areas were classified according to their location within the river basin and the administrative jurisdiction. The cities located in upstream provinces in inter-provincial basins are classified as upstream, and those in downstream provinces are classified as downstream.

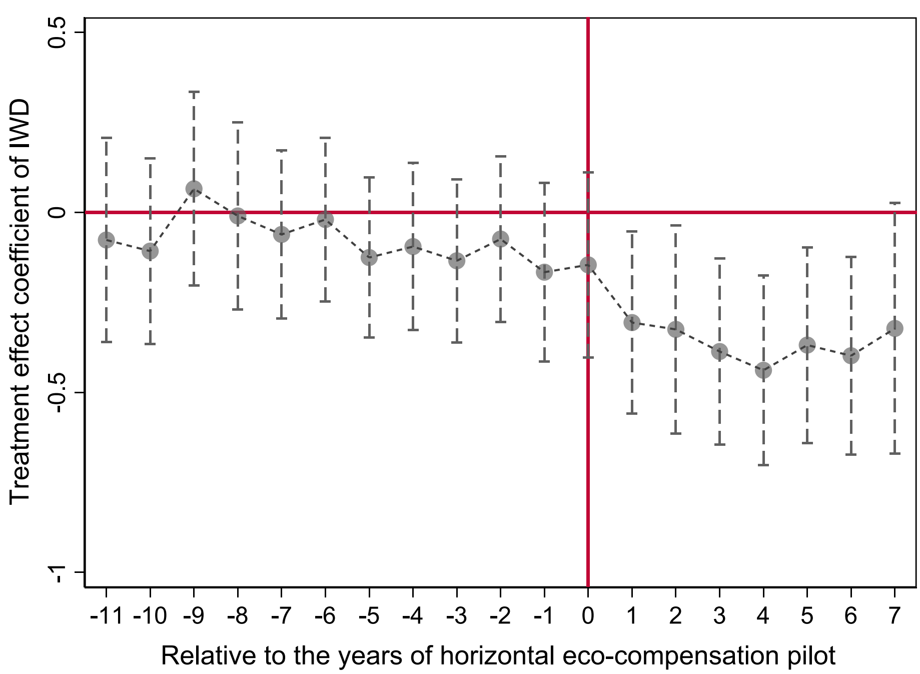

Fig. 5. Dynamic effects of horizontal ecological compensation pilots.

Table 5
Regression results of industrial wastewater discharge intensity (IWDI), per capita discharge (PCIWD), and discharge density (IWDD).

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	IWDI		PCIWD		IWDD	
HEC	−0.1384*	−0.1384	−0.0065***	−0.0065*	−0.0030***	−0.0030*
	(0.0717)	(0.1347)	(0.0017)	(0.0033)	(0.0011)	(0.0017)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Watershed FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3679	3679	3679	3679	3679	3679
R^2	0.540	0.540	0.636	0.636	0.796	0.796

Note: *, **, and *** indicate a significance level of 10%, 5%, and 1%, respectively; columns (1), (3), and (5) are robust standard error in parentheses, and robust standard error clustered at the city level in columns (2), (4), and (6).

intensity was likely due to the broad research scope and sample size; thus, the average effect on the policy treatment group was reduced. The impact coefficients of horizontal ecological compensation on per capita discharge and discharge density were significantly negative. Therefore, for these substituted variables, the regression results support the conclusions of the benchmark regression.

5.3.2. *Water pollution indicators at state-controlled monitoring points*

5.3.2.1. Weekly water pollution indicators. The above analyses focused on industrial wastewater discharges; thus, to further measure the severity of water pollution, the examination of point source pollution was comprehensively extended to include industrial, urban domestic, and agricultural non-point source pollution. The water pollution indicators were pH, DO, COD, and NH_3-N. Table 6 shows regression results regarding the weekly surface water-quality monitoring data from state-controlled sections. This data increased the robustness of the basic conclusions from the perspective of surface water pollution, further supporting the policy analysis results.

The regression results consider weekly fixed effects of cities, years, and river basins. The influence coefficient of pH was significantly positive. Nevertheless, this does not indicate that increasing pH aggravates water pollution; the pH may have changed from weakly acidic to weakly alkaline, which could have been caused by several factors, such as seasonality, water temperature, water volume, reduced sewage and industrial wastewater discharges, and natural processes, such as the reproduction of algae and aquatic organisms. Photosynthesis by aquatic plants reduces CO_2 in the water, thereby increasing pH; however, this phenomenon does not negatively impact the health of river ecosystems. Moreover, the water quality might have significantly improved due to a reduction in local acid rain. The influence coefficient of horizontal ecological compensation implementation on the DO was significantly positive, which indicates that DO in policy areas has been controlled, and the water quality has been significantly improved and restored. Additionally, the coefficients of influence on COD and NH_3-N were both significantly negative; the decline in COD was the most pronounced relative to the other indicators. The lower these two variables, better the water quality. Therefore, the water quality has been controlled and improved, and the concentration of pollutants has decreased. The 11th and 12th Five-Year Plans identified COD and NH_3-N as key pollutants, the above indicators reflect their importance in the implementation of horizontal ecological compensation and their effective alleviation.

