Spatiotemporal Variations and Drivers of Ecosystem Services in the Heihe River Basin under Ecological Water Transfer: A Postprint

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Date: 2025-09-01T11:34:34+00:00

Abstract

The implementation of ecological water diversion and other policies in the Heihe River Basin has effectively alleviated the deterioration trend of the ecological environment in the basin, with significant improvements in ecological environmental quality. Among the existing research findings in this basin, studies on the spatiotemporal evolution characteristics of ecosystem services have been limited by short time periods and regional constraints, and most have not conducted qualitative and quantitative analyses of the impacts of environmental governance policies and other driving factors. Taking the Heihe River Basin as the study area, this study aims to reveal the spatiotemporal evolution characteristics of water yield depth, habitat quality, carbon storage, and soil conservation from 1990 to 2022, assess the impact of ecological water transfer on downstream ecosystem services through the coupled InVEST-PLUS model, and analyze driving factors using the geographical detector. The results show that: (1) After 2000, carbon storage and habitat quality in the basin showed an overall increasing trend, while water yield depth and soil conservation exhibited a trend of first increasing and then decreasing. Spatially, they displayed a stepped distribution pattern of "high in the south and low in the north," with high values concentrated in the Qilian Mountains and low values distributed in the desert zones of the middle and lower reaches. (2) Downstream carbon storage and habitat quality are significantly positively correlated with the annual average runoff at Zhengyixia ($P<0.05$). Compared with the natural development scenario, ecological water transfer has caused both to show a year-by-year increasing trend under the actual scenario. (3) Among the driving factors of the geographical detector, digital elevation, temperature, precipitation, and potential evapotranspiration are dominant. The geographical detector results indicate that the interactive explanatory power of factors has a greater influence on ecosystem services than single-factor explanatory power. The research results can provide

a scientific basis for ecological governance and water resource allocation in the Heihe River Basin.

Full Text

Spatiotemporal Evolution Characteristics and Driving Forces of Ecosystem Services in the Heihe River Basin Under the Context of Ecological Water Conveyance

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Abstract

The implementation of ecological water allocation policies in the Heihe River Basin has effectively alleviated the trend of ecological environmental degradation, with significant improvements in environmental quality. However, existing research on the spatiotemporal evolution of ecosystem services in this basin has been limited by short study periods and narrow regional scope, and most studies have not conducted qualitative or quantitative analyses of the impacts of environmental governance policies and other driving factors. Taking the Heihe River Basin as the study area, this research aims to reveal the spatiotemporal evolution characteristics of water yield depth, habitat quality, carbon storage, and soil conservation from 1990 to 2022. The InVEST-PLUS coupled model is used to evaluate the impact of ecological water conveyance on downstream ecosystem services, and geographic detector analysis is employed to parse the driving factors. The results show that: (1) After 2000, carbon storage and habitat quality in the basin showed an overall increasing trend, while water yield depth and soil conservation initially increased and then decreased. Spatially, a stepped distribution pattern of "high in the south, low in the north" was observed, with high values concentrated in the Qilian Mountains and low values distributed in the desert zones of the middle and lower reaches. (2) Downstream carbon storage and habitat quality were significantly positively correlated with the annual average runoff at Zhengyi Gorge ($P<0.05$). Compared with natural development scenarios, ecological water conveyance enabled both indicators to show year-by-year increasing trends under actual scenarios. (3) Among all driving factors in the geographic detector, digital elevation, temperature, precipitation, and potential evapotranspiration were dominant. The geographic detector results showed that the explanatory power of factor interactions on ecosystem services was higher than that of single factors. These findings provide a scientific basis for ecological governance and water resource allocation in the Heihe River Basin.

