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Study on the identification of protection priority areas in the Huaihe River Basin based on ecosystem services

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Intrudution: The Huaihe River is the natural boundary between the north and the south of China. Its basin has important ecological service functions and plays an irreplaceable role in maintaining regional ecological balance and ensuring ecological security.

Methods: Based on the land use data of Huaihe River Basin from 1990 to 2023, InVEST model, Local Moran's I analysis, Spearman correlation coefficient and Marxan model were used to quantify the four ecosystem service functions of habitat quality, carbon storage, water yield and soil conservation.

Results: (1) From 1990 to 2023, the construction land and water in the study area increased by 5.1% and 0.5% respectively, and the cropland, forest, grassland and unused land decreased by 4.8%, 3.2%, 1.5% and 76.1% respectively. (2) Habitat quality, water yield and soil conservation showed a significant downward trend, which were 12.5%, 23.2% and 19.0%, respectively, showing a spatial distribution pattern of high in the south and low in the north. (3) The ecosystem services in the Huaihe River Basin form a high-high aggregation in the mountainous and hilly areas, and the aggregation in the plain areas is not significant, which generally reflects the synergy. (4) The core areas obtained under different protection target allocations of priority protection areas are basically similar, reflecting stability and continuity.

Discussion: Therefore, it is necessary to protect the ecological environment according to local conditions, and finally achieve the goal of jointly improving ecosystem services and green development.

KEYWORDS

ecosystem services, priority protected areas, trade-off synergy relationship, Huaihe River Basin, InVEST model

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1 Introduction

Ecosystem services (ES) are the various benefits that humans obtain from ecosystems, including direct benefits (producing raw materials for people) and indirect benefits (regulating the environment). Interactions among different types of ecosystem services are complex and diverse. These interactions include not only trade-offs, where the enhancement of one service may lead to the relative weakening of another, but also synergistic effects, where two services simultaneously increase or decrease (Li X.F. et al., 2025). As a key medium linking humans and nature, ecosystems (Chen et al., 2019) not only sustain natural ecological processes but also strongly influence human well-being and societal development. Consequently, ecosystems have become a central focus in the field of macroscopic ecology (Chen et al., 2024; Li L. et al., 2025).

With rapid population growth and economic development, ecosystems have gradually degraded, leading to a series of ecological and environmental problems (Li et al., 2023). Priority protected areas are defined as regions with abundant natural resources, scientifically and reasonably managed, possessing stable and complete ecosystems, and exhibiting prominent ecosystem service functions. These areas aim to protect locations that contribute most significantly to ecosystem functions. Establishing priority protection areas enables the effective allocation of scarce resources and represents a key step in ecological protection. This approach can improve fragile local environments, optimize ecological patterns, and ensure the long-term sustainable development of biodiversity and ecosystems (Gong et al., 2024; Yang X.F. et al., 2025). At present, a large number of research methods have been used to study ecosystems at different scales, such as provinces, cities, and watersheds. Pearson correlation, difference comparison method, bivariate local autocorrelation, and other approaches have been applied to show that the research areas are dominated by synergy, with various ecosystem services promoting each other (Wang Y.X. et al., 2025; Zhai et al., 2025; Xun et al., 2024; Zhang N.N. et al., 2025). The least-square method and geographical detector have been used to demonstrate that natural factors play a greater role at the microscale, whereas social and economic factors are more significant on the macroscale, with economic and tourism factors increasingly playing a decisive role (Chen et al., 2020; Zhang et al., 2024; Wang et al., 2024; Yang et al., 2023). The ordered weighted average operator (OWA) and the Marxan model have been employed to divide the study area into multiple scenarios. The results showed that in Anhui Shengjin Lake National Nature Reserve, the southern hilly area, and the Yellow River Basin, protection efficiency was highest under the high-synergy scenario (Wang et al., 2023, 2021; Wu et al., 2022). Therefore, the high-synergy scenario can consider a broader range of ecosystem services and strengthen the interactions among them.

As the natural dividing line between northern and southern China, the Huaihe River Basin is an important ecological transition zone, a grain production base, and a key water resource area, playing a crucial role in ensuring ecological security for both regions. Global warming, population growth, and ongoing resource development and utilization threaten the ecological security and sustainable development of the region. Previously, domestic scholars have identified priority protection areas using indicators such as species diversity and ecosystem services (Wang S.Y. et al., 2025; Shen et al., 2024). In contrast, this study integrates human activities by introducing datasets on human activity footprint, population density, per capita gross domestic product (GDP), and construction land as cost-related indicators, and overlays existing protected areas to identify key regions not adequately covered. Therefore, the InVEST model and Marxan model were used to evaluate the spatial and temporal distribution of habitat quality, carbon storage, soil conservation, and water yield, as well as their trade-offs and synergies, to delineate priority protection areas and ensure the feasibility of spatial zoning and conservation strategies in the Huaihe River Basin.

2 Research area and research methods

2.1 Overview of the study area

The Huaihe River Basin (30°55′–38°05′N, 111°55′–122°45′E) is located in China's north–south climate transition zone and exhibits distinct climatic characteristics. Winters and springs are dry and rainy, while summers and autumns are hot and rainy. The region has a warm temperate semi humid monsoon climate, with an average annual precipitation is 600–1,400 mm. Precipitation decreases from south to north and shows extreme variability both annually and interannually. Geographically and geomorphologically, the Huaihe River Basin is complex and diverse, spanning the provinces of Henan, Anhui, Jiangsu, Shandong, and Hubei. Covering approximately 330,000 km^2, the basin includes various terrains such as plains, hills, and mountains (Figure 1).

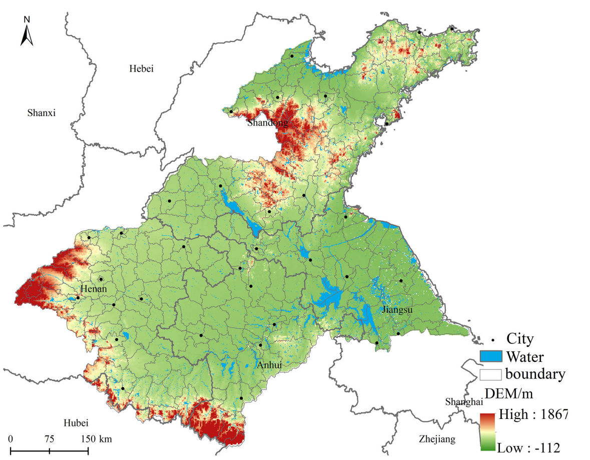

FIGURE 1
Overview of study area.

2.2 Data source

The land use data of the Huaihe River Basin, collected every 5 years from 1990 to 2023, are derived from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn), with a spatial resolution of 1 km. Meteorological data, including annual average temperature and annual average precipitation, are obtained from the China Meteorological Data Network (https://data.cma.cn), also with a spatial resolution of 1 km. Soil data were sourced from the World Soil Database (HWSD) and the Chinese Soil Dataset. DEM data were obtained from the Geospatial Data Cloud (https://www.gscloud.cn). Population density and per capita GDP are derived from the statistical yearbooks of each city. The human footprint index was obtained from the Human Footprint dataset. Wetland reserve and nature reserve data were obtained from the Zenodo website (https://zenodo.org/records/14875797).

2.3 Research methods

From the ecology and hydrology perspective of the Huaihe River Basin, the selection of ecosystem services follows the principles of scientific rigor, comprehensiveness, significance, and data availability (Zhang W.D. et al., 2025; Liu Y.L. et al., 2025; He et al., 2025). Four main ESs—water yield, carbon storage, soil conservation, and habitat quality—were selected for the Huaihe River Basin. The specific calculation methods are as follows:

2.3.1 Water yield

Water yield is estimated using Budyko's water–heat coupling balance principle (Lin et al., 2021) through the water production module of the InVEST model. Higher water production indicates a greater water supply. The specific calculation formula is as follows:

$$Y_{(x)} = (1 - \frac{AET_{(x)}}{P_{(x)}}) \times P_{(x)}$$

In the formula, $Y_{(x)}$ represents the annual water yield (mm) of a land use type; $\mathrm{AET}_{(x)}$ is the annual actual evapotranspiration (mm) of the grid unit; and $P_{(x)}$ is the annual precipitation (mm) of the grid unit.