Table 6
Regression results of horizontal ecological compensation effects on regional pollution indicators on a weekly basis.

Variables	(1)	(2)	(3)	(4)
	pH	DO	COD	NH_3-N
HEC	0.0335*	0.7581***	−1.9314***	−0.7084***
	(0.0184)	(0.0956)	(0.2704)	(0.1191)
Controls	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Watershed FE	Yes	Yes	Yes	Yes
Weekly FE	Yes	Yes	Yes	Yes
Observations	84,236	84,236	84,236	84,236
R^2	0.361	0.405	0.468	0.353

Note: *, **, and *** indicate a significance level of 10%, 5%, and 1%, respectively; robust standard errors in parentheses. Refer to *the Comprehensive Sewage Discharge Standard* (GB8978–1996) and *Surface Water Environmental Quality Standard* (GB3838–2002) to obtain the range for these values. The pH range was 6–9. DO is dissolved oxygen; COD is chemical oxygen demand of potassium permanganate; and NH3-N is the aqueous concentration of ammonia nitrogen.

5.3.2.2. Annual and quarterly water pollution indicators. To further verify the regression results, yearly and quarterly values were also calculated to support the above conclusions (see appendix C). Table 7 shows the regression estimates of the annual and quarterly means, with the control of fixed effects. The results show that except for the regression results of pH, which were statistically significant, the annually (Panel A) and quarterly (Panel B) regression results are in line with the weekly results, and the gap between the impact coefficients is small. Additionally, R^2 values for the yearly and quarterly estimates were higher those of the weekly results.

Table 7
Regression results of horizontal ecological compensation effects on regional pollution indicators, calculated annually and quarterly.

Variables	(1)	(2)	(3)	(4)
	PH	DO	COD	NH_3-N
Panel A: Annually				
HEC	0.0470	0.7638***	−1.2334***	−0.4669**
	(0.0380)	(0.2704)	(0.4395)	(0.1818)
Controls	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Quarterly FE	No	No	No	No
Watershed FE	Yes	Yes	Yes	Yes
Observations	2128	2128	2128	2128
R^2	0.731	0.758	0.781	0.781
Panel B: Quarterly				
HEC	0.0321	0.7841***	−1.9257***	−0.6467***
	(0.0299)	(0.1927)	(0.3407)	(0.1594)
Controls	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Quarterly FE	Yes	Yes	Yes	Yes
Watershed FE	Yes	Yes	Yes	Yes
Observations	7604	7604	7604	7604
R^2	0.627	0.677	0.744	0.664

Note: *, **, and *** indicate a significance level of 10%, 5%, and 1%, respectively; robust standard errors in parentheses.

5.3.3. Propensity score matching difference-in-differences

The areas under horizontal ecological compensation pilots are generally important drinking water sources, lakes, and inter-provincial watersheds in both economically underdeveloped and developed areas; thus, they are representative to a certain extent. Therefore, the choice of pilot area depends on observable control variables. The treatment group is the administrative area of the watershed undergoing horizontal ecological compensation. However, the treatment and control groups have different initial conditions. Pilot area locations for horizontal ecological compensation usually arise from non-random policy choices, which may cause sample selection bias. To overcome this bias, this study utilized propensity score matching (PSM) with DID (Heckman et al., 1998), implemented a front-end screening control group for the treatment group, and performed state matching to evaluate the effect of horizontal ecological compensation on water pollution prevention and control. The samples with the closest propensity scores to the control group are the paired treatment group samples, and the systematic differences between these groups in terms of economy, society, and nature are reduced by the matching method, thereby reducing the estimation bias.

Considering that the selected control variables may have negatively impacted horizontal ecological compensation, all control variables were lagged by one period to reduce potential endogenous problems, based on Wang et al. (2021b). Table 8 presents the results of PSM. Columns 1–3 contain the regression results obtained through 500 iterations of radius matches, kernel matches, and neighbor matches, respectively. Columns 4–6 display the regression results with the lag period. These results align with those of the benchmark regression and demonstrate a limited difference. Although the results with the lagged control variables show a slight decrease in relative influence compared with those of the benchmark regression, the results still verify its robustness.