Keywords: ecosystem services; InVEST-PLUS coupled model; driving forces research; Heihe River Basin

1 Study Area and Methods

1.1 Study Area Overview

The Heihe River Basin is located in the central Hexi Corridor, with geographical coordinates between 38°–42°N and 98°–101°E. As the “mother river” of the Hexi Corridor, the basin covers a total area of approximately 14.29$×10^{4}$ km^2, spanning Qinghai, Gansu, and Inner Mongolia. From south to north, it contains semi-arid, arid, and extremely arid climate zones, representing the second largest inland river system in northwest China. The lower reaches of the Heihe River Basin are predominantly desert areas. This study focuses on river-lake coastlines and oases in the downstream region to analyze the spatiotemporal distribution of ecosystem services. A buffer zone along downstream river coastlines was created to remove most desert areas, yielding the study area schematic diagram [Figure 1: see original paper]. The terrain slopes from high in the south to low in the north, with the Qilian Mountains situated in the southern upstream area, plateaus and plains distributed in the middle reaches, and deserts dominating the downstream region. The Zhangye Oasis in the middle reaches and the Ejina Banner Oasis in the downstream are important ecological barriers that restrain the expansion of the Badain Jaran Desert and reduce sandstorm disasters.

1.2 Data Sources

Table 1 summarizes the primary data used in this study, including their resolution and sources. Monthly precipitation, monthly potential evapotranspiration, monthly temperature, and land use type data were obtained from the National Tibetan Plateau Center at 1 km$$\times 1kmresolution.TheGLC_{FCS30D}datasetwasreclassifiedintosixlandusecateg$ km resolution.

1.3.1 InVEST Model

The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model, developed by the Natural Capital Project, is applied to evaluate various ecosystem services. This study uses the InVEST model to assess four ecosystem services in the Heihe River Basin: water yield depth, carbon storage, habitat quality, and soil conservation.

Water Yield Module: The InVEST model calculates water yield depth using annual average precipitation and actual evapotranspiration. The primary formula is:

$$Y_x = \left(1 - \frac{AET_x}{P_x}\right) \times P_x$$

where Y_x is the annual water yield depth value for a grid cell (mm), AET_x is the annual actual evapotranspiration for the grid cell (mm), and P_x is the mean annual precipitation for the grid cell (mm).

Habitat Quality Module: The habitat quality module in the InVEST model estimates habitat quality primarily based on land use data. The main formula is:

$$Q_{xj} = H_j \times \left(1 - \frac{D_{xj}^z}{D_{xj}^z + k^z}\right)$$

where Q_{xj} is the habitat quality of the x-th pixel unit in land use type j (dimensionless, ranging from 0 to 1); H_j, k, D_{xj}, and z represent the habitat suitability factor, half-saturation constant, habitat degradation degree, and normalization constant, respectively. In this study, the z value is set to 2.5.

Soil Conservation Module: The soil conservation module in the InVEST model is based on the Revised Universal Soil Loss Equation (RUSLE). The main formulas are:

$$usle_x = R_x \times K_x \times LS_x \times C_x \times P_x$$

$$rlkls_x = R_x \times K_x \times LS_x$$

$$sc_x = rlkls_x - usle_x$$

where $usle_x$ is the actual soil erosion amount ($\mathrm{t} \cdot \mathrm{km}^{-2}$), $rlkls_x$ is the potential soil erosion amount ($\mathrm{t} \cdot \mathrm{km}^{-2}$), and R_x, C_x, K_x, LS_x, and P_x represent the rainfall erosivity factor, vegetation cover and management factor, soil erodibility factor, slope length and steepness factor, and conservation practice factor, respectively.

Carbon Storage Module: The carbon storage module in the InVEST model calculates carbon storage by integrating land use data and carbon pool data. The primary formula is:

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

where C_{total}, C_{above}, C_{below}, C_{soil}, and C_{dead} represent the total carbon storage, aboveground carbon storage, belowground carbon storage, soil carbon storage, and carbon storage in dead organic matter, respectively ($\mathrm{Mg} \cdot \mathrm{hm}^{-2}$).