2.3.2 Habitat quality

Habitat quality plays an important role in maintaining biodiversity. Based on the InVEST model, the main parameters were set with reference to previous research (Zhou et al., 2024), expert interview results, and the model's user manuals, while also considering the characteristics of the study area. The calculation principle is as follows:

$$\mathrm{Q}_{(xj)} = H_j[1 - (\frac{D_{xj}^z}{D_{xj}^z + k^z})]$$

In the formula, Q_{xj} represents the habitat quality index of grid x in land use type j; H_j is the habitat suitability of land use type j; D_{xj} is the habitat degradation degree of grid x in land use type j; k is a semi saturation constant; and Z is the default model parameter.

2.3.3 Soil conservation

Soil conservation services are evaluated using the revised universal soil loss equation (RUSLE) (Xiang et al., 2025). Greater soil erosion corresponds to higher sediment output and lower soil conservation. The specific calculation is performed using the following formula:

$$A_c = A_p - A_r = R \times K \times LS \times (1 - C \times P)$$

In the formula, A_c is the amount of soil conservation (t/hm^2), determined by the difference between potential erosion (A_p) and actual erosion (A_r). R is the rainfall erosivity factor (MJ mm hm^{-2} h^{-1}); K is the soil erodibility factor (t hm^2 h hm^{-2} MJ^{-1} mm^{-1}); LS is the terrain factor; C is the vegetation coverage factor; P is the factor of soil and water yield measures. In the model, the rainfall erosivity factor R is calculated from annual rainfall, the soil erodibility factor K is calculated based on the content of sand, silt, clay, and organic carbon in the soil, and C is calculated using the normalized vegetation index.

2.3.4 Carbon storage

Carbon sequestration services are evaluated based on the four major carbon pools in the InVEST model. Carbon stocks are calculated by multiplying the carbon density of each land use type (Wang et al., 2018; Meng and Wu, 2023). The basic principle is as follows:

$$C_z = C_{above} + C_{below} + C_{dead} + C_{soil}$$

In the formula, C_{above}, C_{below}, C_{dead}, C_{soil}, and C_z represent aboveground carbon storage, underground carbon storage, dead organic matter carbon storage, soil carbon storage, and total carbon storage, respectively.

2.3.5 Marxan model

Marxan is a system protection planning model based on the simulated annealing method. It delineates the scope of protected areas under certain cost conditions (Ban et al., 2009) and helps in constructing, designing, and evaluating the spatial planning of protected areas (including land, marine, and freshwater systems). In this study, a 5-km^2 unit was used as the research unit, and the protection targets were set as 70%, 50%, and 30% of the study area, respectively (Woodley et al., 2019). The number of software iterations is set to 1,000,000, and the boundary length was corrected while keeping the remaining parameters unchanged. The model objective function is:

$$T_{target\ \ function} = \sum_{PUs} Cost + BLM \sum_{PUs} Boundary + Penalty \sum_{ConValue} CFPF$$

In the formula, T denotes the value of the objective function; Cost represents the total cost of the planning unit (PU); and Boundary is the length of the boundary of the protected area system. The boundary length correction coefficient (BLM) is a parameter that determines the aggregation of the protected area

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system. Penalty refers to the penalty incurred for failing to achieve the protection goal, calculated based on the protection cost of the planning unit. The protection feature penalty factor (CFPF) is used to emphasize the relative importance of different protection features.

3 Results and analysis

3.1 Spatiotemporal pattern change characteristics of land use

According to the National Land Use Status Classification Standard (GB/T21010-2007), land use types in the Huaihe River Basin are divided into six categories: cropland, forest, grassland, water, construction land, and unused land. ArcGIS10.8 was used to process the land use data of the Huaihe River Basin from 1990 to 2023, and Excel was used to calculate the area of each land use type for each period (Table 1). Over this time span, the intensity of land use change in the Huaihe River Basin followed the order: unused land > construction land > cropland > forest > grassland > water. During these 33 years, land use types in the Huaihe River Basin have undergone substantial changes. The cropland, forest, grassland, and unused land have shown a downward trend, while water and construction land have shown an increasing trend. Among them, the area of unused land decreased significantly from 1,162.11 km^2 in 1990 to 277.70 km^2, a total decrease of 884.41 km^2 (76.1%), which was the most significant decrease among all land use types. Cropland decreased from 239,511 km^2 in 1990 to 228,013 km^2 in 2023, a total decrease of 11,497 km^2 (4.8%). Forest decreased from 24,379 km^2 in 1990 to 23,591 km^2 in 2023, a total decrease of 788.63 km^2 (3.2%), while grassland decreased from 16,623 km^2 in 1990 to 11,817 km^2 in 2023, a total decrease of 4,806.25 km^2 (1.5%). The increase in construction land was the most obvious, from 30,408 km^2 in 1990 to 45,925 km^2 in 2023, a total increase of 16,517 km^2 (5.1%), while water increased from 14,438 km^2 in 1990 to 15,906 km^2 in 2023, an increase of 0.5%.

On the spatial scale, the distribution of land use types in the Huaihe River Basin from 1990 to 2023 (Figure 2) shows that cropland and forest occupy the largest areas, making them the most important land use types in the Huaihe River Basin. Together, they account for more than 80.0% of the total land area, while the remaining land use types occupy a relatively small proportion. Cropland is evenly distributed across the Huaihe River Basin with a wide spatial range, although its area changes over time as it is gradually replaced by other land use types. Grassland and forest are interspersed, mainly around Tongbai Mountain, Yantai, and Dongying, and their area decreases over time. Water bodies are concentrated in Xuzhou, Suqian, Huai'an, and near Lianyungang and Yantai, with the water area near Suzhou and Huai'an continuing to expand. Construction land is mainly located near water bodies and urban areas, and occupies a small area. Unused land accounts for the smallest proportion.

3.2 Spatiotemporal variation characteristics of ecosystem services

3.2.1 Spatiotemporal pattern change characteristics of habitat quality

The average habitat quality index of the Huaihe River Basin over the past 33 years was 0.399, 0.370, 0.363, 0.396, 0.383, 0.351, 0.349, and 0.349, respectively, and the habitat quality showed a fluctuating downward trend (Table 2). Habitat quality showed a downward trend in 1990–2000 and 2005–2023, with the most significant decline in 2010–2015, which may be related to human activities. The upward trend in 2000–2005 may be related to the Interim Regulations on Water Pollution Prevention and Control in the Huaihe River Basin promulgated in 1995, which reduced wastewater discharge and improved watershed habitat. From 1990 to 2023, the habitat quality was mainly at a relatively low level. The land types in 1990 (70.2%), 1995 (69.6%), 2000 (69.5%), 2005 (69.0%), 2010 (68.3%), 2015 (67.6%), 2020 (67.1%), and 2023 (66.9%) were all cropland.

TABLE 1 Changes in land use types in the Huaihe River Basin.

