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Ecological impacts and supply demand evolution of the Yangtze to Huaihe water transfer project in Anhui section

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Human activities have profound impacts on land use and the supply–demand balance of ecosystem services (ESs). Various activities, such as urban construction, urban and rural planning, and inter-basin water transfer projects, continuously reshape land use patterns. This is a case study of the Anhui section of the Yangtze-Huaihe Water Diversion Project. Data from 2000, 2010, and 2020 is analyzed. Additionally, the patch-generating land use simulation (PLUS) model is utilized to quantify the specific impacts of the water diversion project construction on the supply and demand of ESs. The results indicate that the comprehensive dynamic attitude of land use during the project construction period significantly increased, rising from 0.16 to 13.79%, and mainly affected forest, water areas, construction land, and unused land. Specifically, the construction of the project led to significant changes in water purification, biodiversity, and, especially, hydrological regulation services. Additionally, the migration of residents significantly impacted the demand for ESs. The study also found a significant correlation between land use changes and the balance of ES supply and demand: the proportion of cultivated land and construction land is positively correlated with the balance, while the proportion of forest, grassland, and water areas is negatively correlated. This study provides empirical data for understanding the environmental and socio-economic impacts of large-scale water diversion projects and offers a scientific basis for local mitigation and control of adverse impacts. Through quantitative analysis and model prediction, this research effectively bridges the gap between theory and practice, providing important references for sustainable regional development.

Keywords Inter-basin water transfer project, Ecosystem services (ESs), Supply–demand, Patch-generating land use simulation (PLUS) model, The Yangtze-to-Huaihe Water Diversion (YHWD) Project

Human activities, as the primary drivers of land use change, have had profound impacts on the supply–demand balance of ecosystem services (ESs) globally. These activities include a wide range of human endeavors such as inter-basin water transfer projects, urban construction, and urban and rural planning[1]. These activities not only alter land use types and patterns but also significantly affect the structure and function of ecosystems. Among the diverse human activities[2], inter-basin water transfer projects are one of the key factors influencing land use and the supply–demand balance of ESs. Projects such as the Central Valley Project in the United States, the Indus Basin Project in Pakistan, and China's South-to-North Water Transfer Project have played important roles in national development and regional policy-making[3]. Taking China's Yangtze-to-Huaihe Water Diversion Project as an example[4], this project has the potential to bring significant benefits in navigation, irrigation, freshwater supply, hydropower development, and tourism, and it also holds national strategic significance[5]. However, under the backdrop of accelerating urbanization and continuously adjusting urban and rural planning[6,7], the impacts of urban construction and planning on land use cannot be ignored[8]. The Yangtze-to-Huaihe Water Diversion Project, as a link between the Yangtze River Delta urban agglomeration and the Central Plains urban agglomeration, plays a special role in alleviating drought and water shortages in the Huaihe River, constructing a major north–south water transportation artery, and improving the aquatic environment of Chaohu Lake and the Huaihe River[9,10]. Nevertheless, the project itself is not the sole factor influencing changes in land use types[11,12]. Urban construction, urban and rural planning, and climate change also play important roles[13]. This study aims

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to consider the water transfer project as one of the factors influencing land use changes, while also incorporating the impacts of other human activities such as urban construction and planning, to deeply analyze how these factors collectively affect the supply–demand balance of ESs. Against this backdrop, this paper takes the Anhui section of the Yangtze-to-Huaihe Water Diversion Project as an example to explore the specific impacts of human activities, particularly water transfer projects, on land use and the supply–demand balance of ESs[14], as well as the potential implications of these changes for regional sustainable development[15–17]. Through comprehensive analysis, this study aims to provide scientific evidence for understanding and mitigating conflicts between project construction and ecological protection, and to offer important references for regional sustainable development.