5.4. Placebos and other policies

5.4.1. Placebos

5.4.1.1. Fictitious processing samples. To eliminate the interference of omissions or unobservable factors, the impacts of horizontal ecological compensation policies on the scale, intensity, per capita scale, and density of water pollution were estimated by constructing random samples. Various cities were randomly selected as treatment groups and this was repeated 500 times (Chetty et al., 2009; Cai et al., 2016; Zheng et al., 2022). Fig. 6 shows the coefficient distribution of the randomly selected treatment groups for the scale, intensity, per capita scale, and density of industrial wastewater. The coefficient values of the fictitious policy samples are clustered near zero, which is completely independent of the distribution of the original calculated coefficient. Although the original coefficient of industrial wastewater discharge intensity was within the core density, the proportion of probability density was approximately 5.8%, indicating a low probability that the null hypothesis is correct. Therefore, the baseline estimate was not likely interfered with by unobservable factors.

5.4.1.2. Virtual policy time. To identify whether water pollution prevention and control was affected by other policies or macro shocks, this study examined the impact of these factors on the severity of water pollution via pollutant indicators. The earliest pilot for horizontal ecological compensation in a watershed was in 2011. Drawing on the research of Behr and Sonnekalb (2012), the following time of policy occurrence is advanced by 1–4 year to construct virtual policy time points that are still affected by horizontal ecological compensation policies. The explanatory variables were the pollutant indicators COD and NH_3-N as proposed in the 11th and 12th Five-Year Plans, respectively. The equations $F_1DID = HEC_{it-1}$, $F_2DID = HEC_{it-2}$, $F_3DID = HEC_{it-3}$, and $F_4DID = HEC_{it-4}$ represent the policy time points advanced by 1, 2, 3, and 4 year, respectively, and their regression results are presented in Table 9. Changing the horizontal ecological compensation period in each basin did not significantly reduce the discharge of pollutants, thereby eliminating external impacts and further strengthening the conclusion of the baseline regression.

5.4.2. Exclusion of the effects of other policies

5.4.2.1. Implementation of the river chief system. The significance of the river chief system as an institutional innovation in the governance of water pollution in China cannot be ignored (Tang et al., 2020). The river chief system sets positions of both official and non-governmental river and lake chiefs, who act through fine management and multi-pronged and collaborative governance. In 2016, China aimed to fully establish the river chief system throughout the country by the end of 2018. However, this system was implemented at different times in different locations; thus, time-varying DID was used to identify its policy effects on water pollution governance.

In Table 10 from the perspective of pollutant indicators, since its full implementation, the river chief system has not effectively reduced the industrial wastewater discharge intensity, per capita scale, and density. Despite the implementation of the river chief system has increased the pH, its impact on the other indicators has not been statistically significant. These results are inconsistent with the conclusions of Kunrong and Gang (2020), possibly because the sample size was larger and the time span was longer in this study than those in the previous study. Moreover, Kunrong and Gang (2020) conducted an evaluation of the preliminary effects of the river chief system, whereas the present study includes the policy effects after its comprehensive establishment and promotion. After excluding interference from the river chief system, the regression results of the pollution indicators changed minimally. Therefore, despite implementing the river chief system and territorial responsibility, local

Table 8
Regression results demonstrating the propensity score matching robustness.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	IWD					
	Radius	Kernel	Neighbor	Radius	Kernel	Neighbor
HEC	−0.1520***	−0.1504***	−0.1520***	−0.1237**	−0.1237**	−0.1237**
	(0.0557)	(0.0557)	(0.0557)	(0.0576)	(0.0576)	(0.0576)
Controls	Yes	Yes	Yes	–	–	–
Lag of Controls	–	–	–	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Watershed FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2978	2980	2978	2769	2769	2769
R^2	0.8698	0.8701	0.8698	0.8710	0.8710	0.8710

Note: *, **, and *** indicate a significance level of 10%, 5%, and 1%, respectively; robust standard errors in parentheses. The above results were iterated 500 times. The radius of the matching scale was 0.05, and the neighbor matching selection was 1-to-4 matching.