Useland	Cropland	Forest	Grassland	Water	Construction land	Unused land
1990	239,511.24	24,379.79	16,623.89	14,438.22	30,408.36	1,162.11
1995	237,504.00	24,574.60	16,268.60	15,402.70	32,038.80	728.040
2000	237,329.78	24,403.61	15,864.13	15,413.04	32,932.64	570.41
2005	235,417.15	24,375.04	15,618.54	15,965.20	34,631.50	508.22
2010	233,093.29	23,600.96	11,973.51	15,982.60	41,559.50	315.48
2015	230,796.68	23,529.63	11,932.86	15,693.13	44,305.62	272.46
2020	229,074.42	23,539.80	11,905.24	15,650.59	46,087.05	273.28
2023	228,013.63	23,591.16	11,817.64	15,906.35	46,925.51	277.70
area	− 11,497.61	− 788.63	− 4,806.25	1,468.13	16,517.15	− 884.41
%	− 4.8%	− 3.2%	− 1.5%	0.5%	5.1%	− 76.1%

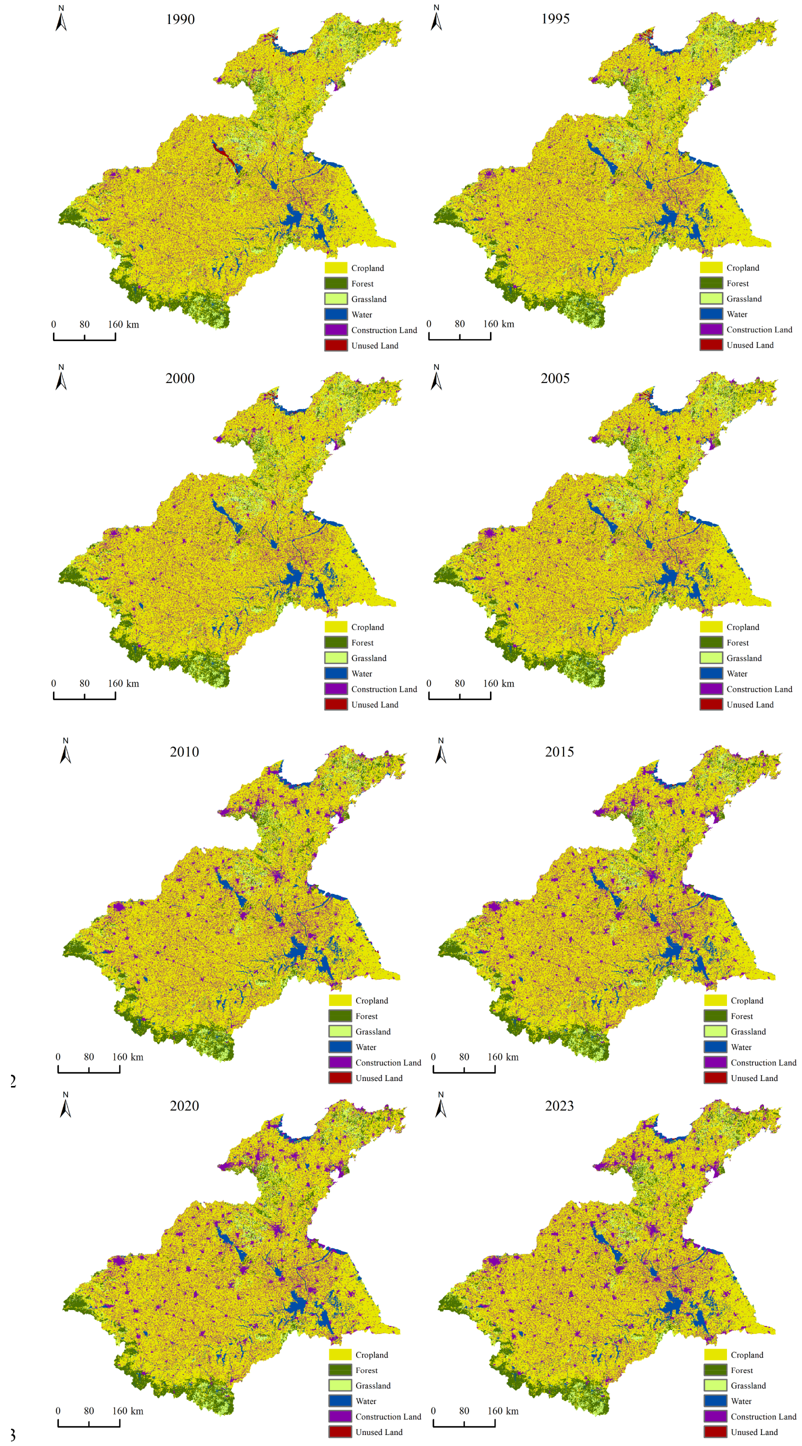

FIGURE 2
Spatial differentiation of land use change in the Huaihe River Basin.

On the whole, the habitat quality of the Huaihe River Basin is low, and there are patterns in its spatial distribution. From 1990 to 2023, areas with low habitat quality were scattered and expanded over time. The relatively low areas are mainly distributed in the plains of the Huaihe River Basin; the proportion of medium and relatively high areas is low, and the coverage change is not obvious, mainly concentrated in the central part of the Shandong Plain, the southern part of the Jiaodong Hills, and the southern part of the Dabie Mountains. The high areas are distributed in the water bodies and the mountainous regions at the edge of the Huaihe River Basin (Figure 3).

This change shows that the habitat quality is highly consistent with the geological characteristics of the basin. The land types corresponding to areas with high habitat quality in the Huaihe River Basin are grassland, forest, and water. These areas are at high altitude, steep in

TABLE 2 The proportion of different grades of habitat quality.

Habitat quality (%)	1990	1995	2000	2005	2010	2015	2020	2023
Low level	12.3	12.7	12.9	13.4	15.5	16.3	16.8	17.0
Relatively low level	70.2	69.6	69.5	69.0	68.3	67.6	67.1	66.9
Middle level	0.1	1.6	2.1	0.1	0.1	1.1	1.1	1.1
Relatively high level	5.3	8.2	8.1	5.0	3.8	7.5	7.5	7.6
High level	12.1	8.0	7.3	12.6	12.4	7.5	7.4	7.5

terrain, and less disturbed by human activities. Areas with relatively low habitat quality are mainly concentrated in cropland, mostly plains and gentle slopes, which are easily affected by human activities. Areas with low habitat quality are mainly concentrated in construction land, primarily due to highly concentrated urbanization and industrialization activities. Therefore, the disturbance of human activities is one of the main reasons for the decline in habitat quality.

3.2.2 Temporal and spatial variation characteristics of carbon storage

From 1990 to 2023, the total carbon storage in the Huaihe River Basin showed a slight upward trend, increasing by 0.91×10^8 t over 33 years (Table 3). Cropland carbon storage decreased from $32.7\ 6 \times 10^8$ to 29.17×10^8 t, but its contribution remained dominant. Construction land carbon storage increased from 2.76×10^8 to 6.73×10^8 t. This may be related to an increase in carbon stocks caused by policy interventions, such as ecological restoration projects including returning farmland to forests, returning grasslands, and natural forest protection. However, due to the expansion of construction land from 1990 to 2015, land types with higher carbon density (cropland, forest) are reduced, offsetting the substantial increase in total carbon.

From the spatial distribution of carbon storage in the Huaihe River Basin, the high carbon density values are mainly concentrated in the eastern part of Yantai, the eastern part of Wuhu, Rizhao, the northern part of Qingdao, and the southern part of the Dabie Mountains, while low values are concentrated near water bodies and construction land, showing a distribution pattern of high in the north and south and low in the middle (Figure 4). Based on the analysis of the distribution characteristics of land use types, the ecological land, such as forest and cropland, is consistent with the spatial layout of high-value areas, and the construction land and water are consistent with the low-value layout. Therefore, the total amount of carbon storage is closely related to land use type, and changes in land use have a significant impact on carbon storage.

3.2.3 Spatiotemporal pattern changes the characteristics of water yield

According to the time change trends of water yield and rainfall in the Huaihe River Basin from 1990 to 2023, the annual precipitation was 810.70, 615.00, 727.03, 800.07, 689.29, 727.19, 859.94, and 659.27 mm, respectively. The annual average water depth was 265.77, 234.86, 208.32, 265.15, 219.20, 216.89, 266.32, and 204.03 mm, respectively. Both water yield and precipitation in the basin showed a “W”-shaped fluctuating downward trend (Figure 5). The water yield decreased by 57.45, 48.26, and 62.29 mm in 1990–2000, 2005–2015, and 2020–2023, respectively. In 2000–2005 and 2015–2020, it showed an upward trend, with increases of 56.83 and 49.43 mm. Therefore, the precipitation in 2020 was the highest, and the water yield reached its peak. In 2023, precipitation is low, and the average water yield falls into a trough.