In recent years, some scholars have attempted to study the supply and demand of ESs from the perspective of cross-basin water diversion projects[18]. For example, Li et al. analyzed the impact of cross-basin water diversion projects on basin ESs based on the soil and water assessment tool model and the total ES index[19]. Moreover, Souza et al. developed a spatial decision support system with a hydro-economic optimization model and used it to identify and analyze the optimal economic allocation of water resources to improve water resource management efficiency[20]. Furthermore, Peng et al. constructed a payment mechanism for inter-basin water transfer ESs, applying the contingent valuation method to examine the willingness of water-receiving areas to pay and their willingness to accept water sourced from eastern route areas of the South-to-North Water Diversion Project[21]. Additionally, Peng et al. created a method for calculating the ecological compensation standards for water-receiving areas in China's cross-basin water transfers[22]. For example, this method was applied to the main water-receiving areas of the South-to-North Water Diversion Project. Based on the characteristics of the selected ES evaluation indicators for the water-receiving areas, the energy theory was used to calculate the increment in ESs[23]. These studies focus on the economic optimization of water resource allocation and ecological compensation[24]. In contrast, this research introduces the patch-generating land use simulation (PLUS) model, deeply analyzes the relationship between land use changes and the balance between ES supply and demand, innovatively reveals the specific impact of cross-basin water diversion projects on ESs, and provides a new management perspective for sustainable regional development[25].

Although the aforementioned studies have made certain progress in water resource management and ecological compensation, methodological challenges in the evaluation of ES supply remain[26]. The evaluation methods for ES supply are mainly based on the equivalent factor method (EFM) and ecological modeling[26]. Although ecological modeling can be used to effectively evaluate the integrity of ecosystems, it involves many parameters, is time-consuming and laborious, and includes various complex calculation equations[13]. The complex evaluation process leads to significant uncertainty in the evaluation results. In contrast, EFM can be tailored to local conditions by modifying equivalent values and corresponding calculated area[27], thereby flexibly and effectively assessing ESs at different scales and effectively avoiding problems with complex multiple calculations of parameters. EFM is based on the evaluation principles, methods, and basic steps created by Costanza. Xie localized Constanza's method, defining the equivalent value per unit area of China's ESs, becoming an important research basis for Chinese scholars to revise ES evaluations[28]. As a universal and reliable method for quantifying ESs, EFM is suitable for large-scale calculations and can provide a solid foundation for ES supply evaluations. The calculation of ES demand is relatively immature, with few quantitative models and methods. Existing studies mostly use expert scoring and socio-economic statistical calculations[29]. Among them, the use of socio-economic statistical indices is widely recognized, reflecting regional ES demand levels through land development intensity, population density, and economic indicators, which is a practical and objective approach[30]. An analysis of the balance between supply and demand is crucial for understanding the impact of water diversion projects on ESs, helping to reveal the dynamic changes in ES supply and demand during project construction and operation[31]. In terms of land use simulation and prediction, compared to other models, PLUS provides high-precision land use simulation[32]. When considering influencing factors, we emphasize the important role of climate factors in service changes or balance changes, especially in large water diversion projects where climate factors are often key factor in ES changes[33]. The management of cross-basin water diversion projects should focus on future trends of ESs, which is crucial for formulating adaptive strategies aimed at protecting the ecological impacts of construction projects[34]. As the construction of the Three Gorges Dam was ongoing, an environmental monitoring network for the dam was established. This network monitored the ecological background and changes in the reservoir area and compiled project environmental impact reports that were adjusted in real-time based on local dynamics, facilitating correct decisions and ensuring the normal operation of the project while preventing harm to the health of the basin's ecological environment.

Generally, the inter-basin water transfer project has brought great social and economic benefits. However, the permanent land cover, water storage inundation, and resettlement resulting from the water transfer project during the construction process have caused significant changes in the land use structure in the basin. These changes have led to spatial differences or imbalances in the supply–demand of ESs in the basin[35], causing severe environmental impacts on the basin[36]. However, presently, most studies only focus on the economic benefits resulting from the project and do not consider the impact of ecological supply–demand changes[37]. Therefore, this paper selected the Yangtze-to-Huaihe water diversion (YHWD) project in the Anhui section as a research area. The selection of land use data from the years 2000, 2010, and 2020 corresponds to key development phases in China over the past two decades, aligning with existing research findings[38–40]. The land use and ecosystem services (ES) changes in Anhui Province between 2000 and 2020 have shown significant patterns, and this period coincided with the construction of the YHWD project. This choice aims to reveal the long-term trends in land use and ES supply and demand, as well as to understand the long-term changes in the study area. The modified equivalent factor methods[41], the GeoDa model[42], and correlation heat maps were used to explore the influence of land use change on the supply–demand of ESs under the inter-basin water transfer project. Moreover, the PLUS model was used to simulate and forecast the land use situation in 2030. Notably, the PLUS model can be used to explore the spatial distribution of ES supply and demand in 2030. The findings of this study provide a basis

