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Original Research

Modification of Ecological Compensation Amount Based on Pollution Control and Health Losses: Evidence from the Anhui and Henan Sections of the Huaihe River Basin

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Abstract

Accurately quantifying ecological compensation amounts is essential for alleviating the conflict between ecological conservation and economic development in the Huaihe River Basin. Using three phases of Landsat remote-sensing imagery for the Anhui and Henan sections of the basin over the period 2010-2020, ecosystem service value (ESV) is estimated using the equivalent factor method. In parallel, health loss values are quantified by integrating the potential years of life lost method, the revised human capital approach, and the morbidity and disability method, and both health losses and pollution control costs are incorporated into the accounting framework for ecological compensation. Building on the established framework, this study employs spatial autocorrelation models and the Grey Model (GM(1,1)) to investigate the historical evolutionary patterns and future developmental trends of ecological compensation. The results indicate that: (1) between 2010 and 2024, the average annual health-related damage across the basin reached 5.66 billion Yuan, with high-value clusters such as Zhengzhou and Hefei experiencing a continuous escalation in losses, while Xinyang alone recorded a significant 61.17% reduction in health damages; meanwhile, the average discrepancy between theoretical and actual environmental remediation investment was approximately 49 million Yuan, with this gap narrowing significantly after 2016. (2) Throughout the research period, Zhengzhou, Xuchang, and Luohe remained entrenched within the ecological deficit zone with their deficit scales continually expanding, whereas Kaifeng (in 2015) and Shangqiu (in 2022) sequentially surpassed the equilibrium threshold, transitioning from "ecological recipients" to "compensation payers". (3) Ecological compensation metrics exhibit pronounced spatial clustering characteristics: in 2010, High-High (H-H) clusters were concentrated in Lu'an and Hefei, while Low-Low (L-L) clusters were limited to Zhengzhou and Xuchang; by 2016, Xinyang transitioned into an H-H cluster, while Zhoukou and Shangqiu shifted into L-L clusters; between 2016 and 2022, L-L clusters expanded into Northern

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Anhui Section, ultimately forming a distinct "high-in-the-south, low-in-the-north" configuration by 2024. (4) Prognostic simulations for the 2024-2034 period suggest that the basin will maintain a "stable south, declining north" trajectory, where municipalities in the Anhui section remain in the high-value recipient zone while the total compensation for the Henan section is projected to contract by 46.6%, leading to a further widening of the ecological profit-and-loss gap between the northern and southern regions of the study area.

Keywords: ecological compensation amount, health loss, pollution control, spatial autocorrelation, Anhui and Henan sections

Introduction

Basin resources are a crucial component of ecosystems and are vital for human survival. With population growth, rapid socio-economic development, and anthropogenic factors such as disorderly exploitation of basin resources and lake reclamation, issues like land desertification, soil erosion, and water eutrophication are intensifying. Significant imbalances exist in the distribution of economic benefits and environmental responsibilities between upstream and downstream areas of river basins. The report of the 20th National Congress of the Communist Party of China emphasized the need to further improve and refine the ecological compensation system. Currently, over 300 policies and regulations directly related to ecological compensation have been issued [1]. The key to ecological compensation lies in clarifying "who compensates whom" and "how much to compensate". In designing ecological compensation mechanisms, establishing reasonable compensation standards is crucial for balancing the interests between providers and consumers of ecological services. Only by fully considering the opportunity costs of providers and the payment capacity of consumers can a consensus be reached within their respective interest ranges, achieving the Pareto effect in economics [2]. Therefore, using quantitative methods to reasonably determine scientific ecological compensation amounts, ensuring all parties are incentivized to protect the environment, is a pressing issue that needs resolution.

The concept of ecological compensation originates from the theory of environmental externalities [3]. From this perspective, watershed ecological compensation fundamentally seeks to internalise environmental benefits and losses through institutional arrangements. However, existing studies in practice have largely focused on providing economic incentives for the positive externalities generated by ecological conservation activities, typically taking ESV as the principal accounting basis. In contrast, insufficient attention has been paid to the negative externalities arising from pollution emissions during industrialization, which may lead to an overestimation of the actual ecological contributions of different regions [4]. Ecological capital theory offers a renewed analytical perspective for ecological compensation accounting. This theory posits that natural ecosystems constitute a form of capital stock whose value is reflected not only in the positive benefits generated by ecosystem services, but also in the social costs associated with environmental pollution and ecological degradation that should be deducted accordingly [5, 6].

Early studies on ecological compensation standards were predominantly policy-oriented and qualitative in nature, with particular emphasis on identifying compensation entities, compensation modes and institutional frameworks [7, 8]. With the advancement of ecological economics and natural resource accounting theories, research in this field has progressively shifted towards quantitative assessment. Existing approaches for determining compensation standards can generally be classified into three categories. The first approach is based on actual prices or costs, typically using pollution abatement costs, resource utilization prices or ecological protection expenditures as compensation benchmarks. The resulting values are often regarded as the lower bound of ecological compensation. However, this approach focuses on cost recovery and fails to capture the comprehensive social benefits of ecosystem preservation [9-10]. The second approach estimates resource cost values from an economic perspective, taking into account the direct, indirect and opportunity costs associated with resource conservation. Commonly used approaches include the willingness-to-pay method, cost analysis and opportunity cost methods. Although these methods are capable of reflecting, to some extent, societal perceptions of the value of ecological resources, their results are highly sensitive to survey design, cognitive biases and scenario assumptions, thereby limiting their robustness [11, 12]. The third approach is grounded in ESV theory, quantifying the integrated contribution of natural resources to ecological maintenance and social development to establish a theoretical upper limit for compensation. However, traditional applications of this approach have largely focused on positive spillovers, while paying insufficient attention to negative externalities such as environmental pollution and health risks [13, 14]. Recent studies have begun to integrate the costs of water and atmospheric remediation, alongside public health losses, into accounting frameworks. For instance, research by Liu et al. and Zhang et al. has refined compensation mechanisms regarding collaborative basin governance and air quality incentives, while Gu incorporated

health losses into provincial-level calculations, thereby expanding the social dimension of compensation accounting [15-17]. This shift from "net value gain" towards a "comprehensive balance of gains and losses" represents an evolution towards more holistic and systematic compensation standards.

At the spatial scale, ecological compensation research has likewise exhibited a clear shift from macro-level analysis towards more fine-grained investigation. Early studies were predominantly conducted at national or provincial scales, which limited their ability to reveal imbalances in ecological provision and pollution-bearing capacity among subregions within a watershed [18, 19]. Driven by the demand for refined governance, recent research has addressed cross-jurisdictional relationships between upstream and downstream entities, attempting to characterise differences in ecological functional positioning, industrial structures, and pollution gradients at the municipal scale [20, 21]. Accordingly, this study examines the Anhui and Henan sections of the Huaihe River Basin. As a typical trans-provincial watershed in China, the Huaihe River Basin has long exhibited pronounced disparities between upstream and downstream regions in terms of economic development level, industrial structure and ecological carrying pressure. From the perspective of economic and pollution characteristics, by the end of the study period (2020), the Henan section (upstream) was characterized by a relatively high degree of industrialization, with the average share of industrial value added in GDP exceeding 40%. Correspondingly, the associated cities generally experienced annual mean $PM_{2.5}$ concentrations above 50 μg m^{-3}, indicating a substantial industrial pollution burden. By contrast, the Anhui section (downstream) plays a critical role in ecological conservation and water-source protection: forest coverage in the Dabie Mountains exceeds 45%, endowing the region with a pronounced ecological supply function within the regional ecological security pattern. Under the constraints imposed by designated ecological functions and conservation requirements, the Huaihe River-related cities in the Anhui section face relatively limited scope for economic development, leading to a gradient difference of approximately 1.2-1.5 times in per capita GDP between Huaihe River-associated cities in Anhui and Henan. This asymmetric pattern, characterised by high-intensity pollution in upstream areas and high-level ecological protection in downstream areas, makes the Anhui and Henan sections of the Huaihe River Basin an ideal case for examining the relationships among ecological provision, pollution absorption, and the allocation of compensation responsibilities within the watershed.