The spatial distribution of water yield services in the Huaihe River Basin closely corresponds to precipitation, showing a generally positive correlation, and there is no obvious spatial correlation with actual evapotranspiration, indicating that the model simulates water production with high accuracy (Figure 6). High water yield values are mainly concentrated in areas of cropland, grassland, and construction land in the southeastern part of the basin, where the precipitation is higher, and vegetation coverage is dense. Strong transpiration and water vapor accumulation in these areas promote precipitation formation. Low water yield values are concentrated in the central and northeastern waters, where precipitation is lower, and transpiration is vigorous.

3.2.4 Temporal and spatial variation characteristics of soil conservation

Soil conservation, from the perspective of temporal distribution, showed a pattern of decrease–increase–decrease over the past 33 years, with an overall downward trend. During this period, it decreased from 37.23 to 30.15 t, a reduction of 7.09 t or 19.0%, reflecting a continuous decline in soil conservation function. The range of soil conservation was 0–12,368.9 t, with an average value of 31.34 t. The area of high-value soil conservation increased, while the other value areas changed slowly. From a spatial distribution perspective, soil conservation exhibited relatively large spatial differences, generally showing the pattern of “high in the south and low in the north”. Most high-value areas are concentrated in grassland and higher-altitude regions (Figure 7), which are less affected by human activities. These areas have higher vegetation coverage and lower actual soil erosion, resulting in better soil conservation.

3.3 Spatiotemporal change analysis of trade-off and synergy relationship of ecosystem services

3.3.1 Local Moran’s I analysis

ArcGIS was used to assign the results of ecosystem services in 1990 and 2023 to the corresponding vector layers in county-level units, and local Moran index analysis was performed. High–low

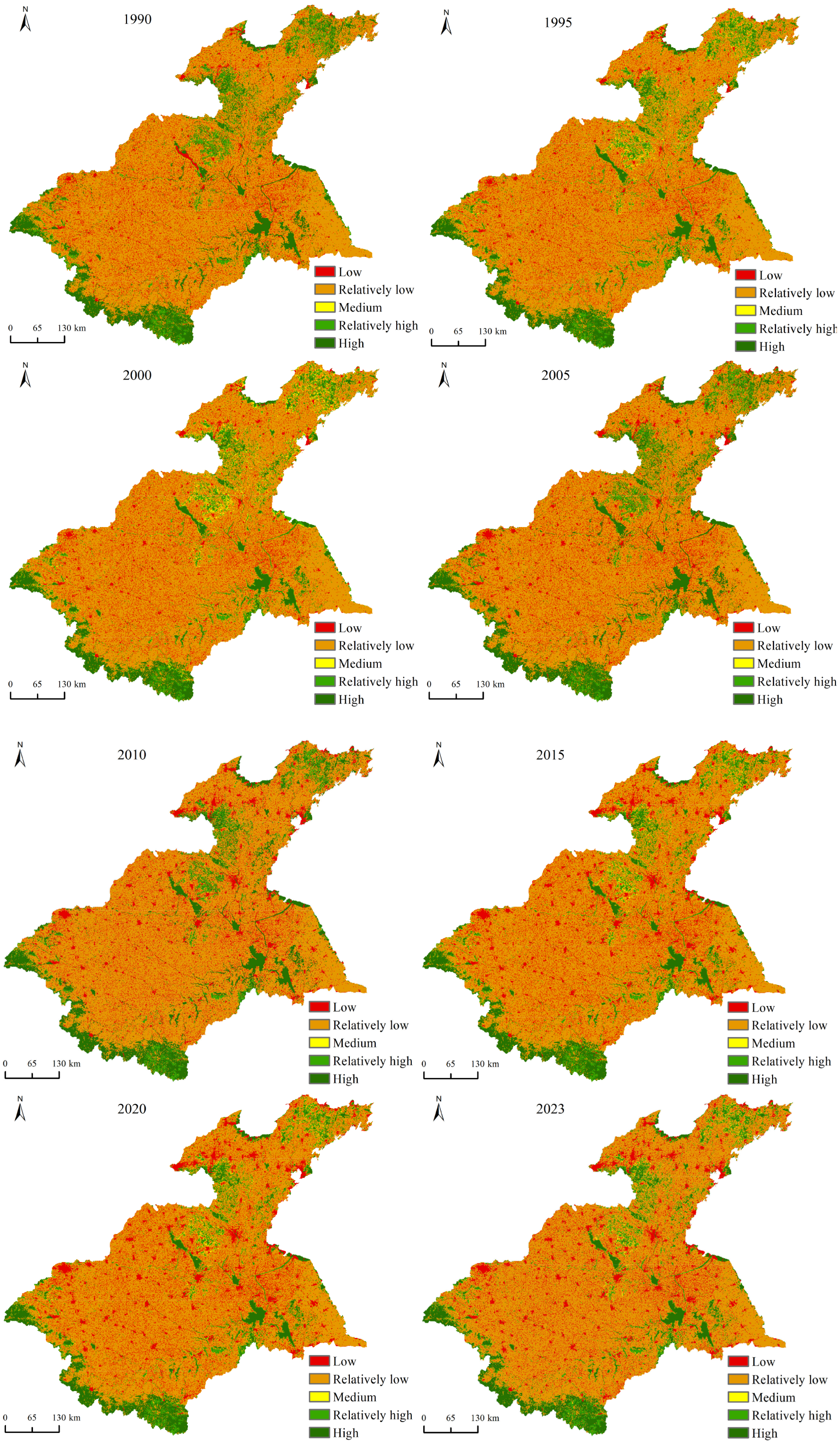

FIGURE 3
Spatial differentiation of habitat quality.

agglomeration and low–high agglomeration showed a trade-off relationship, and high–high agglomeration and low–low agglomeration showed a synergistic relationship. This was done to understand the spatial trade-offs/synergies of the service functions in the basin (Figure 8).

The high–high clustering area is concentrated in the mountainous hills in the south and west of the Huaihe River Basin. The terrain in this area is undulating, the precipitation is prone to cause surface runoff, and the coverage of forest and grassland is high, which is conducive to vegetation interception and soil water storage. At the same time, forest and grassland provide a superior environment for biology, vegetation photosynthesis is enhanced, and soil organic matter is continuously accumulated, so that the ecosystem service level in the south and west is higher than that in other areas, forming a "high–high" cluster; the low–

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TABLE 3 Carbon storage and change of different land use types (× 10^8 t).

Useland	Cropland	Forest	Grassland	Water	Construction land	Unused land
1990	32.76	5.36	2.13	0.21	2.76	0.08
1995	32.45	5.35	2.09	0.32	3.02	0.06
2000	32.43	5.33	2.03	0.33	3.13	0.04
2005	32.16	5.32	2.00	0.42	3.37	0.04
2010	32.60	5.10	1.52	0.53	4.52	0.03
2015	31.27	5.08	1.52	0.54	4.87	0.02
2020	31.04	5.08	1.52	0.55	5.09	0.02
2023	29.17	5.45	1.71	1.12	6.73	0.03

low clustering is concentrated in the plain areas of cropland and construction land distribution in the eastern and western regions, mainly cropland. The cropland has been plowed for a long time, and the vegetation coverage changes with the seasons. The soil is exposed for a long time, and its soil retention capacity becomes weak. The habitat quality is affected by pesticides and fertilizers. The cropland reduces the soil water storage capacity, and many types of ecological service functions are synergistically degraded in the region, so that the ecosystem service function of itself and the surrounding area is at a low level, forming "low–low clustering". High–low clustering sporadically appears in the transition zone from mountain to plain or plain forest and grassland coverage areas. The area has a high vegetation coverage, and the ecosystem service level, such as carbon storage and water yield, is high. However, due to being surrounded by cropland and construction land, it is easy to be disturbed by surrounding human beings, forming a high–low clustering with high itself and low around. Low–high clustering appears in the transition zone from plain to mountainous area, and the utilization type is mostly cropland, which makes the ecosystem service functions such as carbon storage, water yield, and soil conservation low, which may be affected by the radiation effect of the surrounding high–high clustering area. However, due to the limitation of land use type, it is difficult to effectively improve, forming a low–high clustering with low itself and high surrounding. Between 1990 and 2023, due to the expansion of construction land and the polarization phenomenon, the clustering of soil conservation, habitat quality, and water yield showed a decreasing trend, while the protection of returning farmland to forest and natural forest increased the clustering of high carbon storage and decreased other clustering.