1.3.2 Spatial Characteristics Analysis

This study employs global Moran's I index to test for spatial autocorrelation, while local Moran's I index measures the correlation between the attribute of a unit region and the same attribute values of neighboring regions. Using a 2 km$×$2 km fishnet in ArcGIS Pro, mean values of various ecosystem services were extracted through zonal statistics and visualized in cluster maps. The principles and calculation formulas are as follows:

$$I_{global} = \frac{n}{S_0} \times \frac{\sum_i \sum_j w_{ij} z_i z_j}{\sum_i z_i^2}$$

$$I_{local} = \frac{n}{\sum_i z_i^2} \times \frac{\sum_j w_{ij} z_i z_j}{S_0}$$

where I_{global} is the global Moran's I index; I_{local} is the local Moran's I index; n is the total number of features; i represents a certain ecosystem service of a pixel unit; z_i is the deviation of feature i's attribute from its mean; z_j is the deviation of feature j's attribute from its mean; and w_{ij} is the spatial weight between features i and j. The I value ranges from -1 to 1. A positive I indicates global positive correlation, while a negative I indicates global negative correlation. An I value of 0 indicates random distribution, and larger absolute I values indicate greater spatial heterogeneity.

1.3.3 PLUS Model

The PLUS (Patch-generating Land Use Simulation) model is a cellular automata model that simulates land use changes at the patch scale. It consists of two main modules: a land expansion analysis strategy and a cellular automata model. Since the InVEST model primarily operates based on land use data, and land use conditions significantly affect model evaluation results, previous studies have confirmed the feasibility of coupling InVEST and PLUS models to assess ecosystem services under different scenarios. The model requires different inertia coefficients for various land use types, which can be obtained through the PLUS model.

1.3.4 Geodetector

Geodetector is an emerging spatial analysis tool developed by Wang Jinfeng's team for analyzing spatial heterogeneity and its influencing factors. It can effectively avoid endogeneity problems in regression analysis and multicollinearity impacts while enabling qualitative analysis of driving factors and identifying their pairwise interactions. This study uses Geodetector to achieve optimal parameter selection.

Factor Detection: Geodetector can analyze the spatial heterogeneity of factor Y and measure the explanatory power (q) of factor X on the spatial differentiation of Y, expressed as:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}$$

where h represents the stratification of factor X and variable Y; N_h is the number of units in layer h; σ_h^2 is the variance of Y values in layer h; N is the total number of units; and σ^2 is the variance of Y values in the study area. The q value ranges between 0 and 1, with values closer to 1 indicating stronger explanatory power of factor X on the spatial heterogeneity of factor Y.

Interaction Detection: By calculating and comparing the explanatory power of individual factors and the interaction between two factors, this method determines whether interactions exist between factors and characterizes the nature of these interactions. Since the ecosystem stability in the study area is relatively low and sensitive to natural factors such as climate, vegetation, and human activities, and drawing from driving force analysis results in Yellow River Basin studies, this research selected precipitation (X_1), potential evapotranspiration (X_2), temperature (X_3), normalized difference vegetation index (X_4), digital elevation model (X_5), population distribution (X_6), and gross domestic product (X_7) as driving factors.

2 Results

2.1.1 Temporal Variation Characteristics

Analysis of temporal changes in ecosystem services across the study area (Figure 2 [Figure 2: see original paper]) reveals that water yield depth showed an initial increase followed by a decreasing trend (Figure 2a), with the highest average value reaching 58.3 mm in 2018 and the lowest value of approximately 19.8 mm in 2022. Carbon storage showed a continuous increasing trend overall (Figure 2b), reaching a minimum of about 133.7 $\mathrm{t \cdot hm^{-2}}$ in 1995 and peaking at 135.4 $\mathrm{t \cdot hm^{-2}}$ in 2022. Habitat quality was at a low level before 2000, with the minimum value of about 0.73 in 1990. After 2000, habitat quality levels in each study period were significantly higher than before 2000, showing a fluctuating trend and reaching the highest level of about 0.88 in 2022 (Figure 2c). Soil conservation showed a similar fluctuating pattern (Figure 2d), with the peak appearing in 2018 at 4574.2 $\mathrm{t \cdot hm^{-2}}$ and the lowest value of about 2473.1 $\mathrm{t \cdot hm^{-2}}$ in 1995.