Despite substantial insights from existing studies, several limitations persist. Theoretical research often focuses on ecological value estimation or compensation mechanism design, neglecting the internalisation of pollution externalities. Accounting methods typically centre on ecosystem services or resource costs, without integrating negative externalities like pollution and health losses into a unified framework. Spatially, research has been concentrated at national or provincial levels, with limited municipal-scale analysis across administrative boundaries and upstream-downstream gradients, hindering the identification of imbalances in ecological protection and compensation. In response, this study develops a revised ecological compensation accounting method, integrating pollution externality theory and ecosystem service value theory. Specifically, this study uses excess mortality attributable to air pollution and cancer risks associated with water pollution as entry points to systematically quantify multidimensional health-related economic losses, including medical expenses, the value of life lost, and productivity losses. The gap in pollution control costs is also calculated. These negative externality costs are deducted from ESV to construct a revised ecological compensation model. This study employs spatial autocorrelation methods and the Grey Prediction Model (GM(1,1)) to reveal the spatial heterogeneity and future evolution patterns of ecological compensation amounts in the Anhui and Henan sections of the Huaihe River Basin.

The potential contributions of this study are as follows. (1) It extends the accounting of total ecosystem service value towards an estimation of net ecological capital. Within the integrated framework of pollution externality theory and ecological capital theory, this study regards environmental pollution as a continuous depletion of natural capital stock. Deducting pollution control costs and residents' health losses from the positive contributions of ecosystem services overcomes the traditional one-sided "value reward" approach and establishes a compensation evaluation paradigm that accounts for both ecological benefits and environmental losses, providing a theoretical pathway for shifting watershed ecological compensation from a single incentive mechanism to a balanced gain-loss mechanism. (2) It develops an ecological compensation accounting framework that incorporates pollution control and health losses. By introducing these two key categories of negative external costs and focusing on air pollution and water pollution-induced cancer risks, the framework systematically quantifies economic losses from mortality, medical expenses, and productivity reductions, while incorporating gaps in pollution control expenditures. This approach renders the social costs of environmental pollution explicit and improves the accuracy of ecological compensation calculations. (3) It reveals the spatial heterogeneity of ecological compensation responsibilities in trans-provincial watersheds. Focusing on the typical asymmetric structure of high-intensity upstream pollution and high-level downstream protection, and using the Anhui and Henan sections of the Huaihe River Basin as a case study, the analysis expands the spatial scope of ecological compensation research and provides empirical support for clarifying cross-provincial

ecological protection responsibilities and formulating differentiated compensation policies.

Materials and Methods

Study Area

The Huaihe River Basin is located between the Yangtze River and the Yellow River, is rich in mineral, agricultural, and industrial resources, and has obvious locational advantages. It is an important water transportation hub and traditional grain base in China, and one of the regions with the greatest socio-economic potential [22]. The Huaihe River Basin faces increasingly severe water scarcity problems. The average annual total water resources in the basin are 79.4 billion cubic meters, but the total usable water resources are only 44.5 billion cubic meters, and the per capita water resources are about one-fifth of the national average. Meanwhile, the discharge of wastewater and sewage is increasing year by year, seriously affecting water quality and the ecological environment. In years such as 2000, 2004, 2007, 2008, and 2010, major water pollution incidents occurred multiple times in the Huaihe River Basin, putting tremendous pressure on the local ecosystem and residents' health. The water resources of the Huaihe River Basin account for only 3% of the nation's total, yet they support a large population and economic scale: 12% of the nation's population, 11% of its arable land, and 9% of its GDP depend on it, while the region also contributes 16.7% of the nation's grain production. The Henan section is located in the upper reaches of the Huaihe River Basin, and the Anhui section is in the middle reaches, including 9 cities in Anhui and 9 cities in Henan, accounting for 67.5% of the total area of the Huaihe River Basin. Therefore, calculating the ecological compensation amount for the Anhui and Henan sections of the Huaihe River Basin, clarifying regional differences, and studying their dynamic trends are conducive to promoting the healthy ecological development of the Huaihe River Basin.

Data Sources

This study focuses on the Anhui section (9 cities) and Henan section (9 cities) of the Huaihe River Basin as the research area for calculation and analysis. The data employed cover three key categories: land use, economic and social indicators, and basic geographical information. Specifically, the land use data for the Anhui and Henan sections of the Huaihe River Basin are sourced from the CLCD land use data provided by Wuhan University, China. Statistical data on the economic, social, and environmental sectors were obtained from publications including the Anhui Statistical Yearbook, Henan Statistical Yearbook, Anhui Statistical Communique, and Henan Statistical Communique. Basic geographic data, including administrative divisions, geographic coordinates, water system distribution, etc., are sourced from the 1:1 million National Fundamental Geographic Information Database provided by the National Geomatics Center of China.

Methods

Ecological Compensation Theoretical Framework

The essence of the ecological compensation mechanism lies in constructing a two-way regulation system of "incentive-constraint". On one hand, it incentivizes ecological protection behaviors through economic compensation; on the other hand, it constrains environmentally damaging activities through punitive measures. Under this framework, ecological compensation should clarify the division of ecological damage responsibility and beneficiary responsibility, ensuring a balance between compensation and punishment. Combining this concept and referring to the ecological compensation theoretical models constructed by Xu Qiyang et al. and Pagiola et al. [23, 24], this study develops a theoretical framework for ecological compensation based on ecological value accounting. It conducts a comparative analysis of two ecological compensation theoretical models: one considering only pollution control, and the other integrating both pollution control and health losses, as shown in Fig. 1.

The left side of Fig. 1 constructs an ecological compensation assessment model incorporating pollution control elements. This model determines the ecological-economic status by quantitatively analyzing the difference between the regional ESV and pollution control costs. Specifically, when (ESV - Theoretical Control Cost + Actual Control Input) > 0 (as shown by City A on the left side of Fig. 1), it indicates that the area is in an ecological surplus state, making a net contribution to national ecological construction; conversely, when this value <0 (as shown by City B on the left side of Fig. 1), it reflects that the area has an ecological deficit, and its development consumes cross-regional ecological capital.

The right side of Fig. 1 shows the ecological compensation theoretical model incorporating pollution control and health loss. Against the backdrop of rapid urbanization and industrialization, ecological issues such as environmental pollution and resource depletion have become increasingly severe. These problems degrade the quality of human living environments, trigger a range of health issues, and result in increasingly significant health losses. The model adopts a four-step accounting method: (1) Calculate ESV, (2) Deduct the cost of pollutant emissions, (3) Add actual control input, (4) Subtract health damage costs. The positive or negative value of the final accounting result reflects the net contribution status of the regional eco-economy. If (Ecosystem Service Value - Theoretical Pollution Control Input + Actual Pollution Control Input - Health

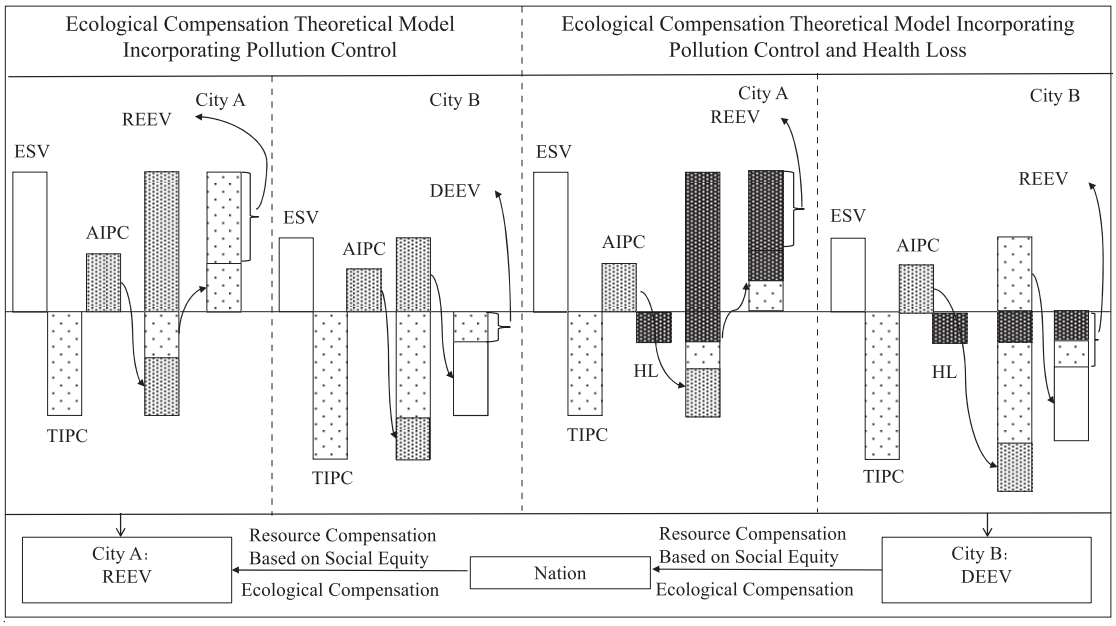


Fig. 1. Theoretical framework for ecological compensation. AIPC: Actual Investment in Pollution Control, TIPC: Theoretical Investment in Pollution Control, REEV: Residual Ecology Economic Value, DEEV: Deficit in Ecology Economic Value.