3.3.2 Spearman correlation analysis

Spearman correlation analysis identified a total of six correlations between the four ecosystem services and explored the correlation between the ecological functions in five different periods (Figure 9). Each ecosystem promotes the other, and the relationship between them is dominated by synergy. Among them, the relationship between habitat quality and soil conservation was strongly synergistic, and the average degree of synergy was above 0.45. The relationships between carbon storage and habitat quality, carbon storage and soil conservation, and carbon storage and water yield were moderately synergistic, and the average degree of synergy was between 0.21 and 0.4. The relationship between habitat quality-water yield and soil conservation-water yield showed a low synergistic relationship, and the average degree of synergy was between 0 and 0.2. Habitat quality-soil conservation showed a strong synergy. The lush vegetation in the mountainous and hilly areas of the basin provided habitats for animals and plants, reduced soil erosion, and created a positive feedback loop, enhancing both habitat and soil retention. Carbon storage and other ecosystem service functions maintain a moderate synergy, indicating that the other three ecosystem services are strongly affected by other related factors. The low synergy degree of habitat quality-water yield and even the trade-off in 2000 was mainly due to the fact that the higher habitat areas were mainly in mountainous and hilly areas, while the water yield capacity was not as good as that in plain areas, which made it difficult to achieve synergy between the two. In order to reduce soil erosion, the construction of terraces, engineering soil reinforcement, and other measures may reduce surface runoff to a certain extent, making the soil conservation-water yield synergy low.

From 1990 to 2023, among the ecosystems in the Huaihe River Basin, carbon storage-soil conservation, carbon storage-water yield, and habitat quality-soil conservation showed a downward trend, which was related to urbanization development and transitional development. Habitat quality-water yield, and soil conservation-water yield are on the rise. Policy support has improved water quality in the basin. At the same time, the development of projects such as returning polders to lakes and soil and water conservation is conducive to the simultaneous improvement of habitat and soil conservation.

3.4 Ecological protection area

3.4.1 Priority protection areas

Irreplaceability provides a protection priority sequence for all planning units, which facilitates assigning protection levels to each unit (Figure 10). Usually, areas with irreplaceability values above 80 are designated as first-level protection priority areas, which have the highest protection value. Areas with values in the range (60,80] are considered second-level protection priority areas, which high

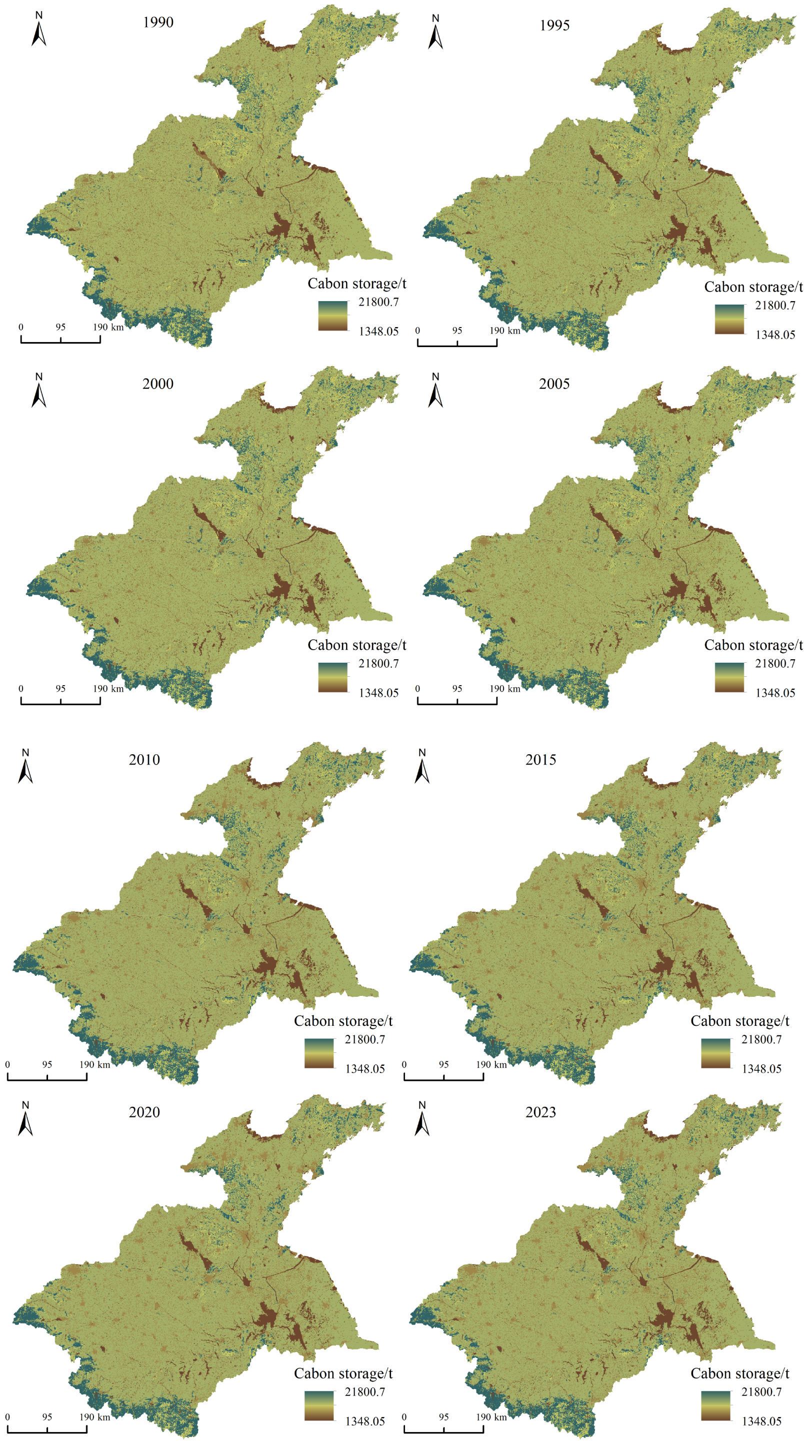

FIGURE 4
Spatial differentiation of carbon storage.

protection value. Areas with values irreplaceable in the range (40,60] are designated as third-level protection priority areas (Guo et al., 2018; Shi et al., 2018; Crouzeilles et al., 2015), which have moderate protection value and are overlaid with wetland protection areas, nature reserves, and soil erosion prevention and control zones. Among the 30% of the targets, only the third-level priority protection areas are located in water bodies, mountainous, and hilly areas, accounting for a small proportion of the total area. The 50% target secondary protected areas cover 2.09% of the study area and are situated near designated natural protected areas. This may be because nature reserves provide a stable ecological environment, and establishing priority protected areas nearby helps construct ecological corridors. Proximity to nature reserves facilitates resource sharing and reduces management costs. Overall,

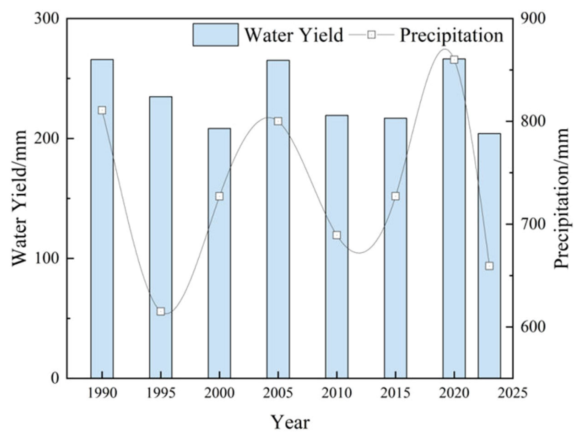

FIGURE 5
Time variation trend of precipitation and water yield.

third-level protection areas account for 90% of the total area. Its essence is to provide light protection for the entire area while strengthening protection in key regions. The first-level priority area at 70% of the target is largely consistent with the second-level priority area at 50%. The protection priority of the core ecological area is highly stable and continuous, remaining the key protection under varying levels of protection effort. The second-level priority area has expanded significantly, covering more than 80% of the total study area, indicating that the areas with certain ecological value, though noncore, are included in the secondary protection level. The third-level protection area overlaps with soil erosion remediation zones, creating a spatial synergy between ecological protection and restoration. While maintaining ecological functions, each protection area should also undertake ecological restoration tasks, such as soil erosion control, thereby linking protection with restoration.