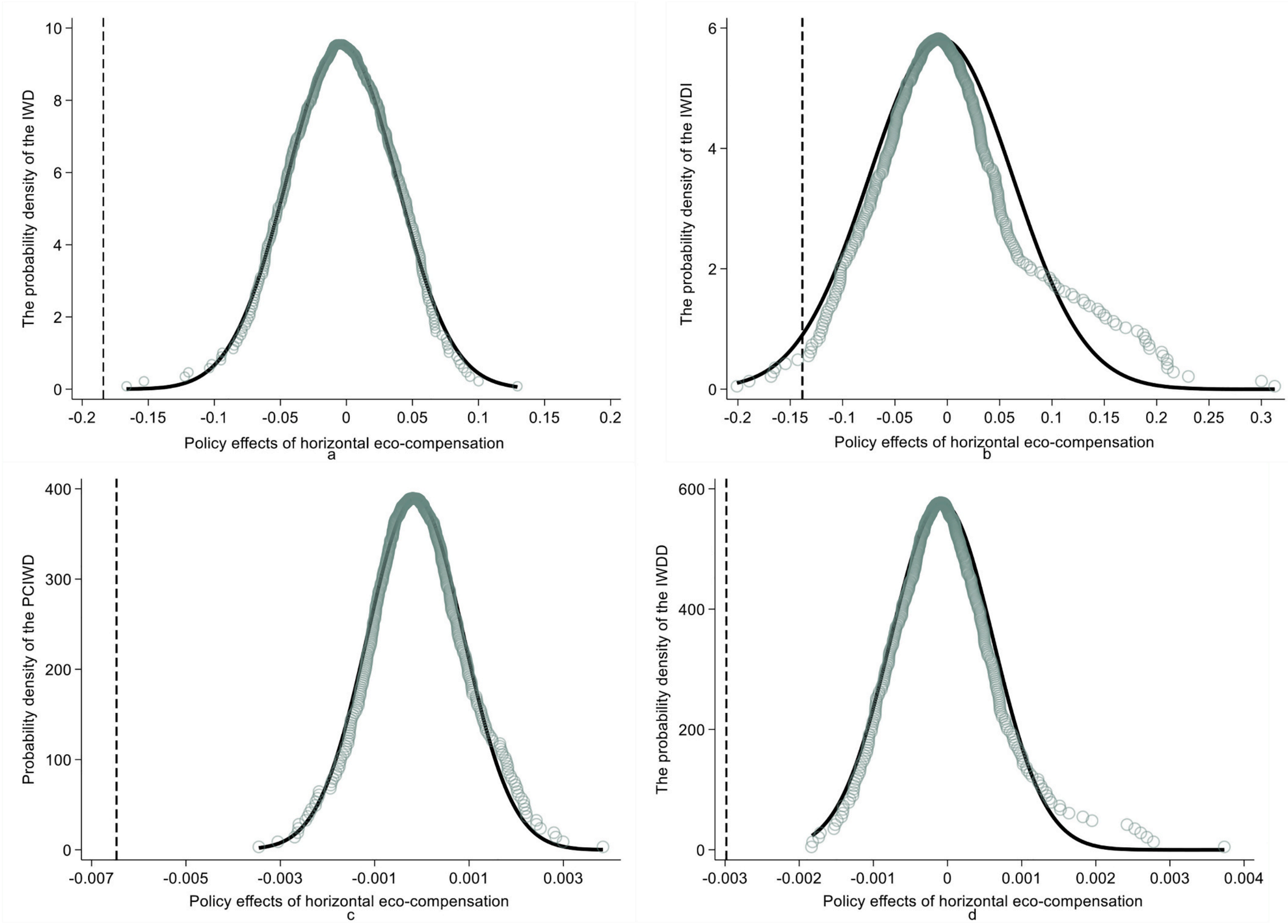

Fig. 6. Kernel density plots of fictitious processing samples.
Note: **a** is the probability density of industrial wastewater discharges. **b** is the probability density of industrial wastewater discharge intensity. **c** is the probability density of per capita industrial wastewater discharge. **d** is the probability density of industrial wastewater discharge density. The distribution of all fictitious sample is far from the initial coefficients.

Table 9
Placebo testing of the point where the policy occurs in advance.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	COD	NH_3-N	COD	NH_3-N	COD	NH_3-N	COD	NH_3-N
F_1DID	−0.3314 (0.4235)	−0.2368 (0.1849)						
F_2DID			−0.2430 (0.4527)	−0.1678 (0.1937)				
F_3DID					−0.1247 (0.4430)	−0.0899 (0.1972)		
F_4DID							0.0215 (0.4181)	−0.0555 (0.2107)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Watershed FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1291	1291	1291	1291	1291	1291	1291	1291
R^2	0.760	0.771	0.760	0.771	0.760	0.771	0.760	0.771

Note: *, **, and *** indicate a significance level of 10%, 5%, and 1%, respectively; robust standard errors in parentheses.

governments have not comprehensively improved water pollution prevention and control (Kunrong and Gang, 2020), and the impacts of this system on pollution can be excluded from that of horizontal ecological compensation.