Loss) > 0, the area is in an ecological-economic value surplus state (as shown by City A on the right side of Fig. 1). Conversely, when the result is negative, the area is in an ecological-economic value deficit state (as shown by City B on the right side of Fig. 1).

Ecosystem Service Value

This study follows the research path of "international theory-latest progress-regional application". First, it draws on Costanza's basic theory of ESV [25]. It then references recent related research results [26-28]. Finally, based on the equivalent factor system developed by Xie Gaodi et al., it establishes ESV assessment standards specific to the Huaihe River Basin [29]. To eliminate human-induced biases, the value of one unit equivalent factor is defined as the economic value of the average annual yield from 1/7 of a hectare (hm²) of farmland, with the calculation formula adapted from the research of Zhou Yaping et al. After adjustment based on the economic value of major agricultural products such as rice and wheat, the ecosystem service value equivalents for Anhui and Henan provinces show significant differences: Anhui Province (2038.23 yuan/hm²) > Henan Province (1768.17 yuan/hm²).

Health Loss
Estimation of Health Loss from Air Pollution

Scholars have employed a range of approaches to assess the economic value of health damages caused by environmental pollution. With the acceleration of industrialisation in China and the increasing frequency of extreme weather events, air pollution has attracted growing attention. Among various atmospheric pollutants, particulate matter exerts the most pronounced adverse effects on human health. According to the 2020 Bulletin on China's Ecological and Environmental Status, days on which $PM_{2.5}$ was identified as the primary pollutant accounted for as much as 77.7% of days classified as heavily polluted or worse [30, 31]. Moreover, among all days exceeding national air quality standards, $PM_{2.5}$ ranked first among major pollutants, accounting for 51.0% of such occurrences [32]. These figures indicate that $PM_{2.5}$ remains a critical determinant of air quality and public health in China. Accordingly, this study selects $PM_{2.5}$ as the core air pollution indicator for quantifying health losses attributable to atmospheric pollution.

(1) Economic Loss from Premature Death due to Air Pollution

Considering that China's air quality monitoring network mainly covers urban areas and air pollution has a more significant impact on urban air quality, this study defines the urban population as the pollution-exposed population for health risk assessment. Referring to existing research methods, the formula for calculating excess deaths related to air pollution is as follows [17]:

$$Q_{ed} = 10^{-5} \times (k_p - k_t) D_e \quad (1)$$

$$k_p = k_t \times RR \quad (2)$$

$$0Q_{ed} = 10 - 5 \times (\frac{RR-1}{RR}) F_p D_e \quad (3)$$

Where Q_{ed} is the number of premature deaths from all causes under the current air pollution level, k_p is the all-cause mortality rate under the current air pollution level, f_t is the all-cause mortality rate under clean air

concentration, RR is the relative risk attribution ratio for all causes attributable to air pollution, and D_e is the urban exposed population. RR has a linear or logarithmic relationship with air pollution concentration. This study selects the linear model for estimation, calculated as follows:

$$RR = \exp[\beta(C - C_0)] \quad (4)$$

Where β is the exposure-response relationship coefficient. When β is very small, RR = 1+β(C-C_0). According to relevant scholars' research, under the 95% confidence interval, the mean exposure-response coefficient for $PM_{2.5}$ and related diseases is 0.00296; C and C_0 are the pollutant concentrations in the study area and the background concentration, respectively; C_0 is taken as 15 μg/m³ based on China's Grade I air quality standard.

Economic loss from premature death due to air pollution:

$$EC_{a1} = P_{ed} \times HC_{mu} = P_{ed} \times \sum_{i=1}^{t} GDP_{pic}^{pv} \quad (5)$$

Where t is the average loss of life years for all-cause premature death caused by air pollution. Based on mortality rates from diseases related to air pollution across different age groups, the average value of t is taken as 18 years; HC_{mu} is the per capita human capital, in 10,000 yuan/person; GDP^{pv}_{pic} is the per capita GDP in the i-th year.

(2) Health Loss from Related Diseases due to Air Pollution

The air pollution health economic loss assessment system includes three dimensions: 1) Outpatient costs, combining internal medicine and pediatric outpatient fees (assuming consistent outpatient composition ratios across provinces) and single-day work loss; 2) Hospitalization costs, covering medical expenses, patient work loss, and work loss for one accompanying person (calculated based on hospitalization days); 3) Chronic disease disability loss, mainly considering the reduced labor capacity of chronic bronchitis patients. The formula for calculating the incidence of related diseases is as follows:

$$P_{\text{ed}} = \sum_{i=1}^{n} f_{pi} \frac{\Delta c_i \times \beta/100}{1+\Delta c_i \times \beta/100} \quad (6)$$

Where f_{pi} is the number of illness cases or hospitalizations under the current air pollution level; β is the regression coefficient, representing the percentage impact of unit pollutant concentration change on health hazard i; ΔC_i is the difference between the actual pollutant concentration and the health hazard pollutant concentration threshold (here, the WHO-recommended pollutant concentration threshold of 15 μg/m³ is used).

Outpatient Expenses = Number of Outpatient Visits × Average Outpatient Expenses per Person

Medical Expenses = Number of Sick Person – Times × Average Medical Expenses per Person

Hospitalization Related Work Loss Cost = Number of Hospitalizations × Length of Hospital Stay Days × Daily Average GDP

Work Loss Cost of In-Hospital Caregiving = Number of Hospitalizations × Length of Hospital Stay (Days) × Daily Average GDP

Chronic bronchitis has a long course, severely damages health, and greatly affects patients' labor capacity. The disability weight for chronic bronchitis is 40%, meaning 40% of per capita GDP is taken as the disability loss due to chronic bronchitis; according to relevant scholars' research, the baseline prevalence of chronic bronchitis is taken as 6.3‰. Therefore, the economic loss caused by disability from chronic bronchitis incidence triggered by air pollution can be estimated.

$$EC_{a2} = \gamma \times P_{\text{ed}} \times HC_{mu} = \gamma \times P_{\text{ed}} \times \sum_{i=1}^{t} GDP_{\text{pci}}^{pv} \quad (7)$$

Where t is the average loss of life years for premature death from chronic bronchitis caused by air pollution; typically, the average course of chronic bronchitis is 23 years. γ is the disability loss coefficient for chronic bronchitis; HC_{mu} is the per capita human capital of the urban population.