According to the division of different protection targets, it can be seen that 50% is the optimal result when the protection target is 50%. The reasons are as follows: covering more than 80% of the core ecological protection areas, the ecosystem services are better; since the entire study area is protected, it is easy to form the ecological radiation effect; the overlap with the existing nature reserve domain is high, so the maximum protection area is generated when the cost is the lowest.

3.4.2 Optimal protected areas

Based on Zonal Statistics as Table software, the population density, per capita GDP, construction land area, and human footprint index were counted as cost factors. The evaluation results of ecosystem service function were standardized, and the areas with functional values greater than the average were analyzed as protection objects, so that the minimum cost could be used to achieve maximum biodiversity protection (Figure 11). The optimal protection area with a protection target of 30% was mainly concentrated in mountainous hills and high-biodiversity areas. When the protection target was low, the core area of ecological protection was preferred, and the maximum ecological protection benefit could be obtained with the minimum economic cost. The optimal protection area of 50%–70% protection target continued to expand to plains, waters, and wetlands, shifting from scattered distribution to contiguous development and reflecting the expansion from the core area to sub ecological value areas.

4 Discussions

In the face of challenges such as global climate change, biodiversity loss, and ecosystem degradation, protecting ecosystem services and identifying priority protection areas have become crucial strategies for maintaining national ecological security. The Huaihe River Basin lies within China's north–south climate transition zone. It is not only an important agricultural production area but also experiences frequent population and economic activities, resulting in a prominent conflict between people and land. Clarifying priority protection areas is therefore of great significance to ensure ecological security in the region.

The changes of land use types across different periods in the Huaihe River Basin show considerable variation, primarily in unused land, followed by construction land and cultivated land. Among them, cropland, forest, grassland, and unused land fluctuated and decreased, whereas water areas and construction land increased, consistent with existing research (Liu et al., 2024). This is because the Huaihe River Basin has a vast area and a population density four times the national average. Human activities and socioeconomic development continually alter the types of land use. In addition, policies controlling the Huaihe River and the establishment of a long-term ecological compensation mechanism have encouraged farmers to return farmland to lakes (Yu W.X. et al., 2017). Land policies and resource development over different periods have led to significant changes in land use. The ecosystem service functions of the entire basin showed a downward trend, and the spatial distribution is generally consistent with the findings of other scholars (Yu et al., 2025; Qiao et al., 2023; Chang et al., 2024). Areas with high vegetation coverage for water yield services in mountainous and hilly areas were lower than those in plain areas. High values of soil conservation services were concentrated in the southern and southwestern regions of the basin. Given that these southern and southwestern regions are mountainous, with high altitudes, abundant precipitation, low annual evaporation, sparse populations, and high habitat quality, carbon storage services exhibit a trend of "high in the north and south, low in the middle", which has a strong consistency with land use types. High habitat quality values are distributed in the Dabie Mountain area in the south of the basin, the Funiu Mountain area in the west, the central and southern mountainous areas of Shandong in the northeast, and other high-altitude regions with limited human activity (Lian et al., 2025).

After discussing the spatial and temporal changes of various ecosystem services, the trade-off and synergy relationships among these services were clearly explained. This study showed that, except for the trade-off between soil conservation–water conservation

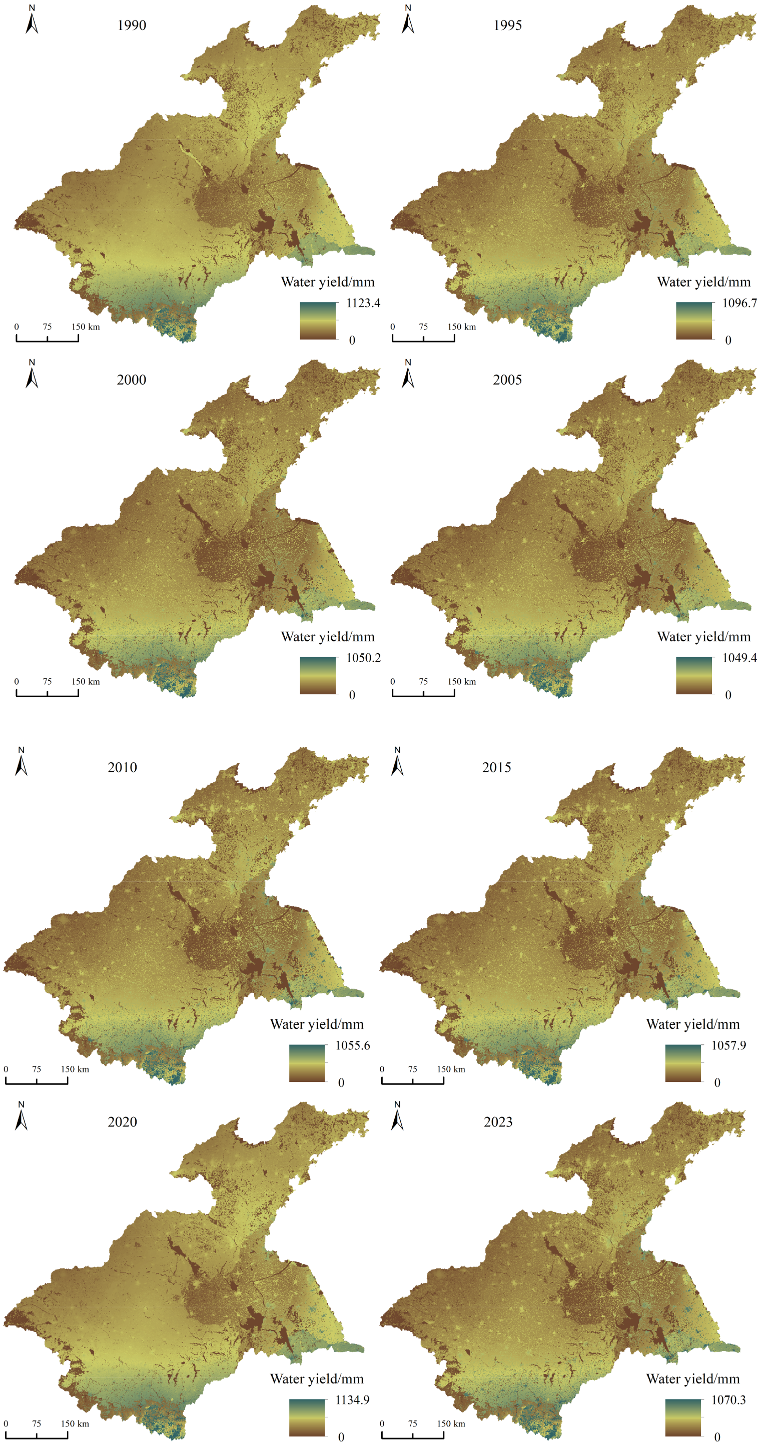

FIGURE 6
Spatial variation trend of water yield.