5.4.2.2. Impact of water ten and other policies. In 2015, the Chinese government released "*The Action Plan for the Prevention and Control of Water Pollution*" (referred to as "Water Ten") in an effort to enhance water pollution prevention and advance the development of an ecological civilization. To control industrial pollution, this policy

Table 10
Effects of the implementation of the river chief system on the prevention and control of water pollution.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	IWD	IWDI	PCIWD	IWDD	PH	DO	COD	NH_3-N
HEC	−0.1843***	−0.1217*	−0.0065***	−0.0030***	0.0489	0.7609***	−1.2294***	−0.4689**
	(0.0538)	(0.0698)	(0.0017)	(0.0011)	(0.0378)	(0.2701)	(0.4391)	(0.1821)
Riverchief	0.0450	−0.0141	−0.0009	0.0009	0.0644***	−0.1005	0.1386	−0.0698
	(0.0323)	(0.0474)	(0.0010)	(0.0011)	(0.0199)	(0.0954)	(0.1268)	(0.0810)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Watershed FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3679	3679	3679	3679	0.732	0.758	0.781	0.781
R^2	0.866	0.542	0.636	0.797	2128	2128	2128	2128

Note: *, **, and *** indicate a significance level of 10%, 5%, and 1%, respectively; robust standard errors in parentheses.

comprehensively investigated small industrial enterprises with minimal equipment and poor environmental protection facilities. To control domestic pollution, Water Ten intensified the treatment of urban black and odorous water and instituted a tiered pricing scheme for residential water consumption. Regarding rural pollution, Water Ten aimed to regulate agricultural non-point source pollution and scientifically delineated areas where livestock and poultry breeding is prohibited. Therefore, this study identified whether the effects of horizontal ecological compensation on water pollution prevention and control were affected by the Water Ten policy and subsequently excluded its impact. The results remained significant after controlling for a dummy variable for the Water Ten policy as a fixed effect, as shown in columns 1–4 of Table 11.

Considering that vertical ecological compensation transfer payments will also contribute to water pollution prevention and control, vertical transfers were set as a dummy variable to measure their impacts on regional water pollution. Due to a lack of data on vertical transfer payments to river basins, the presence of nature reserves in each region was used to measure the strength of the transfer payments from the central government. After controlling for this dummy variable as a fixed effect, the regression results were still significant, as shown in columns 1–4 of Table 11. While the values of the dummy variables Water Ten and the vertical transfer payment are different, it's important to note that the coefficients for the main effect and control variables remain consistent when each of the two variables is controlled separately. Therefore, we can consolidate the results in Table 11. At the same time, this study add the regression results of water pollutant indicators 5–8 in Table 11, indicating that the Water Ten and the vertical transfer payment do not affect the effect and coefficient direction and significance of the horizontal ecological compensation policy.

Additionally, because the study period was 2006–2018, the 11th, 12th, and 13th Five-Year Plans applied to all samples. Therefore, the policy impacts on water pollution prevention and control during the various Plan periods were disregarded because they were reflected in the time trend changes, which were controlled by the fixed year effects.

5.5. Further discussion

5.5.1. Heterogeneity discussion

5.5.1.1. Impacts on different watersheds. China has nine major river basins (RESDC, 2022), namely the Songliao, Haihe, Huaihe, Yellow, Yangtze, Pearl, Southeast, Southwest, and Inland River basins (Chen et al., 2021b). The extent of water resources, their development and utilization, as well as the level of water pollution, vary among different river basins. Additionally, rivers have downstream flows with spatial spillover; thus, the intersections between basins or jurisdictions vary. Moreover, the disparities in water resources across basins also impact the level of efforts to prevent water pollution.

To test the heterogeneity of pollution prevention among different river basins, Table 12 demonstrates that, in most river basins, the horizontal ecological compensation policies have effectively reduced industrial discharges. However, the effects in the Songliao, Haihe, and Pearl River basins were negligible; nevertheless, the coefficients were negative. Based on surface water quality data released by the Chinese Ministry of Ecology and Environment from January to December 2022, the Songhua, Haihe, and Huaihe River basins currently have light pollution. Although the influence coefficient in the Huaihe River Basin was positive, it was not significant. Additionally, the horizontal ecological compensation implemented in the Chu River Basin belongs to the Huai River Basin. These results show that although upstream and downstream entities jointly fund horizontal supervision and cooperation, they only regard pollution prevention as a policy banner and cater to the policy requirements, but do not effectively control and improve water pollution.