Estimation of Health Loss from Water Pollution

(1) Health Value Loss from Premature Death due to Water Pollution

Five types of cancer, namely gastric cancer, liver cancer, colorectal cancer, oesophageal cancer and bladder cancer, were selected for analysis. According to the Research Report on the Indicator System for Urban Environmental Sustainability in China, 25% of the mortality associated with these five cancers is attributable to water pollution. In addition, water pollution contributes to economic losses through its role in inducing a range of related diseases. Therefore, in addition to the five cancers listed above, this study also incorporates three waterborne infectious diseases, specifically typhoid fever, dysentery, and viral hepatitis. It should be noted that data from the National Central Cancer Registry of China are subject to a reporting lag, which is generally about three years. Nevertheless, cancer incidence rates have shown limited variation in recent years. Consequently, this temporal delay is unlikely to exert a substantial influence on the robustness of the results [29].

$$Total\ PYLL\ (Person/Years) = \sum (EY - DY_i + 0.5) \times DN_i$$
$$Average\ PYLL\ per\ Case\ (Years\ per\ Case) = PYLL(Total)/\sum DN_i \quad (8)$$

Where EY is the average life expectancy, with data sourced from the 2020 population census; DY_i is the median age of death for a certain disease; DN_i is the number of deaths from that disease in that age group. Therefore, the formula for calculating premature death loss is:

$$\text{H1} = \text{PYLL} \times \text{Per Capita GDP} \quad (9)$$

(2) Health Value Loss from Related Diseases due to Water Pollution

Medical Expenses for Related Diseases H2 = Number of Patients × Average Medical Expenses per Patient

Patient Work Loss H3 = Number of Inpatients × Average Work Loss Days per Patient × Daily Average Income Caregiver's Care Loss Cost H4 = Number of Inpatients × Work Loss Days per Patient × Daily Average Income

Pollution Control

(1) Theoretical pollution control cost. Environmental pollution mainly comes from wastewater, waste gas, and solid waste [33]. According to the externality characteristics of ecological compensation, wastewater and waste gas have strong spatial externalities, mainly reflected in their diffusion to other areas through the movement of the atmosphere and rivers. The treatment methods for solid waste are more complex; local landfilling not only causes serious damage to the local soil environment but also seriously threatens regional sustainable development. Considering data availability, this paper selects the treatment costs of urban "three wastes" as the basis for calculating the pollution control amount for each city. The specific formula is as follows:

$$C_i = A_i F_{ai} + W_i F_{wi} + S_i F_{si} \quad (10)$$

Where C_i is the theoretical pollution control cost for a city; A_i is the concentrations of sulphur dioxide and $PM_{2.5}$ in the ambient air pollution of city i, in 10^4 t; W_i is the wastewater discharge of city i, in 10^4 t; S_i is the solid waste discharge of city i, yuan/t; F_{ai} is the unit treatment cost of sulphur dioxide and $PM_{2.5}$ for city i, yuan/t; F_{wi} is the unit treatment cost of wastewater for city i, yuan/10^4 t; F_{si} is the unit treatment cost of solid waste for city i, yuan/10^4 t.

(2) Actual Pollution Control Cost. Data are sourced from the pollution control costs in the statistical yearbooks of each city.

Results

Health Loss Analysis

To elucidate the temporal evolution and spatial distribution of health losses attributable to environmental pollution, this study systematically assesses health losses across 18 prefecture-level cities in the Anhui and Henan sections of the Huaihe River Basin from 2010 to 2024 (Fig. 2). The findings reveal that, overall, Zhengzhou and Hefei exhibit high health loss values, with Zhengzhou's total loss increasing from 16.11 billion yuan in 2010 to 27.69 billion yuan in 2024, reflecting a growth rate of 71.9%. Similarly, Hefei's losses rose from 7.21 billion yuan to 13.09 billion yuan, with the most significant increase occurring between 2010 and 2016. Cities such as Huaibei and Lu'an maintained relatively low levels of health loss throughout the study period. Notably, Xinyang's health loss value plummeted from 8.50 billion yuan to 3.30 billion yuan, marking it as the only city in both provinces to achieve a halving of its health losses. In terms of pollution source-driven characteristics, health losses from air pollution have undergone a shift from "rapid expansion" to "controlled fluctuation". Xinyang's air pollution-related health loss decreased sharply from 5.25 billion yuan in 2010 to 1.27 billion yuan in 2024, a reduction of 75.9%, highlighting the significant impact of environmental regulation policies in certain areas. However, in cities such as Zhengzhou, Xuchang, and Zhoukou in the Henan section, while the growth rate of air pollution losses slowed after 2016, these losses have remained at a high plateau, which can be closely linked to the region's reliance on energy production and heavy industries within its industrial structure. Water pollution-related health losses, on the other hand, have shown a steady upward trend. Both Zhengzhou and Hefei reported an increase in water-related health losses of over 80%, with values reaching 9.85 billion yuan and 8.35 billion yuan, respectively, by 2024. Notably, cities in the Anhui section, such as Fuyang and Chuzhou, have experienced particularly rapid increases in water pollution-related losses, indicating that, as population size expands and urbanisation accelerates, the capacity of the water environment is under ongoing stress. From an inter-provincial perspective, the average health losses in the Henan section are significantly higher than in the Anhui section. Henan not only has Zhengzhou, the core city with exceptionally high health losses, but also cities such as Zhoukou, Shangqiu, and Xuchang, where the total health loss exceeds 8 billion yuan by 2024. In contrast, apart from Hefei, most cities in the Anhui section, such as Bozhou, Huainan, and Huaibei, still experience losses in the range of 2-4 billion yuan. These provincial differences are primarily driven by the higher population base and heavier resource-dependent industrial burdens in Henan.

Pollution Control Costs Analysis

Based on the unit treatment cost of pollutants as outlined in "A Study on the Cost Calculation Method for Environmental Pollution", the pollutant treatment costs for 18 prefecture-level cities were calculated by substituting the values into Formula (9), as shown in Table 1. The results indicate that, from 2010 to 2024, the pollution control disparities in most cities shifted from a

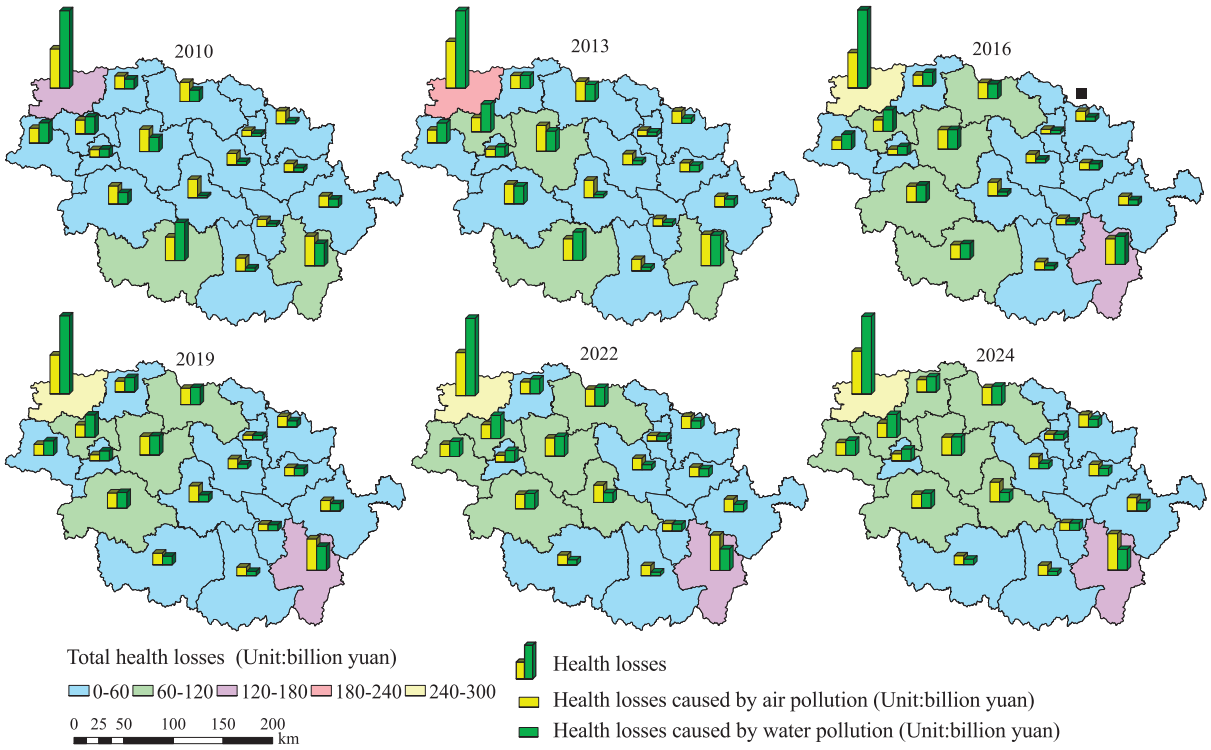


Fig. 2. Health losses in the Anhui and Henan sections of the Huaihe River Basin, 2010-2024.