for the formulation of regional ecological compensation and land improvement policies affected by inter-basin water transfer projects. Therefore, this study focuses on investigating the impact of the construction process of the Anhui section of the YHWD Project on the supply and demand of ESs.

The research data from 2000, 2010, and 2020 were analyzed using the modified EFM, GeoDa model, and related heat maps. To predict future land use changes, the PLUS model was used to simulate and forecast land use scenarios for 2030 (Fig. 1). Additionally, 2030 is a critical time point for YHWD program operations. On this basis, the spatial pattern of ES supply and demand for 2030 was further assessed. This study advances the theory of ES supply and demand, especially in the research field of the impact of land use changes on the balance between ES supply and demand. Through a specific case analysis of the Anhui section of the YHWD project, we not only identify the impact of land use changes on the balance between ES supply and demand but also further clarify the specific relationship between different land use types and the dynamics of ES supply and demand, providing theoretical and methodological guidance for future research.

Material and methodology
Study area
The middle and lower reaches of the Yangtze-Huaihe River Basin suffer from severe water pollution. The water bodies have lost their original resource value. Soil erosion is severe in the Yangtze-Huaihe River Basin. The water conservation capacity has decreased, and riverbeds are silted with sediment, affecting navigation, the efficiency of water conservancy projects, and flood control safety. The YHWD Project is a large-scale inter-basin water transfer project in China, with a total water conveyance length of 723 km, of which the Anhui section is 587 km long, accounting for 81.3% of the entire project. The project consists of three segments: the Yangtze-to-Chaohu, the Jianghuai Canal, and the Northward Water Transfer. It closely connects the Yangtze River Delta
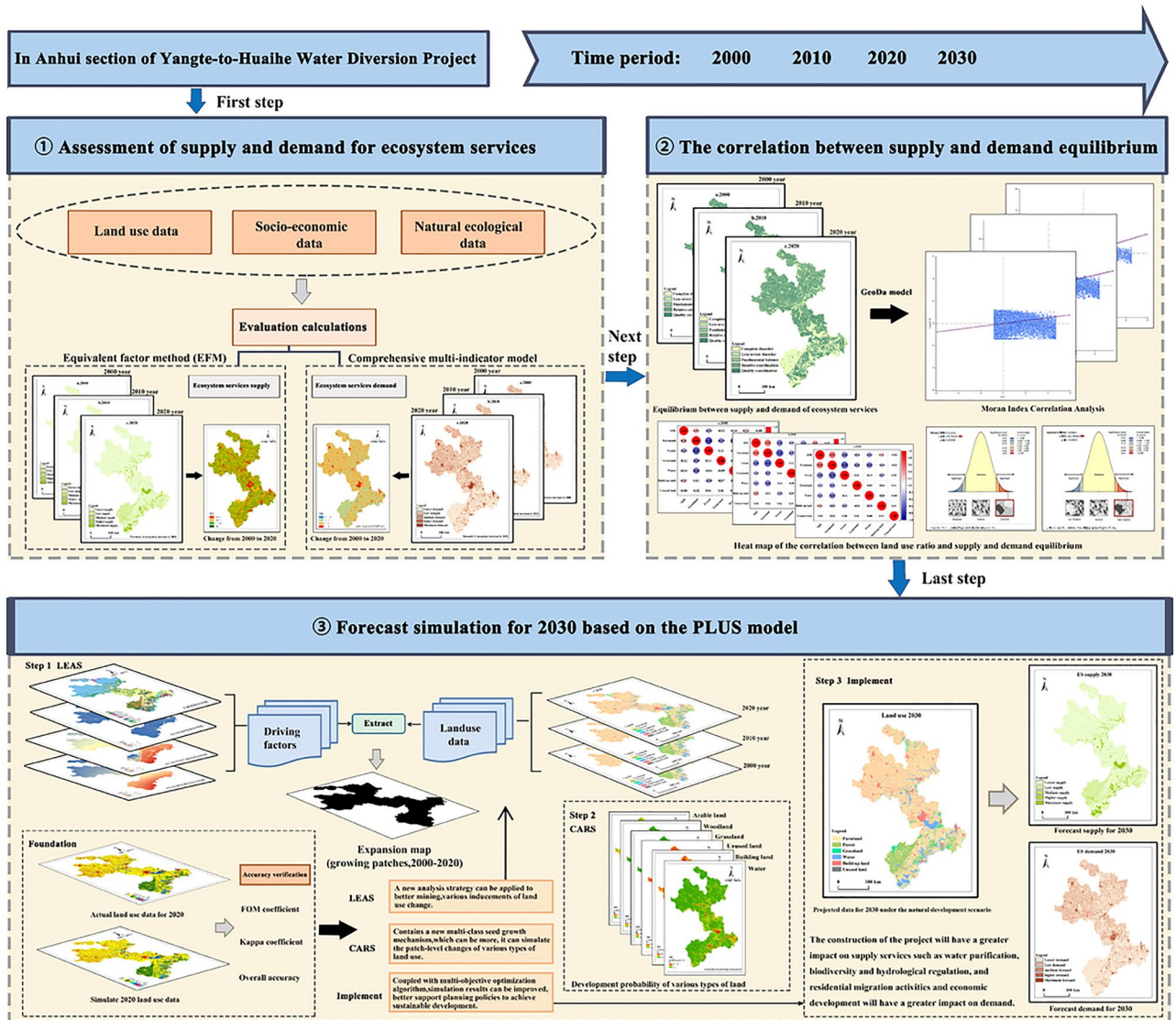