To further understand the spatial distribution and changes of ecosystem services in local regions of the basin, zonal statistics were conducted to obtain temporal changes in ecosystem services for the upper, middle, and lower reaches (Table 2). The spatial differentiation characteristics of ecosystem services showed a gradient decreasing pattern in the same year (upper > middle > lower), with service provision significantly limited in the downstream due to the high proportion of desert area. The temporal evolution trends of service quantities in the upper and middle reaches were consistent with the overall basin trend, showing synchrony. Downstream carbon storage and habitat quality showed continuous increasing trends, while water yield depth and soil conservation showed initial increase followed by decrease.

2.1.2 Spatial Distribution Characteristics

Based on the spatial distribution and changes of ecosystem services from 1990 to 2022 (Figure 3 [Figure 3: see original paper]), the study area exhibits the following patterns: For water yield depth, high-value areas ($ 84*mm*)*remainedconcentratedintheupperreaches*, *withamaximumof*403*mmin*2022, *whilethemiddleandlow*
valueareas(24.2×10^{3}$ t · hm^{-2}) were concentrated in the upper and middle reaches, with a maximum absolute change of 13.36$×10^{3}$ t · hm^{-2}; the middle reaches showed scattered distribution with a maximum change of 31.3 t · hm^{-2}, while the lower reaches mostly showed zero values. For carbon storage, high-value areas (22.3 t · hm^{-2}) were generally higher in the upper and middle reaches than in the lower reaches, with urban areas below 6.9 t · hm^{-2}. The high-value areas of habitat quality expanded in 2022 compared to 1990, further strengthening the south-high-north-low gradient distribution, with overall increases showing the pattern: upper > middle > lower.

Global Moran's I index results for ecosystem services from 1990 to 2022 (Table 3) show that the P-values for all ecosystem services were less than 0.05, passing significance tests, and all showed extremely strong positive spatial autocorrelation, indicating that ecosystem services have significant spatial clustering characteristics. Compared with 1990, the global Moran I index for water yield depth in 2022 showed a relatively large increase, while those for soil conservation, carbon storage, and habitat quality remained stable.

Local I cluster analysis yielded LISA cluster maps (Figure 4 [Figure 4: see original paper]). High-high clusters of water yield depth, soil conservation, carbon storage, and habitat quality were mainly distributed in the southern Qilian Mountains, while low-low clusters were primarily distributed in the northern desert zones, with non-significant clusters mostly in the central transition zones. The areas of northern low-low clusters and southern high-high clusters for water yield depth and soil conservation increased. The high-high cluster distribution for habitat quality shifted southwestward.

Statistics on the proportion of spatial clustering patterns of ecosystem services (Table 4) show that for high-high cluster areas, water yield depth increased from 12.69% (1990) to 12.94% (2022), while soil conservation and carbon storage remained stable, and habitat quality increased from 25.34% (1990) to 41.04% (2022). For low-low cluster areas, soil conservation decreased from 44.48% (1990) to 39.76% (2022). The proportion of non-significant areas for habitat quality showed relatively large fluctuations.

2.2.1 Impact of Ecological Water Conveyance on Downstream Ecosystem Services

Considering the impact of water allocation policies on the downstream region, the relationship between water discharge to the downstream area and ecosystem services was analyzed. Based on the evolution of water allocation policies, annual runoff changes at Zhengyi Gorge from 1990 to 2022 were divided into four periods: baseline period (before 2000), emergency scheduling period (2000–2004), regular scheduling period (2005–2017), and ecological scheduling period (2018–2022). As different water transfer modes changed, discharge at Zhengyi Gorge showed a phased increasing trend (Figure 5 [Figure 5: see original paper]). During the baseline period before 2000, the maximum annual runoff was 1.128$\times10^{8}$ m^3 in 1995. During the emergency scheduling period, the maximum appeared in 2003 at 1.216$\times10^{8}$ m^3, when runoff showed strong fluctuation trends. During the regular scheduling period, the maximum appeared in 2014 at 1.592$\times10^{8}$ m^3, with relatively stable fluctuations. During the ecological scheduling period, the peak reached 1.200$\times10^{8}$ m^3 in 2022, showing an overall trend of initial increase followed by decrease.