5.5.1.2. Effects on domestic sewage, rural non-point source pollution, and lake transparency. To comprehensively assess water pollution

Table 11
Regression results excluding the effects of the Water Ten and vertical transfer payments.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	IWD	IWDI	PCIWD	IWDD	PH	DO	COD	NH3-N
HEC	−0.1840***	−0.1218*	−0.0065***	−0.0030***	0.0470	0.7638***	−1.2334***	−0.4669**
	(0.0537)	(0.0699)	(0.0017)	(0.0011)	(0.0380)	(0.2704)	(0.4395)	(0.1818)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Watershed FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Dummy of Water Ten	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Dummy of vertical transfers	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3679	3679	3679	3679	2128	2128	2218	2128
R^2	0.866	0.542	0.636	0.796	0.731	0.758	0.781	0.781

Note: *, **, and *** indicate a significance level of 10%, 5%, and 1%, respectively; robust standard errors in parentheses.

Table 12
Regression results in different watersheds.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Songliao	Haihe	Huaihe	Yellow	Yangtze	Pearl	Southeast	Other
			IWD					
HEC	−0.3009 (0.2745)	−0.0457 (0.1226)	0.0885 (0.1167)	−0.3594*** (0.0800)	−0.1392** (0.0707)	−0.0881 (0.1067)	−0.3738*** (0.1133)	−0.5720* (0.3445)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Watershed FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	507	468	611	819	1456	650	364	481
R^2	0.746	0.873	0.835	0.908	0.890	0.852	0.905	0.906

Note: *, **, and *** indicate a significance level of 10%, 5%, and 1%, respectively; robust standard errors in parentheses. This table does not include regression results for the Southwest and Inland River basins, because they did not include the treatment group.

prevention efforts, it is necessary to examine not only industrial point source pollution but also domestic sewage treatment, agricultural non-point source pollution, and the transparency of lakes. Regarding domestic sewage, this study used the urban *DST* to describe water pollution by urban residents. The abuse and excessive use of chemical fertilizers has gradually become a main factor in rural environmental and water pollution, and can lead to eutrophication in water bodies, particularly due to nitrogen and phosphate fertilizers (Puckett, 1995). Owing to a lack of rural non-point source pollution data at the prefecture and city levels (Zou et al., 2020), and considering to the difficulty in measuring and monitoring it, this study used the GDP index of the primary regional industries to characterize the development of agriculture in each region. Additionally, the provincial application rates of nitrogen and phosphate fertilizer were matched to the proportion of primary industries in various cities within the province to estimate the applied amounts of nitrogen fertilizer (*NF*) and phosphate fertilizer (*PF*) in each region to estimate agricultural non-point source pollution. Additionally, based on the Forel-Ule Index constructed by Wang et al. (2020) and Wang et al. (2021a), this study used lake transparency to represent the clarity of lakes and reservoirs, evaluated their water quality (eutrophication), and identified the prevention effects of horizontal ecological compensation. Generally, the higher the transparency of lakes and reservoirs, the better the water quality and the more ideal the watershed ecological environment (Wang et al., 2020; Wang et al., 2021a). Hence, the regression results were supported by examining urban point source pollution, agricultural non-point source pollution, and lake transparency, as detailed in Table 13.

Table 13 illustrates the regression results, revealing that while coefficients of horizontal ecological compensation on the domestic sewage treatment rate, nitrogen fertilizer, and lake transparency were positive, and that for phosphate fertilizer was negative, they were not statistically significant. Therefore, horizontal ecological compensation in river basins has not effectively improved urban domestic sewage treatment, agricultural non-point source pollution, and lake transparency. The incentive effects are primarily reflected in the reduction of industrial pollution.

Table 13
The regression results for urban pollution, rural pollution, and lake transparency.

Variables	(1)	(2)	(3)	(4)
	Urban point source pollution	Agricultural non-point source pollution		Lake transparency
	DST	NF	PF	FUI
HEC	0.0158 (0.0129)	0.6547 (1.5486)	−0.3210 (0.6313)	0.0964 (0.1623)
Controls	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Watershed FE	Yes	Yes	Yes	No
Observations	3679	3674	3674	533
R^2	0.646	0.974	0.974	0.951

Note: *, **, and *** indicate a significance level of 10%, 5%, and 1%, respectively; robust standard errors in parentheses.

5.5.2. Impact of economic development

Consistent with the multi-task development goals, this study analyzed the governance effect of horizontal ecological compensation on both water environmental protection and economic development tasks to provide empirical evidence for the correlation and overlap between these goals. Hence, real GDP scale (*GDP*) and growth rate (*GDPR*) were used as indicators to measure jurisdictional economic development. The incentive effect of horizontal ecological compensation on economic development was analyzed, and the degree of influence between upstream and downstream entities was observed (Table 14). The results show that for both indicators, horizontal ecological compensation throughout river basins significantly improves economic development therein. Considering economic development scale, its degree of influence was higher downstream than that upstream, and vice versa for the economic growth rate. Therefore, horizontal ecological compensation with transfer payments as the main compensation can effectively achieve water pollution prevention and control, affect economic development, and implement the development concept of ecological priority and green development for areas throughout river basins.