Fig. 1. Graphical abstracts.

urban agglomeration with the Central Plains urban agglomeration, playing a crucial role in alleviating drought and water shortages in the Huaihe River, constructing a major north–south water transportation artery, and improving the aquatic environment of Chaohu Lake and the Huaihe River. This study focuses on nine cities within Anhui Province, covering a watershed area of approximately 73,700 km² (Fig. 2). The impact area of the project is defined as the regions directly affected by the project, including areas along the water diversion route and the surrounding benefiting regions. Specifically, the project's impact area includes: (1) the Yangtze-to-Chaohu segment, which diverts water from the Yangtze River to Chaohu Lake, with a total length of about 170 km; (2) the first segment of the Northward Water Transfer, from Chaohu Lake to the Huaihe River, with a total length of about 224 km; and (3) the second segment of the Northward Water Transfer, from the Huaihe River to the Yangtze River Delta urban agglomeration, with a total length of about 193 km. The project's impact area not only covers the Jianghuai basin but is also closely linked to the Yangtze River Delta and Central Plains urban agglomerations. With the implementation of the water diversion project and the advancement of economic and social development, the supply–demand balance of ecosystem services (ESs) has undergone significant changes.

Datasets

The provision of ESs encompass several datasets, namely land use status, food production, and food price data. The land use information primarily originated from the Resource and Environment Science and Data Center (http://www.resdc.cn). Including 30 m accuracy data in 2000, 2010 and 2020. Although we were unable to obtain land use data for consecutive years between 2000 and 2020, the data for these three time points has been meticulously calibrated to ensure its reliability. ArcGIS 10.2 was employed to reclassify the land utilization data. Grain output and grain price are derived from Anhui Provincial Statistical Yearbook.

ESs' demand data primarily encompass the ratio of land designated for construction, population density, and Gross Domestic Product (GDP). The building land ratio is determined by dividing the total building land are by the total land area. It can be obtained from the Resources and Environmental Science and Data Center's website, that information on population density and GDP for the period from 2000 to 2020 (http://www.resdc.cn).