services in 2000, the other relationships were synergistic, consistent with previous research (Zhou et al., 2025; Gai et al., 2025). Synergistic relationships were found in areas with high altitude, steep terrain, and complex landforms (Zhan et al., 2025). The complex terrain and favorable climate in these regions promote biodiversity, low population density, and minimal economic interference, thereby providing greater benefits to humans (Mou et al., 2021; Yang S. et al., 2025). It is necessary to strengthen the construction of ecological conservation forests, implement afforestation and ecological water replenishment, return farmland to wetlands, enhance ecological monitoring, further implement zoning protection, build a land ecological security system

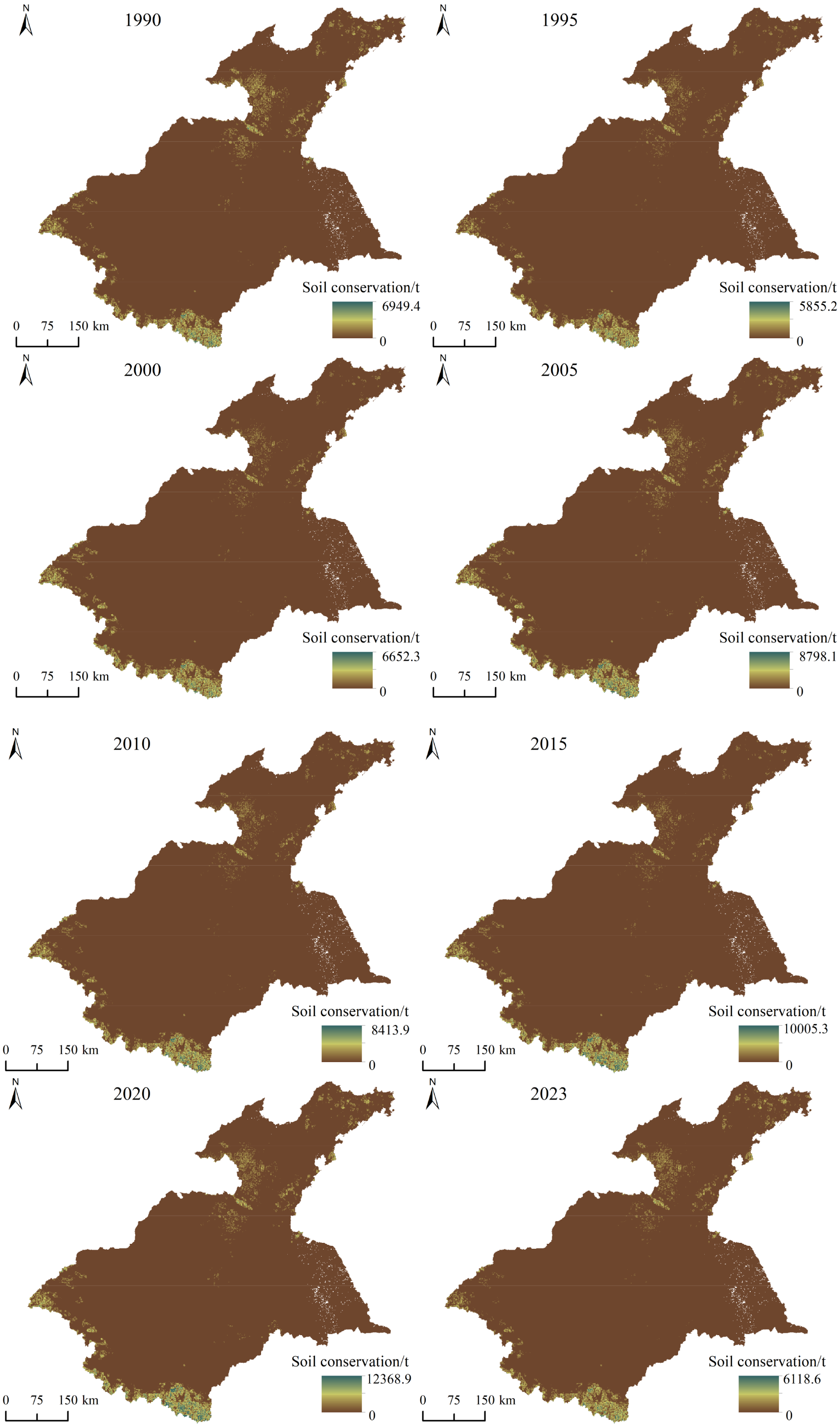

FIGURE 7
Spatial variation trend of soil conservation.

centered on forests and woodlands, and promote ecological restoration. In the plains, it is necessary to limit the excessive exploitation of cultivated land, protect ecosystem stability, emphasize ecological conservation, and increase forest and grass coverage. The development of water-saving agriculture is also needed to prevent overuse of cultivated land resources, which can lead to further deterioration of the ecological environment.

By integrating multiple ecosystem services to delineate protected areas, minimal resources and costs are invested in key conservation zones, thereby maximizing benefits to human well-being and

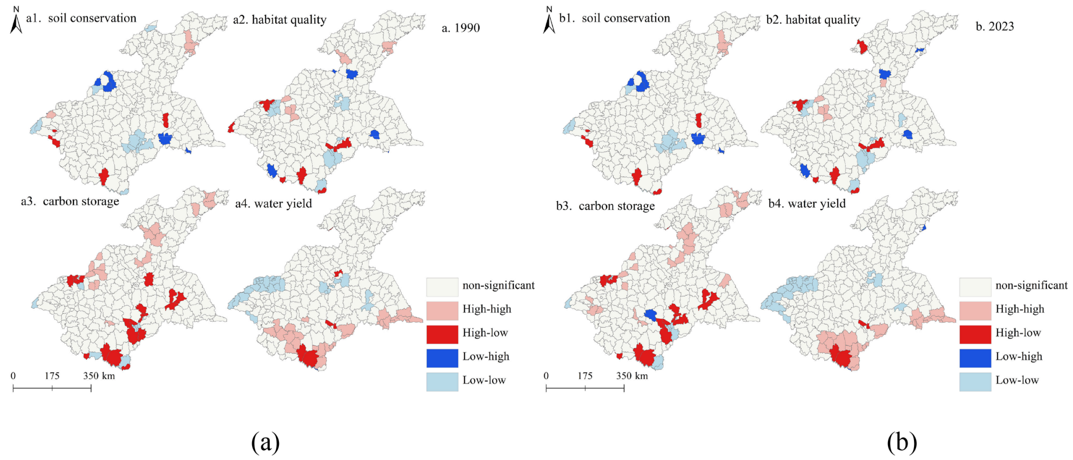

FIGURE 8
Spatial distribution of **(a)** 1990 and **(b)** 2023 local Moran's index of ecosystem services in the study area.

promoting sustainable development. The results show that the core areas are located near existing protected areas or expand outward from natural protection cores, consistent with previous studies (Zeng et al., 2025; Mu et al., 2021). Considering that the protection target focuses on areas providing more than four ecosystem services, with multiple protection objectives overlapping, the 70% protection target essentially covers the entire study area, ranging from "core area protection" to "global integrated protection" (Ou et al., 2020). The study indicates that setting the protection target at 50% is optimal, as it achieves maximum protection at minimal cost. Therefore, it is necessary to limit human activities that damage the ecology in the core (secondary protection) areas, increase policy support—such as scientific investigations and ecological restoration—and stabilize the core area's ecological condition. Efforts should focus on protecting the