Combined with changes in precipitation and potential evapotranspiration, the study area maintained high levels of potential evapotranspiration with small fluctuation amplitude. During the baseline period before 2000, changes in Zhengyi Gorge runoff were consistent with natural precipitation trends. During the emergency scheduling period, runoff changes showed some lag compared to precipitation changes. During the regular and ecological scheduling periods, runoff changes showed opposite trends to precipitation in some years—for example, precipitation decreased significantly in 2021 while Zhengyi Gorge runoff increased slightly. These results indicate that after implementing ecological water conveyance in the lower Heihe River Basin, human regulation of discharge at Zhengyi Gorge reduced the impact of natural condition changes, making it a comprehensive factor affecting the downstream ecological environment. Therefore, to distinguish it from natural conditions and human activities, it was treated as a separate driving factor.

Correlation analysis between annual average runoff at Zhengyi Gorge and downstream ecosystem service quantities (Table 5 and Table 6) shows that the Pearson and Spearman correlation coefficients between runoff and both downstream carbon storage and habitat quality were higher than 0.5 and passed significance tests, indicating significant positive correlations. The changes in Zhengyi Gorge runoff were synchronized with habitat quality and carbon storage, both reaching maximum values by 2022.

Based on these correlation results, to further verify the impact of ecological water conveyance and quantify changes in habitat quality and carbon storage in the lower Heihe River, the InVEST-PLUS coupled model was used to simulate natural development scenarios. The 1990–2020 land use prediction results were used for model calibration, showing a Kappa coefficient of 0.82 and overall accuracy of 0.89, meeting reliability requirements for spatial simulation. Comparison of simulated and actual downstream carbon storage and habitat quality from 1990 to 2022 (Table 7) reveals that under ecological water conveyance scenarios, both indicators showed continuous increasing trends, while under natural development scenarios they showed decreasing trends. The simulated results were significantly lower than actual results, particularly in 2022, when actual carbon storage was 35.16 $\mathrm{t} \cdot \mathrm{hm}^{-2}$ compared to 30.39 $\mathrm{t} \cdot \mathrm{hm}^{-2}$ under natural scenarios, and actual habitat quality was 0.45 compared to 0.38 under natural scenarios. These differences demonstrate that ecological water conveyance has effectively curbed environmental degradation in the lower Heihe River Basin.

2.2.2 Driving Force Analysis Results from Geodetector

Analysis of factor explanatory power and ranking from the Geodetector model (Table 8) shows that for water yield depth, precipitation (X_1) ranked first with a q-value of about 0.45; for soil conservation, digital elevation model (X_5) had the highest q-value of about 0.38; for carbon storage, digital elevation model (X_5) had the highest q-value of about 0.42, followed by temperature (X_3); for habitat quality, digital elevation model (X_5) had the highest q-value of about 0.41. Overall, digital elevation model, temperature, precipitation, and potential evapotranspiration had relatively large impacts on ecosystem services. The q-values for habitat quality and carbon storage were higher than those for water yield depth and soil conservation, indicating that these environmental factors had greater influence on the former two services.

Comparative analysis shows that the explanatory power of individual driving factors was lower than that under two-factor interactions (Figure 6 [Figure 6: see original paper]). The interaction between precipitation (X_1) and potential evapotranspiration (X_2) showed the strongest explanatory power for water yield depth, revealing that topographic gradients in the basin have an amplifying effect on moisture redistribution. For soil conservation, the interaction between precipitation (X_1) and digital elevation model (X_5) was strongest, highlighting that soil conservation is significantly affected by rainfall erosion. For carbon storage and habitat quality, the interaction between digital elevation model (X_5) and normalized difference vegetation index (X_4) showed the strongest explanatory power, as terrain constrains vegetation distribution, which further affects carbon storage and habitat quality.