Table 1. Theoretical and actual pollution control costs in the Anhui and Henan sections of the Huaihe River Basin.

City	Theoretical						Actual					
	2010	2013	2016	2019	2022	2024	2010	2013	2016	2019	2022	2024
Hefei	6.22	8.67	8.26	10.37	12.68	14.68	1.82	3.16	4.62	5.16	5.80	6.39
Fuyang	1.45	1.90	2.30	2.46	2.65	3.01	0.48	0.85	1.50	2.49	3.48	3.89
Lu'an	1.53	1.67	2.15	3.49	4.35	4.62	0.56	0.82	1.36	1.90	2.37	2.68
Suzhou	1.67	1.85	1.72	2.16	2.48	2.55	0.59	0.87	1.25	1.40	1.56	1.75
Huainan	7.54	8.26	8.86	8.26	8.70	9.01	2.97	3.88	4.58	4.83	5.49	5.64
Huaibei	2.80	3.55	3.68	3.78	3.82	4.27	1.27	1.79	2.33	2.35	2.56	3.00
Chuzhou	0.82	1.36	1.56	2.01	2.55	2.70	0.36	0.68	1.20	1.70	2.43	2.64
Bengbu	2.41	2.52	2.68	2.49	2.96	3.10	0.83	1.15	1.46	1.53	1.61	1.76
Bozhou	0.90	1.05	1.35	1.86	2.25	2.94	0.39	0.52	0.82	1.03	1.34	1.52
Anhui Section	25.34	30.83	32.58	36.87	42.45	46.89	9.28	13.71	19.11	22.37	26.64	29.27
Xinyang	1.74	1.72	1.72	1.95	2.27	2.59	1.93	1.94	2.11	2.49	2.99	3.16
Zhumadian	1.44	1.54	1.65	1.53	1.51	1.55	1.22	1.65	2.00	2.24	2.46	2.51
Zhoukou	0.34	0.52	0.79	1.27	1.27	1.34	0.42	0.80	1.12	1.28	1.43	1.52
Shangqiu	1.08	1.56	2.35	1.46	1.35	1.42	1.23	2.46	2.90	3.10	3.22	3.33
Luohe	1.72	1.50	1.43	1.30	1.28	1.36	1.42	1.46	1.49	1.52	1.56	1.57
Pingdingshan	5.50	6.59	6.35	5.86	5.65	5.21	5.38	6.86	8.75	8.98	9.29	9.32
Xuchang	1.65	1.55	1.51	1.48	1.41	1.36	1.42	1.85	2.27	2.46	2.53	2.62
Zhengzhou	7.21	10.27	10.55	8.68	8.65	8.35	6.65	8.25	10.79	11.49	11.80	12.33
Kaifeng	1.94	1.84	1.83	1.90	1.95	1.90	1.71	1.93	2.57	2.65	2.68	2.80
Henan Section	22.62	27.09	28.19	25.41	25.35	25.09	21.37	27.20	33.98	36.20	37.95	39.15

"passive deficit" model to a "proactive surplus" model. In Zhengzhou, the acceleration of industrialisation between 2013 and 2019 caused a sharp increase in theoretical costs. However, with increased environmental investment, by 2024, the actual investment exceeded the theoretical cost by 398 million yuan, resulting in a reversal of treatment efficiency. Hefei, on the other hand, exhibited a positive surplus in the early stages of pollution control, but by 2024, the pressure to improve governance led to an expanded gap, which reached -829 million yuan. From a temporal evolution perspective, between 2010 and 2013, Xinyang, Zhoukou, and Zhumadian showed only slight fluctuations in their governance disparities, maintaining a balanced supply and demand at a low level. However, after 2016, the governance gap in cities like Fuyang and Chuzhou rapidly narrowed and shifted from negative to positive. Fuyang, in particular, achieved a governance surplus of 8.8 million yuan by 2024, becoming one of the cities in the Anhui section with the most ample investment in pollution control. In contrast, cities such as Lu'an and Bozhou experienced a rebound in the governance gap in the later stages of the study, primarily due to the rapid increase in theoretical costs driven by the accelerated urbanisation process. At the provincial level, the governance disparities in Henan cities exhibited greater robustness after 2019. Cities such as Shangqiu, Xuchang, and Kaifeng demonstrated a high degree of alignment between actual investments and theoretical costs, with the disparity values remaining locked in a narrow range for an extended period. Conversely, cities in the Anhui section displayed more variability, with high-growth cities (such as Hefei and Fuyang) coexisting with pressure-type cities (such as Lu'an).

Variation Characteristics and Evolutionary Trends Before and After the Adjustment of Ecological Compensation Amounts

To systematically elucidate the differences in ecological compensation amounts before and after the inclusion of environmental costs, and their evolving characteristics, Table 2 presents the adjusted ecological compensation amounts for each city from 2010 to 2024. Fig. 3 further illustrates the evolution of the compensation nature across the study area's cities, categorising them into ecological compensation zones and ecological payment zones.

As shown in Table 2, prior to adjustment, all cities exhibited positive ecological asset surpluses. In 2010, the total original compensation for the 18 cities in the study area amounted to 286.65 billion yuan, slightly decreasing to 269.55 billion yuan by 2024. Among these, cities such as Lu'an, Hefei,

Table 2. Average ecological compensation by municipality, 2010-2024 (billion yuan)

Area	Ecological compensation amount before revision						Ecological compensation amount after revision					
	2010	2013	2016	2019	2022	2024	2010	2013	2016	2019	2022	2024
Hefei	360.25	358.45	361.87	358.97	355.24	354.32	283.73	255.37	237.86	227.46	220.47	215.16
Fuyang	103.09	106.87	111.34	105.32	97.48	94.36	73.35	73.77	71.39	53.01	37.06	29.00
Lu'an	476.25	474.98	480.36	499.26	471.34	470.37	452.40	449.45	451.97	468.03	438.09	435.98
Suzhou	91.78	89.56	90.89	91.66	89.23	87.65	68.59	60.75	58.76	52.40	44.11	40.06
Huainan	154.47	154.71	159.61	156.49	150.26	151.26	136.44	132.03	132.87	124.60	114.58	112.72
Huaibei	32.12	30.26	32.59	33.89	31.41	29.87	17.93	12.71	13.09	11.42	6.41	2.23
Chuzhou	349.94	347.34	356.37	353.48	349.21	347.56	322.49	317.62	324.00	311.88	303.39	297.86
Bengbu	145.19	143.01	148.36	152.04	138.64	134.71	125.88	117.28	117.78	115.35	97.82	90.97
Bozhou	73.05	70.94	73.89	72.49	71.00	71.45	51.62	46.58	45.71	38.20	32.94	30.04
Xinyang	352.25	349.64	358.64	355.26	354.78	350.01	267.43	271.42	292.65	308.92	321.24	317.57
Zhumadian	175.63	172.54	173.17	171.04	171.01	167.2	134.40	113.18	99.82	101.70	105.63	102.93
Zhoukou	91.62	88.12	90.71	89.45	90.22	87.91	41.65	16.04	3.78	2.72	4.91	4.64
Shangqiu	80.55	77.69	79.87	78.88	76.14	75.02	38.73	21.23	11.37	4.10	**-2.47**	**-5.42**
Luohe	20.87	18.99	21.69	22.41	20.03	18.31	**-1.48**	**-8.99**	**-9.89**	**-14.15**	**-20.72**	**-25.17**
Pingdingshan	131.89	128.67	131.87	130.09	130.59	126.27	83.36	77.20	79.61	74.88	72.98	66.38
Xuchang	40.15	37.51	40.26	39.58	38.55	36.32	**-3.01**	**-28.68**	**-33.04**	**-38.98**	**-43.80**	**-47.83**
Zhengzhou	99.56	96.47	98.45	97.66	96.36	94.79	**-62.12**	**-100.98**	**-154.37**	**-165.24**	**-170.18**	**-178.14**
Kaifeng	52.24	49.34	51.49	51.88	52.64	48.14	20.48	8.06	**-2.44**	**-4.86**	**-6.29**	**-15.33**