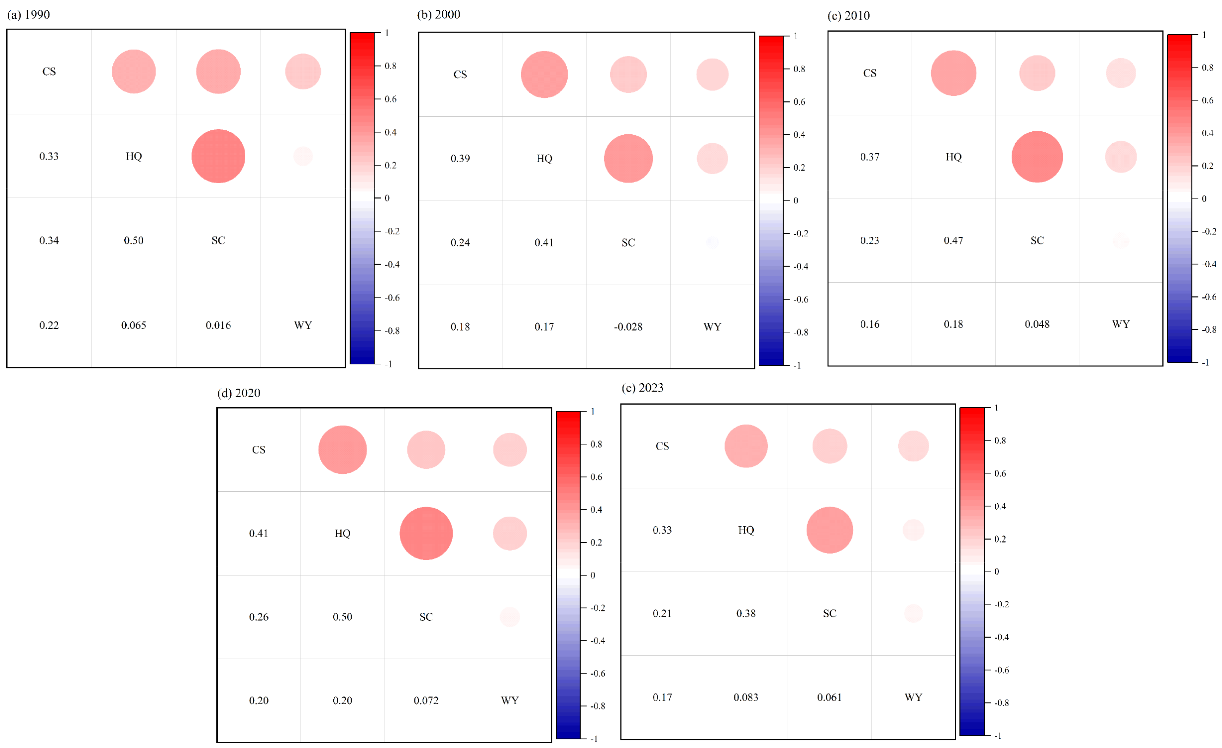

FIGURE 9
Spearman correlation analysis of **(a)** 1990, **(b)** 2000, **(c)** 2010, **(d)** 2020, and **(e)** 2023 ecosystem services in the Huaihe River Basin. WY, water yield; CS, carbon storage; SC, soil conservation; HQ, habitat quality.

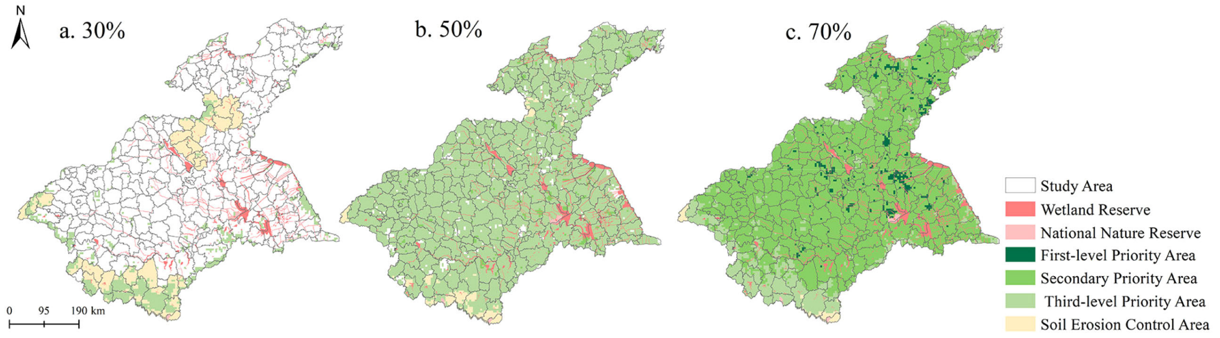

FIGURE 10
Priority protection area.

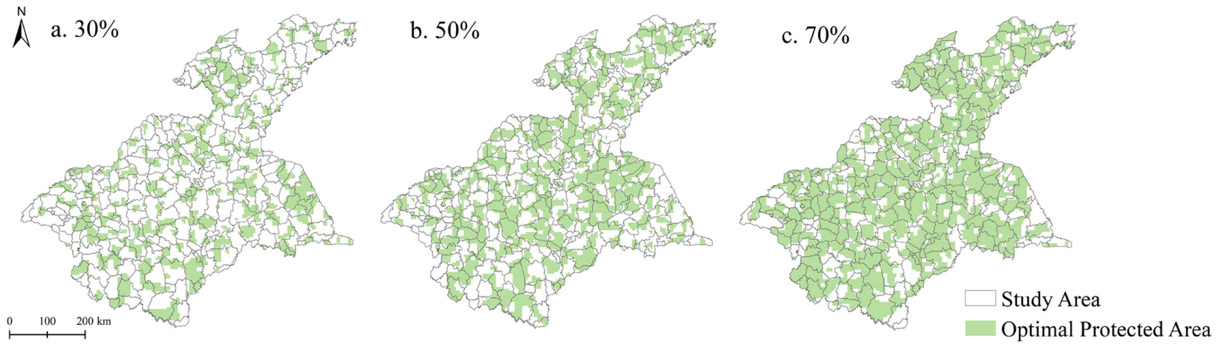

FIGURE 11
The optimal protected area in the study area.

ecological environment while controlling soil erosion, implementing coordinated activities for ecological protection and soil erosion remediation in areas overlapping natural and priority protection zones, actively establishing cross-sectoral coordination mechanisms, and avoiding the dispersion of resources resulting from multisectoral management.

Based on the availability of data and the characteristics of the study area, this study has some limitations. The ecosystem service assessment considered only four indicators—water yield, soil conservation, habitat quality, and carbon storage—so the evaluation of ecosystem service capacity in the basin is not comprehensive. In the future, a unified ecosystem service index system should be developed to provide a more scientific basis for ecosystem management and decision-making.

5 Conclusion

1. The land use types in the Huaihe River Basin have undergone substantial changes over the past 33 years. Cropland, forest, grassland, and unused land have shown a downward trend, whereas water and construction land have shown an upward trend. Cropland and construction land cover the largest areas and remain the main land use type in the Huaihe River Basin.
2. The ecosystem services in the Huaihe River Basin have changed significantly over time, with ecosystem functions generally exhibiting a fluctuating downward trend. This trend is mainly associated with the advancement of urbanization, increased human disturbance, and relevant policies from 1990 to 2023. In addition, climate change influences the structure and distribution of ecosystems, while land use types affect the supply relationships of ecosystem services.
3. Overall, the four ecosystem services are synergistic, with the ecosystems mutually promoting and benefiting each other. In terms of local spatial relationships, the mountainous hills in the southwestern region exhibit high–high clustering, whereas the eastern and central plains show low–low clustering. In 2023, compared with 1990, the clustering of services generally decreased, with only the high–high clustering of carbon storage showing an increase.
4. The results of the priority protection area division for ecosystem services indicate that the first-level priority

protection areas are located near wetlands and nature reserves, while second-level protection areas account for a relatively large proportion. Noncore areas are included in the secondary protection level, and third-level protection areas largely overlap with existing water and soil protection areas.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/supplementary material.

Author contributions

JY: Funding acquisition, Writing – review & editing, Methodology, Formal Analysis, Writing – original draft. SH: Supervision, Formal Analysis, Visualization, Writing – original draft, Methodology, Data curation, Conceptualization. SY: Project administration, Conceptualization, Writing – review & editing, Investigation, Methodology. XY: Formal Analysis, Resources, Conceptualization, Data curation, Writing – original draft. XW: Software, Validation, Supervision, Writing – review & editing, Conceptualization, Data curation, Visualization.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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