Drawing on existing research[43–45] findings and considering the actual operational conditions and data availability of the Yangtze River to Huaihe River Project (Anhui section), this paper identifies eight influencing factors (Table 1). These factors include rainfall, temperature, altitude, slope, GDP, population density, distance from roads, and distance from rivers, covering aspects of nature, socio-economic conditions, and accessibility.

Methods for quantifying the ESs' supply–demand

A quantitative approach to ESs' supply

Initially, we computed the per-unit area factor of ESs, followed by the determination of the per-unit area equivalent of ESs for various land use categories between 2000, 2010, and 2020. To accomplish this, we referenced the
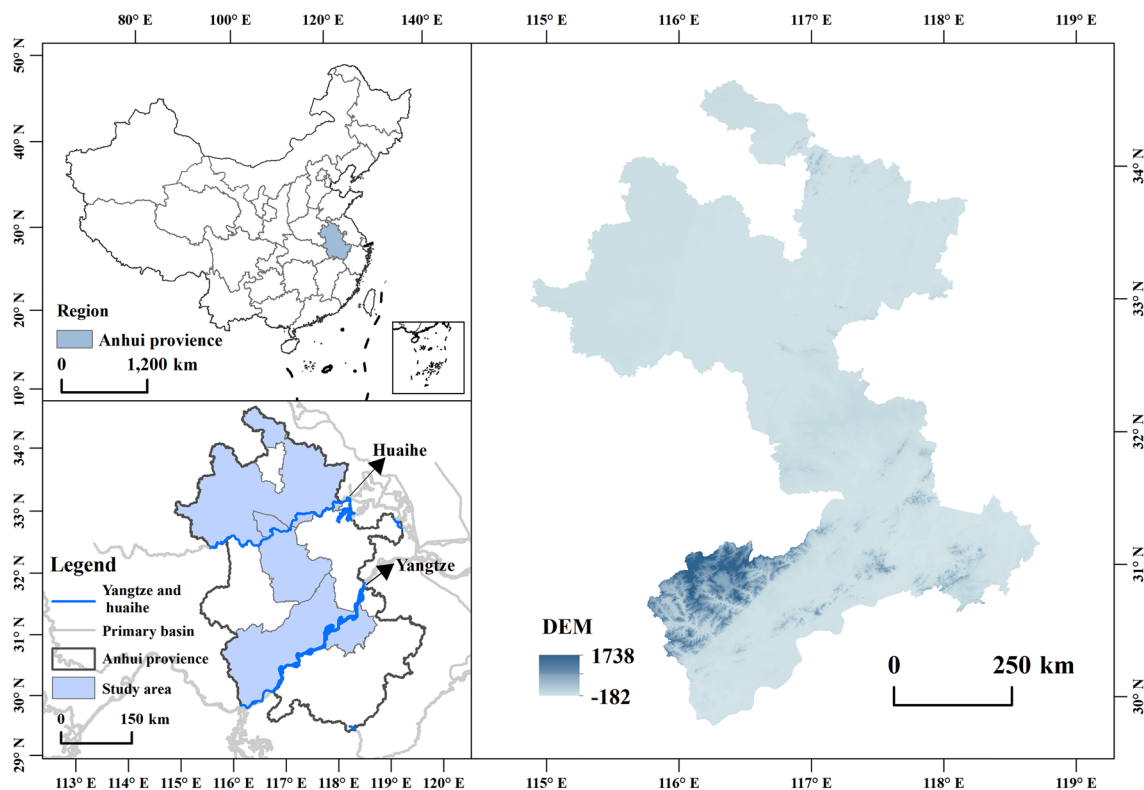

Fig. 2. Study the geographical location of the area.