3 Discussion

Previous research in the Heihe River Basin has mostly focused on direct assessment of ecosystem services with limited service types, short time series, and narrow regional scope, often confined to a single sub-basin, with limited attribution analysis of driving factors. This study systematically assessed ecosystem services across the entire Heihe River Basin over a relatively long time series. Water yield depth and soil conservation showed initial increase followed by decreasing trends. Habitat quality was at low levels before 2000 but improved after 2000, showing fluctuating trends. Carbon storage showed an overall increasing trend. The spatial distribution patterns are consistent with Wang et al.'s research on ecosystem service spatial patterns in the Heihe River Basin, showing a stepped distribution from high in the south to low in the north, with high values concentrated in the upstream Qilian Mountains and low values in the middle and downstream deserts. Moran's I spatial analysis results show significant spatial differentiation characteristics, with high-value clusters distributed in the southern upstream Qilian Mountains and low-value clusters in the northern middle and downstream desert areas.

Temporal changes in ecosystem services in the Heihe River Basin are closely related to natural conditions and policy implementation. The Qilian Mountains in the southern basin block moisture transport northward, and the basin's inland location under continental arid climate influences creates a terrain gradient from cold-humid mountainous chains to dry plain oases to extremely dry desert Gobi. Therefore, differences in climate conditions, topography, and vegetation distribution are important reasons for spatial and temporal differences in ecosystem services. Additionally, to improve the ecological environment and socioeconomic quality in the middle and lower reaches, the government has implemented numerous policies, among which water allocation policies are crucial for improving the downstream ecological environment.

In driving factor analysis, ecological water conveyance to the downstream area significantly positively correlated with habitat quality and carbon storage, and the InVEST-PLUS coupling simulation confirmed that ecological water conveyance effectively curbed environmental degradation. Geographic detector analysis identified digital elevation model, temperature, precipitation, and potential evapotranspiration as dominant factors affecting ecosystem service distribution and changes. For example, increased precipitation and temperature led to increases in various ecosystem services. In two-factor interaction detection, the explanatory power after factor interaction was higher than that of single factors, indicating that ecological environmental changes in the study area result from comprehensive effects of multiple driving factors.

4 Conclusions

1) Carbon storage and habitat quality in the Heihe River Basin showed overall increasing trends after 2000, while water yield depth and soil conservation initially increased and then decreased. All ecosystem services showed significant spatial autocorrelation and differentiation characteristics, with high values distributed in the southern upstream Qilian Mountains and low values clustered in the northern middle and downstream desert areas, presenting a stepped distribution pattern of high in the south and low in the north.

2) Downstream carbon storage and habitat quality were significantly positively correlated with water discharge to the downstream area at Zhengyi

Gorge. Simulation of natural development scenarios showed decreasing trends in carbon storage and habitat quality, while actual scenarios under ecological water conveyance showed year-by-year increasing trends.

3) In the Geodetector analysis, digital elevation model, temperature, precipitation, and potential evapotranspiration were dominant driving factors. The results showed that the interactive driving effects of factors were stronger than single-factor effects.

5 Limitations and Prospects

Since 2000, the overall ecological environment of the Heihe River Basin has improved, which is closely related to water allocation policies and socioeconomic development policies in addition to natural conditions. Therefore, studying the impact of water allocation on ecosystem services is significant, particularly the mechanisms behind these effects require focused attention.

Due to data limitations, this study did not conduct year-by-year analysis of ecosystem service changes, resulting in insufficiently detailed temporal analysis. Additionally, the precision of land use type classification was not high enough, which may have affected the results, and the underlying mechanisms of how influencing factors affect ecosystem service functions were not deeply explored. Future research should consider obtaining more comprehensive data, using higher-precision land use type data for more accurate assessment of ecosystem services in the Heihe River Basin, while also considering trade-offs and synergies among ecosystem services and their impacts, and conducting further research on the mechanisms of influencing factors.

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