5.5.3. Mechanisms

As an innovation of the ecological civilization system, horizontal ecological compensation in river basins has realized the transformation of one-way compensation to two-way ecological compensation mode. Focusing on the perspectives of horizontal coordination and vertical inspection, this study mainly studies the policy incentive and constraint effects of ecological compensation in transboundary river basins. Although horizontal coordinated governance of transboundary river basins can have a positive impact on water pollution by stimulating the governance behavior of local entities, it is necessary to further explore the constraint effect of vertical inspection to ensure the long-term mechanism of policy.

The horizontal ecological compensation policy has the advantage of horizontal supervision by both upstream and downstream.Furthermore, the Central environmental protection inspection (CEPI), a vertical regulation, is a key institutional arrangement to promote environmental protection and the development of an ecological civilization. CEPI includes routine inspections, special inspections, and “retrospectives,” among which routine inspections cover regional watersheds and remediation of deteriorated ecosystems. In 2015, CEPI pilot work began in Hebei, and in 2016, the initial batch of CEPI was fully launched in eight provinces: Ningxia, Yunnan, Guangxi, Henan, Jiangxi, Jiangsu,

Table 14
Regression results of horizontal ecological compensation on economic development.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	GDP			GDPR		
	Full sample	Upstream	Downstream	Full sample	Upstream	Downstream
HEC	0.0519***	0.0378**	0.0727***	0.0214***	0.0261***	0.0163***
	(0.0120)	(0.0183)	(0.0146)	(0.0052)	(0.0076)	(0.0063)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Watershed FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3679	3471	3432	3679	3471	3432
R^2	0.991	0.991	0.991	0.592	0.592	0.588

Note: *, **, and *** indicate a significance level of 10%, 5%, and 1%, respectively; robust standard errors in parentheses.

Heilongjiang, and Inner Mongolia. Subsequently, the second, third, and fourth batch were launched in the remaining provinces in 2016, thereby achieving full inspection coverage in all provinces. CEPI can strengthen the supervision of governance and ensure ecological environment governance throughout river basins. Therefore, the effect of the CEPI on the prevention of water pollution was examined for the upper and lower reaches of river basins through the CEPI pilot. The regression results presented in column 1–4 of Table 15 incorporate the product of the implementation of horizontal ecological compensation policies and CEPI, which was significantly negative. Therefore, promoting the implementation of the CEPI pilot synergizes with the execution of horizontal ecological compensation policies and can further stimulate their treatment effects on water pollution prevention and control. Furthermore, 5–8 of Table 15 displays regression results for horizontal ecological compensation policies, focusing exclusively on samples involving two-way compensation. These results indicate a general trend of increasing coefficients, which enhances the clarity and confidence in our findings.

This study not only examines the central environmental protection inspection but also evaluates the impact of local government environmental protection policy support and enterprise sewage treatment investment projects on policy effectiveness. However, the results indicate that these two variables do not have a direct influence on local water pollution prevention and control outcomes. This suggests that local governments continue to heavily rely on fiscal funds in environmental governance. Furthermore, it highlights the limited capacity of micro-enterprises to drive improvements in water governance, underscoring the need for further examination of incentives for horizontal ecological compensation policies through central environmental protection inspection.

6. Conclusions and policy recommendations

The modernization of water environment governance urgently requires to change from fiscal supply to independent development, and horizontal ecological compensation in the river basin, as an innovation of ecological civilization system, has realized the transformation of one-way to two-way ecological compensation mode. Focusing on the perspectives of horizontal coordination and vertical supervision, this study mainly estimates the policy incentive and constraint impact of ecological compensation in transboundary river basins. Unlike previous numerical simulations, time-varying DID, combined with pilot cases of transboundary horizontal ecological compensation policies in China during 2006–2018, were used to expand the data from local river basins to national river basins, and the observations were refined to the city-level. Moreover, water quality data from urban state-controlled monitoring sections were matched to their administrative divisions, which solved the problem of unstable estimation results caused by local samples. These data support transboundary horizontal ecological compensation for effectively stimulating coordination between upstream and downstream governments and controlling pollution. Furthermore, this study evaluated the effects and contributions of horizontal ecological compensation to the construction of an ecological civilization.