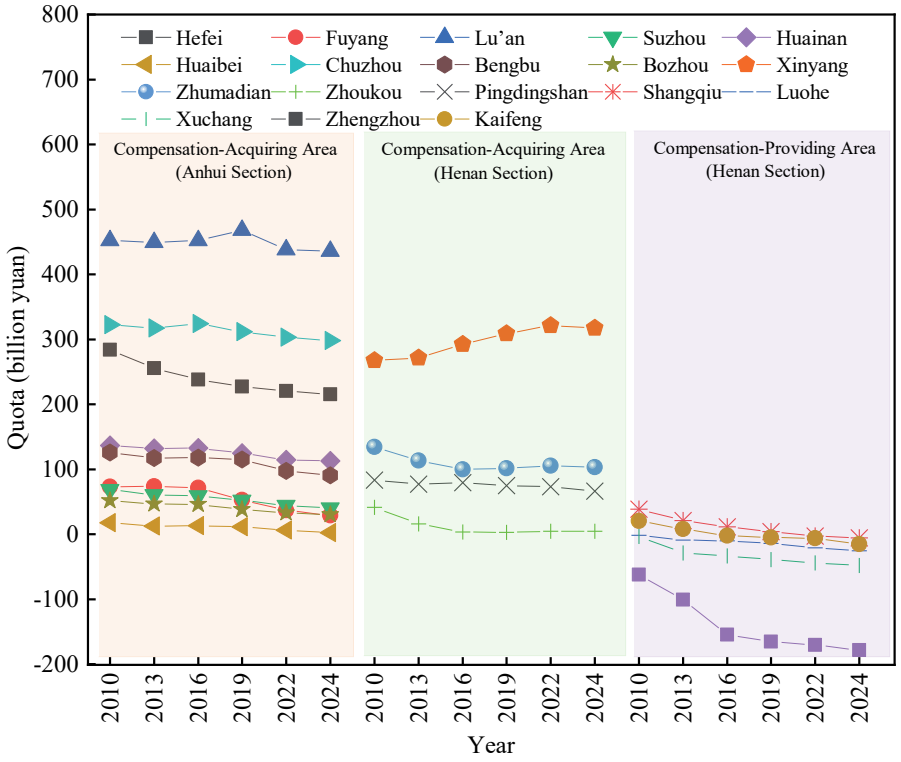


Fig. 3. Trends in the amount of ecological compensation.

Chuzhou, and Xinyang consistently maintained leading positions in terms of original compensation value, reaching 47.04 billion yuan, 35.43 billion yuan, 34.76 billion yuan, and 35.00 billion yuan, respectively, by 2024. During this phase, the compensation logic relied heavily on natural endowments and failed to reflect the negative environmental outputs resulting from economic activities. After the introduction of pollution control costs and health loss adjustments, the overall compensation level in the study area tightened significantly. The average compensation amount decreased sharply from 10.76 billion yuan in 2010 to 7.45 billion yuan in 2024, reflecting the offsetting effect of environmental degradation on ecosystem

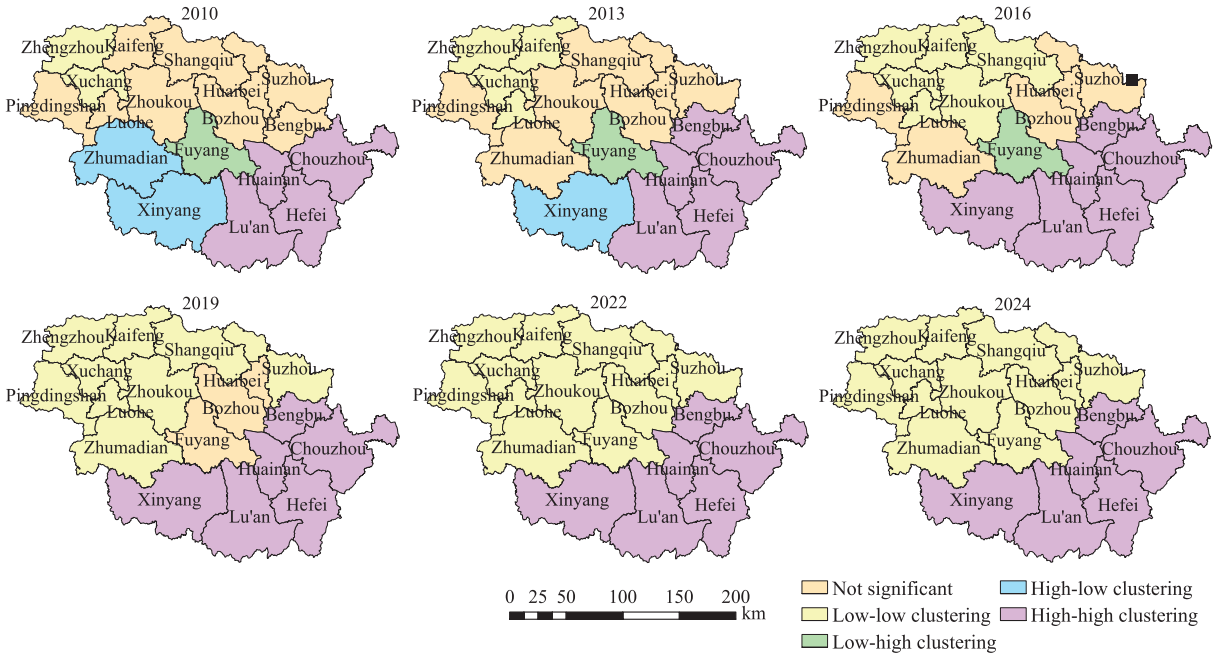


Fig. 4. Cluster distribution of ecological compensation amount between the Anhui and Henan sections of the Huaihe River Basin.

service benefits. Between 2010 and 2024, Hefei saw a reduction of 39.3% in its ecological compensation amount. Cities such as Fuyang, Suzhou, and Bozhou experienced declines in adjusted compensation ranging from 60% to 70% compared to the original values. The most significant change was observed in several cities where the compensation nature reversed from "positive" to "negative". Zhengzhou, Xuchang, and Luohe all showed negative values as early as 2010, with their deficits expanding each year. More notably, Shangqiu and Kaifeng, which had surpluses of 3.87 billion yuan and 2.05 billion yuan in 2010, respectively, crossed the break-even point between 2015 and 2022, falling into deficits, and by 2024, their compensation amounts had decreased to -0.54 billion yuan and -1.53 billion yuan, respectively. In contrast, Xinyang became the only city in the study area to experience countercyclical growth, with its adjusted compensation amount steadily increasing from 26.74 billion yuan to 31.76 billion yuan, primarily due to a significant reduction in air pollution-related health losses and increased governance investment, enabling its ecological value to achieve net growth after environmental offsets.