Data type	Data name	Data sources
Natural factors	Quantity of rainfall	http://www.resdc.cn
	Temperatures	http://www.resdc.cn
	Elevation	http://wwwgscloud.cn/
	Slope	http://wwwgscloud.cn/
Social and economic factors	Gross Domestic Product (GDP)	http://www.resdc.cn
	Population density	http://www.resdc.cn
Accessibility factors	Distance from road	https://www.openstreetmap.org/
	Distance from river	https://www.openstreetmap.org/

Table 1. Data type and source.

per-unit area equivalent of ESs in China, as suggested by Xie Gaodi[46,47]. Additionally, the equivalent factors for different time periods were adjusted based on the grain output data derived from the Anhui Statistical Yearbook. Ultimately, the estimation model for ESs valuation was employed to assess the provision of ESs by the YHWD Project within the Anhui section.

ESs equivalent per unit area. Due to the disparity in land use data classification and ecosystem categorization criteria employed by the Xie team[9], it is necessary to make adjustments according to the research needs. Specifically, it is necessary to merge the dry land and paddy field categories into arable land, combine the mixed conifer, needle width, broadleaf, and shrub categories into woodland, reclassify the shrub category as grassland, and designate the water system and wetland categories as water. Additionally, the urban land and rural residential areas should be considered as building land, while the bare land and marshland should be regarded as unused land. To evaluate the ESs function value, the research findings should be averaged and then compared to a standard equivalent[48], allowing for the determination of the basic equivalent value for various ESs functions in the study area.

Modified equivalent factor. Taking into account the spatiotemporal dynamics of ESs, we have revised the equivalent variables for the research area spanning from 2000, 2010, and 2020. To accomplish this, the following step-by-step process was executed: Initially, the yield of grain per unit area on average within the research area over a 20-year period was computed as 4884 kg/hm² using data from the Anhui Statistical Yearbook[49].

$$D = \frac{1}{7} \times P \times Q \tag{1}$$

where D is an equivalent factor, that is, ESs value per unit area, 1/7 is the ratio of consideration of grain income to cost, P is grain output per unit area, which is obtained by dividing grain output by grain arable land area, and Q is grain price.

ES value estimation model. The value denoting the equivalent factor of the research area between 2000, 2010, and 2020 equates to 1779.17 yuan/hm². Based on this, we have calculated the ES value per unit area of the adjusted research area (Table 2)[50].

$$ESV = \sum (Bk \times VCK) \tag{2}$$

where, ESV is total value of ESs; Bk is area of the k species; VCk is ecological value coefficient.

A quantitative approach to ESs' demand
The demand for ESs reflects the need for human utilization. This study chooses three indicators that exhibit a positive correlation with the demand for ESs, specifically the percentage of developed land, density of inhabitants, and economic intensity. A comprehensive model encompassing multiple indicators is employed to calculate the demand index[51,52].

$$N = Di \times \lg(Pi) \times (\lg Gi) \tag{3}$$

where: N represents the demand index; Di, Pi, and Ei represent the percentage of developed land, developed land, and economic intensity.

Methodologies for determining ESs' supply–demand
ESs' supply–demand matching
The Z-score standardized method was adopted to eliminate the unit influence. Supply and demand are represented on the x and y axes[53]. The relationship is depicted through four quadrants: high supply-high demand (HS-HD), low supply-high demand (LS-HD), low supply-low demand (LS-LD), and high supply-low demand (HS-LD)[54].

Primary ecosystem services	Secondary ecosystem services	Value of ecosystem services per unit area (yuan/hm²)					
		Arable land	Woodland	Grassland	Water	Building land	Unused land
Supply service	Food production	2300.2	617.6	485.7	1363.5	0	10.4
	Raw material production	510.0	1408.6	714.7	759.8	0	31.2
	Water supply	− 2716.5	728.6	395.5	11,324.1	0	20.8
Regulatory services	Gas regulation	1852.7	4642.0	2511.8	2779.0	0	135.3
	Climate regulation	968.0	13,898.3	6640.4	6130.4	0	104.1
	Decontaminate the environment	281.0	4059.2	2192.7	9523.5	0	426.7
	Hydrological regulation	3112.0	9013.5	4864.1	131,631.8	0	249.8
Support services	Soil conservation	1082.5	5662.0	3060.0	3372.2	0	156.1
	Maintaining nutrient cycling	322.7	430.2	235.9	260.2	0	10.4
	Biodiversity	353.9	5148.6	2782.4	10,845.3	0	145.7
Cultural service	Aesthetic landscape	156.1	2262.0	1228.2	6890.2	0	62.5
Total		8222.4	47,870.5	25,111.4	184,879.9	0	1353.1

Table 2. Value of ESs per unit area in the AnHui Section in the YHWD Project.