The main conclusions are as follows. First, horizontal ecological compensation policies in transboundary river basins affect water pollution governance in upstream and downstream areas, indicating that, under the constraints of bilateral agreements and the incentives of central rewards and punishments, the two-way ecological compensation model will promote local governments to strive to control water sources, and the horizontal ecological compensation policy has the expected effect on the prevention and control of water pollution in China. Secondly, heterogeneity analysis indicated that the prevention and control of

Table 15
Regression results regarding CEPI.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	All samples				Two-way compensation mode			
	IWD	IWDI	PCIWD	IWDD	IWD	IWDI	PCIWD	IWDD
HEC × CEPI	−0.1376*	−0.1670*	−0.0054***	−0.0033**				
	(0.0736)	(0.0857)	(0.0019)	(0.0016)				
HEC2 × CEPI					−0.1955**	−0.1704	−0.0061**	−0.0040*
					(0.0794)	(0.1176)	(0.0026)	(0.0024)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Watershed FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3601	3601	3601	3601	3601	3601	3601	3601
R^2	0.885	0.606	0.677	0.807	0.885	0.606	0.677	0.807

Note: *, **, and *** indicate a significance level of 10%, 5%, and 1%, respectively; robust standard errors in parentheses. It is important to note that the variable HEC2 pertains to the sample of policy implementation after eliminating the one-way compensation mode and proportional allocation. This variable of HEC2 is associated with the subset of policy implementation in the two-way compensation mode.

water pollution is mainly reflected by industrial sewage discharges and the reduction of water pollution indicators. However, point source domestic sewage, non-point source agricultural pollution, and lake water quality did not show treatment effects. Nevertheless, horizontal ecological compensation policies encourage the mutual promotion and integration of ecological protection and economic development. Third, policy incentives rely on compensation via fiscal transfers, and ecological and environmental accountability via the CEPI can effectively avoid improper behavior and inaction by local governments in environmental monitoring. Moreover, horizontal ecological compensation effectively combines bilateral rights, interests, and responsibilities with rewards and punishments, encourages upstream and downstream responsible entities to collaboratively govern, and is effective against water pollution. These results provide reference and policy support for the subsequent promotion of horizontal ecological compensation in provinces and key river basins.

First, previous water pollution policies focused on managing point source pollution, such as industrial wastewater and domestic sewage. However, it must be recognized that agricultural non-point source pollution is an important cause of water pollution, exacerbating problems such as eutrophication of lakes and reservoirs. As the challenge of collecting agricultural non-point source pollution data exacerbates the difficulty of agricultural non-point source pollution control, agricultural non-point source pollution is often underestimated. To address this, we must reduce the excessive use of chemical fertilizers and pesticides, control livestock and poultry pollution, and strictly regulate straw burning, so as to help prevent water pollution with green agriculture.

Second, to enhance the effectiveness of ecological compensation, it is essential to transition from a singular fund subsidy to a more comprehensive compensation. The comprehensive ecological compensation strategy encompasses various elements, extending beyond government-led horizontal fiscal transfers. Simultaneously, it's crucial to explore multiple compensation models that combine government intervention with market mechanisms. This approach can effectively attract private capital investments and promote market-oriented trading of emission rights and water rights between upstream and downstream river basins. While embrace diversified ecological compensation models within the market, it must also maintain and strengthen the pivotal role of government transfer payments in compensation.

Third, the coverage of horizontal ecological compensation needs to be further deepened. All regions need to further expand the coverage of surface water quality monitoring sections, ensure that key surface water can be covered, reasonably allocate cross-section control levels according to the impact range of surface water, increase the monitoring of water pollution prevention and control, and timely monitor and warn the change trend of water environment quality in their jurisdiction.

Although this study has made some progress, there are still some limitations that require further exploration in future research. Firstly, due to constraints related to nationally controlled cross-sectional pollutant indicator data, the data sample is limited up to 2018. Consequently, it is not possible to timely capture the policy effects beyond 2018. Secondly, the empirical research does not incorporate horizontal ecological compensation within the province for comparison. The difficulty lies in obtaining precise data regarding the timing of horizontal ecological compensation at the county level within the province. In terms of future prospects for policy effect assessment, future research should incorporate provincial-level horizontal ecological compensation data to broaden the range of policy samples and accurately assess the policy effects of the horizontal ecological compensation policy pilot. Additionally, this study has access to relatively comprehensive pollutant indicator data for China's nationally controlled sections from 2006 to 2018, and these data will be valuable for conducting more in-depth analyses in future research.

CRediT authorship contribution statement

Jie Yu: Conceptualization, Methodology, Data curation, Funding acquisition, Writing – original draft, Writing – review & editing. **Qin Xian:** Formal analysis, Visualization, Software, Writing – review & editing. **Shulei Cheng:** Methodology, Supervision, Validation, Writing – review & editing. **Jiandong Chen:** Supervision, Funding acquisition, Resources, 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

Data will be made available on request.

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Appendix A. Supplementary data

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