Fig. 3 further reveals the spatial evolution of the transformation from "compensation" to 'payment". During the study period, Zhengzhou, Xuchang, and Luohe remained in the ecological payment zone, while Shangqiu and Kaifeng underwent a transition from the compensation zone to the payment zone. Zhengzhou, as the regional core, saw its adjusted compensation amount drop continuously from -6.21 billion yuan in 2010 to -17.81 billion yuan in 2024, with the deficit expanding by 186.8%, making it the most typical ecological compensation payment source in the basin. Xuchang and Luohe, similarly, due to the concentration of high-energy-consuming industries, maintained negative compensation amounts for an extended period, with values reaching -4.78 billion yuan and -2.52 billion yuan by 2024, respectively. This transformation highlights the deep coupling of high economic concentration and

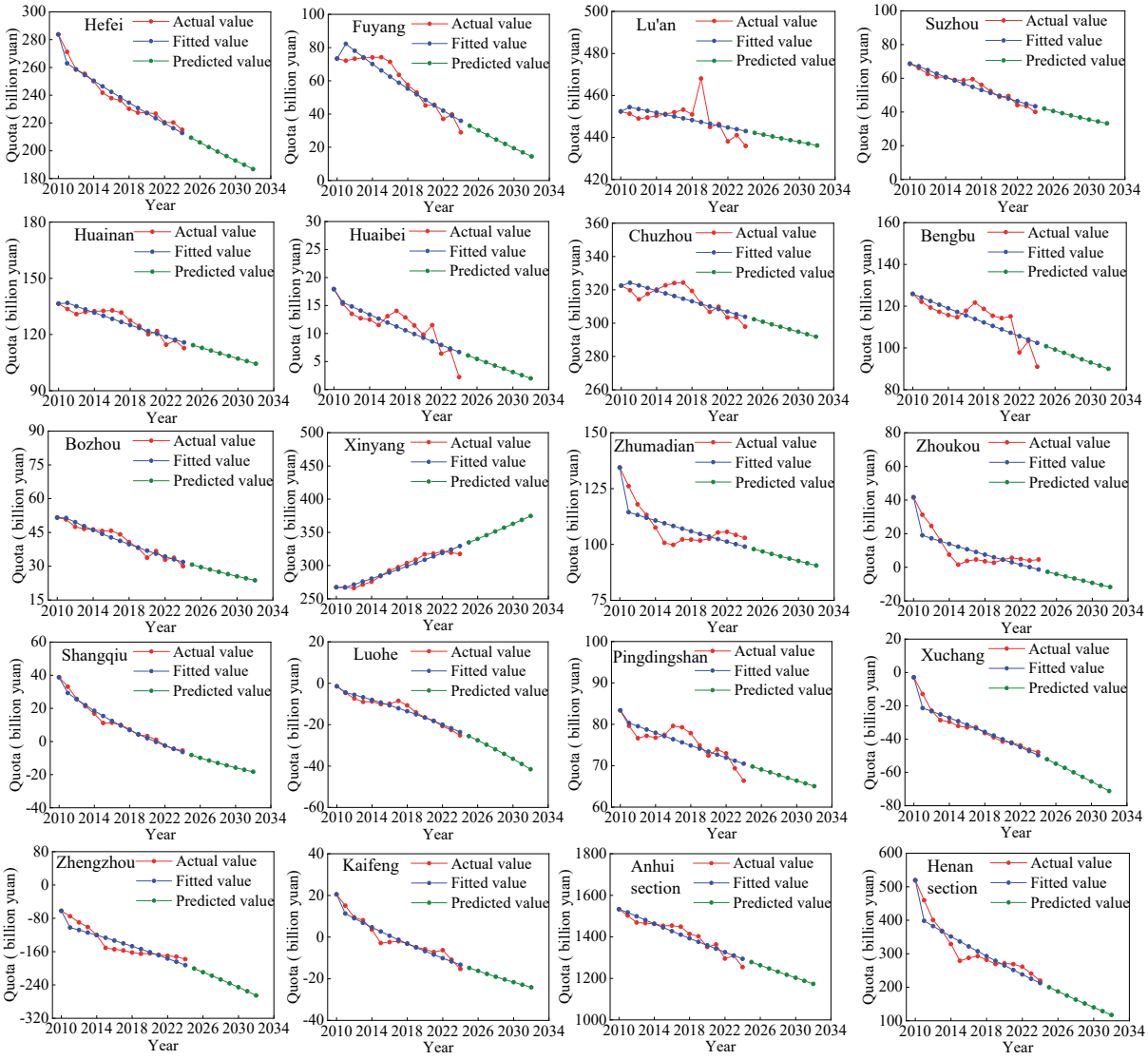


Fig. 5. Prediction of ecological compensation amounts for the Anhui and Henan sections of the Huaihe River Basin.

high environmental consumption in the Zhengzhou metropolitan core. Shangqiu and Kaifeng's ecological capital surpluses, accumulated between 2015 and 2022, were exhausted and turned negative, with Kaifeng's deficit reaching -1.53 billion yuan by 2024. This suggests that as industrial spillover effects and population aggregation increased, the share of environmental losses and governance costs in the compensation calculation gradually expanded, ultimately leading to the depletion of ecological assets and forcing these cities to shift from compensation recipients to bearers of environmental responsibility.

Spatial Changes in Ecological Compensation Amount

To objectively assess the spatial heterogeneity and evolutionary patterns of ecological compensation during the study period, this research employs a univariate spatial autocorrelation model to analyse the adjusted compensation amounts. The global Moran's I indices for the years 2010, 2013, 2016, 2019, 2022, and 2024 were 0.448, 0.385, 0.333, 0.346, 0.378, and 0.392, respectively, all passing the 1% significance test, indicating a significant positive spatial autocorrelation of ecological compensation amounts in the study area. The Moran's I index displayed a fluctuating trend of "first decreasing, then increasing", reflecting an evolutionary characteristic in which the intensity of spatial clustering weakened at certain stages before being reinforced.

As shown in Fig. 4, from 2010 to 2016, the spatial clustering pattern was primarily characterised by point distributions. In 2010, the H-H clusters were concentrated in ecological core areas such as Lu'an, Hefei, and Chuzhou, while the L-L clusters appeared only in Zhengzhou and Xuchang. 2013 was a pivotal year, with Bengbu transitioning from a non-significant zone to an H-H cluster, marking the preliminary integration of high-value areas in the Anhui section. Kaifeng and Luohe, on the other hand, displayed L-L clusters, with a trend of declining values spreading across the Central Plains urban agglomeration. In 2016, this trend expanded across regions. Xinyang shifted from an early H-L pattern to an H-H cluster, forming a stable ecological barrier in the south, while Zhoukou and Shangqiu transitioned into L-L clusters, indicating the emergence of contiguous areas of environmental degradation in Eastern Henan. From 2016 to 2022, the expansion of L-L clusters permeated from the Henan section to the Anhui section and intensified. Between 2016 and 2019, the number of L-L areas increased significantly, with cities such as Zhumadian, Pingdingshan, and Suzhou (Anhui section) transitioning into L-L clusters, reflecting the spatial spillover effects of environmental pollution and governance deficits. From 2019 to 2022, this trend further expanded, with previously non-significant cities like Huaibei and Bozhou evolving into L-L clusters, indicating that cities in the northern and central regions, under the dual pressure of environmental health risks and resource consumption, had shifted from individual disparities to systemic regional low-value areas. From 2022 to 2024, the spatial pattern exhibited strong stability. With the exception of Xinyang, the entire Henan section and three cities in the northern Anhui section remained in the L-L cluster zone. Meanwhile, the southern H-H clusters (Lu'an, Hefei, Xinyang, etc.) consolidated their position as core ecological compensation output sources across the entire basin due to favourable natural endowments and ecological governance investments. The spatial pattern of "high-value aggregation and low-value contiguous areas" from south to north in both Henan and Anhui provinces signals the gradual stabilisation of regional ecological compensation's spatial homogenisation.

Prediction and Analysis of Ecological Compensation Amounts

Using the Grey Prediction Model (GM(1,1)), the ecological compensation amounts for the next eight years were simulated, with results indicating that the model's average accuracy exceeds 95%, as shown in Fig. 5. The Anhui section exhibits a "high-level gradual decline" trend. From 2010 to 2024, the total compensation in the Anhui section decreased from 153.24 billion yuan to 125.40 billion yuan. The ecological compensation amount for Lu'an is expected to stabilise at 43.62 billion yuan. In contrast, Hefei's compensation amount will continue to shrink from 21.52 billion yuan in 2024 to 18.68 billion yuan, reflecting the compression effect of economic expansion in the provincial capital urban agglomeration on ecological value. Fuyang's predicted decline is similarly steep, expected to fall from 2.899 billion yuan to 1.45 billion yuan. Within the Henan section, a severe "polarization" is evident. Xinyang is the only city in the study area projected to experience countercyclical growth, with its compensation amount steadily increasing from 26.74 billion yuan to 31.76 billion yuan, and the forecast trend indicates that it may surpass 37.47 billion yuan by 2034, consolidating its position as a core recipient of compensation in the basin. In contrast, Zhengzhou, a typical ecological payment zone, is expected to see its deficit further expand from -17.81 billion yuan to -26.52 billion yuan. Cities such as Xuchang, Kaifeng, Shangqiu, and Luohe also exhibit an expanding deficit trend, with Kaifeng and Shangqiu, after crossing the break-even point, projected to have their deficits expand to -2.41 billion yuan and -1.83 billion yuan, respectively. Overall, the total compensation in the Anhui section is expected to gradually converge from 125.40 billion yuan to 117.32 billion yuan, while the total compensation in the Henan section will decrease from 21.96 billion yuan to 11.72 billion yuan. This "stability in the south and decline in the north" spatial pattern suggests that the risk of ecological benefit imbalance is increasing. If deficit cities fail to implement effective governance, it could

lead to an imbalance in the ecological compensation pressure within the basin.

Discussion

Building upon the conventional framework for calculating ecological compensation amounts, this study draws on ecological capital theory to integrate ecosystem service values with health losses and pollution abatement costs arising from pollutant emissions, thereby shifting the assessment from gross ecological compensation to net ecological compensation. Previous studies have adopted different principles for determining ecological compensation levels. Approaches proposed by Shen Juqin et al. and He Huishuang et al. rely primarily on ecosystem service value [34, 35], whereas difference-based methods developed by Liu Chunla et al. and Pan Jinghu et al. subtract actual pollution control expenditures from these values [36, 37]. By contrast, the accounting framework proposed in this study more directly captures the economic logic of pollution externality internalisation. Simultaneously, by incorporating both health losses and governance costs, the present framework provides a more comprehensive accounting from the dual perspectives of social welfare and fiscal expenditure, thereby offering a complementary enhancement in both spatial resolution and accounting dimension.

Specifically, affluent urban centres such as Zhengzhou and Hefei have experienced a continuous escalation in health-related damages. In Zhengzhou, the valuation of health losses rose from 16.11 billion Yuan in 2010 to 27.69 billion Yuan by 2024, representing a substantial increase of 71.9%. Conversely, Xinyang witnessed a significant attenuation in health damages, attributable to the implementation of effective environmental regulatory frameworks. This divergent trend is inextricably linked to the degree of industrialisation and population density within these cities, reflecting the deleterious impact of intensive industrial agglomeration on public health and corroborating the findings of Zhai et al. [38] regarding the health impacts of urban environmental pollution in China. Regarding environmental remediation, a transition from "passive deficit" to "active surplus" was observed across most municipalities. Zhengzhou, in particular, saw a surge in theoretical remediation requirements between 2013 and 2019; however, as environmental investment intensified, actual expenditures progressively exceeded theoretical costs, thereby achieving a reversal in governance efficacy. This alignment with the research of Fan et al. [39] on the enhancement of governance capacity underscores the synergistic role of fiscal investment and green technological support. Following the integration of health damages and remediation costs, the functional roles within the ecological compensation mechanism underwent a profound reconfiguration. Cities such as Zhengzhou and Xuchang transitioned from ecological recipients to payers, as their adjusted compensation values consistently entered negative territory. Zhengzhou's deficit expanded from -6.21 billion Yuan in 2010 to -17.81 billion Yuan in 2024, an escalation of 186.8%. This trend corroborates the theoretical framework of Luo et al. [40], suggesting that economically developed yet pollution-intensive cities are increasingly assuming the role of compensation payers, thereby driving a "functional re-identification" of ecological stakeholders. Notably, Kaifeng transitioned from a recipient to a payer between 2010 and 2015, mirroring the findings of Zhang [41], before reverting to a recipient status during the 2015-2020 period. Whilst urban development between 2010 and 2015 was predominantly characterised by construction and industrial expansion – leading to an ecological deficit – the subsequent period (2015-2024) saw a significant recovery. Driven by the strategic promotion of cultural tourism, sustainable agriculture, and ecological construction, alongside increased environmental investment, ecosystem service outputs rose markedly, resulting in a compensation surplus and a 30% increase in ecosystem service value. This trajectory highlights the critical role of policy intervention and ecological investment in mitigating ecological deficits [42, 43].

Based on the profit and loss analysis of the Anhui and Henan sections of the Huaihe River Basin, the following differentiated policy recommendations are proposed: (1) The Anhui section should ensure the stability of ecological supply and facilitate a transition towards "self-sustaining" development. Policy interventions should focus on the protection of water sources and the enforcement of ecological red-line controls, establishing long-term inter-provincial transfer payment mechanisms. Concurrently, ecological industrialisation pathways should be promoted to enhance capital inflows and elevate the value of ecological conservation. (2) The Henan section should advance the institutionalisation of ecological supply and the transformation of ecological value. Municipalities such as Xinyang and Zhumadian should utilise Gross Ecosystem Product (GEP) accounting to convert implicit ecological supply into institutionalised provision, while refining horizontal ecological compensation mechanisms to bolster the sustainability of compensation revenues. (3) The ecological compensation zones within the Henan section must prioritise deficit reduction by driving industrial transformation and improving governance efficiency. Optimising industrial structures to decrease the proportion of energy-intensive industries and reducing pollution exposure risks are essential to achieving a more balanced compensatory role.

Despite the expansions made in this study regarding the accounting framework and spatial scales, several limitations remain. The valuation of health-related damages did not fully account for population age structures or individual demographic variations. Furthermore, the analysis of pollution remediation gaps did not detail the cost heterogeneities associated with

diverse pollutant treatment technologies. As the research scale was primarily confined to the municipal level, future scholarly endeavours should extend towards county-level or cross-sectional scales to more rigorously investigate the micro-spatial heterogeneity within the basin.

Conclusions

This paper comprehensively estimates ecosystem service value, health loss, and pollution control costs, ultimately deriving the ecological compensation amount, and draws the following conclusions:

(1) The significant offset effect of environmental negative externalities on ecological value. From 2010 to 2024, health losses in high-development cities such as Zhengzhou and Hefei continued to rise, while health losses in Xinyang decreased substantially. The theoretical input for pollution control exceeded the actual investment, and the governance gaps in most cities significantly narrowed after 2016. After adjustments, the overall compensation amount decreased from 10.76 billion yuan in 2010 to 7.45 billion yuan in 2024.

(2) By incorporating health losses and pollution control into the ecological compensation amounts, some economically developed but environmentally burdened regions transitioned from “compensation zones” to “payment zones”. The deficits in Zhengzhou, Xuchang, and Luohe continued to expand, with Zhengzhou’s deficit increasing by 186.8%. Kaifeng and Shangqiu subsequently shifted to being net payers of compensation.

(3) Significant positive spatial correlation of adjusted ecological compensation amounts. The global Moran’s I index exhibited a fluctuating trend of “first decreasing, then increasing”. Local spatial clustering reveals that the spatial structure followed a “fragmented polarisation – banded diffusion – structural locking” characteristic. By 2024, the study area formed a pattern of “high-value aggregation in the south and low-value contiguous areas in the central and northern regions”, with spatial homogenisation trends becoming increasingly stable.

(4) The total compensation in the Anhui section is projected to decrease gradually from 125.40 billion yuan in 2024 to 117.32 billion yuan by 2034, demonstrating strong compensation stability. In contrast, the total compensation in the Henan section is expected to significantly decline from 21.96 billion yuan to 11.72 billion yuan, a decrease of nearly 46.6%. The ecological deficit in the Zhengzhou metropolitan area and cities in eastern Henan is continuously expanding, exacerbating the severe imbalance in the distribution of ecological capital within the basin.

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AI Usage Disclosure Statement

During the preparation of this manuscript, the authors used DeepSeek in a limited manner to assist with the English translation of references, language polishing, and reference format checking. This tool was not used for research design, data collection, data generation, data analysis, interpretation of results, formulation of conclusions, or figure preparation. All content assisted by artificial intelligence was carefully reviewed, verified, and revised by the authors. The authors take full responsibility for all content of this article.

Data Availability Statement

All relevant data are included in the paper or its Supplementary Information.

Conflict of Interest

The authors declare no conflict of interest.

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