ESs' Supply–demand balance
The balance represents the degree of coordination between the ecosystem and human well-being[55].

$$Cv = \sqrt{\frac{P \times N}{((P + N)/2)^2}} \qquad (4)$$

where: Cv is the equilibrium index; P is the supply index; N is the demand index. The higher the equilibrium index is, the better the coordination. 0 means complete dissonance and 1 means good coordination. With reference to relevant literature, this paper divides the equilibrium degree into the following 5 sections (Table 3):

PLUS model

The PLUS model combines two modules: the LESA model and the CA model[56]. This integration enables the accurate simulation of nonlinear relationships associated with land utilization changes and allows for the examination of the effects of land utilization on potential ES functions in different policy scenarios in the future[57].

1. *Confirm model accuracy* Firstly, land utilization data spanning from 2000 to 2010 was used as input for the model, extracting the land use expansion map over this timeframe. Next, the expansion map, along with the driving factors, was loaded into the LEAS module. Generate various types of land development potential maps. Finally, the 2010 land use data and the development potential map for each type of land were input into the CA module, along with the simulation parameters. The simulated data was subsequently juxtaposed with the real data to evaluate the simulation's accuracy. The results show a Kappa coefficient of 0.939. The Kappa coefficient is a statistical indicator used to assess the consistency between model prediction results and actual observed data. The outcome indicates substantial consistency between the simulated data and the real data.
2. *The specific research parameter settings are as follows* In the LESA module, the sampling frequency is set to 0.01, and the number of regression trees is set to 20. The sampling frequency refers to the frequency at which samples are extracted from the original dataset during data processing or model training. Setting the number of regression trees to 20 indicates that the model will use 20 independent regression trees to construct a random forest model. With the sampling frequency set at 0.01 and the number of regression trees at 20, the computational efficiency and performance of the model are optimized. In the CARS module, the domain weight can be determined by evaluating the expansion mode of different land categories during the process of change[58]. This evaluation provides a quantitative measure of the intensity with which various land use types expand, and the resulting value ranges from 0 to 1. This study calculates the area covered by different land use categories using a transfer matrix approach. By applying the formula below, the domain weight for each land use category is derived. The formula is as follows[59]:

Level	Complete disorder	Less severe disorder	Fundamental balance	Relative coordination	Quality coordination
Value of a score	0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1

Table 3. ESs of supply and demand equilibrium.

$$Wi = \frac{Ti - T\min}{T\max - T\min} \qquad (5)$$

It means that Wi is the weight of Class i land domain, Ti is the expansion area of Class i land use, T_{min} is the minimum expansion area of each type of land, and T_{max} is the maximum expansion area of each type of land. The calculation results showed that the factors of arable land, forest land, grassland, water area, building land, and unused neighborhood were set as 0, 0.48, 0.49, 0.52, 1, and 0.51. The setting of the neighborhood factor depends on the conversion probabilities and trends between different land use types, aiming to reflect the interactions and conversion potential among various land use types[60]. Based on the conversion probabilities of various land use types from 2010 to 2020, the neighborhood factors for cultivated land, forest land, grassland, water areas, construction land, and unused land are set to 0, 0.48, 0.49, 0.52, 1, and 0.51, respectively.

Result
Evolution of land use pattern

A comparative analysis was conducted on the land use status of the YHWD project in the Anhui section for the years 2000, 2010, and 2020 (Fig. 3). Across the entire region (Fig. 3), farmland accounts for the largest proportion, followed by build-up land. Over the past two decades, there has been a noticeable decrease in the areas of farmland and forest. Conversely, the coverage of water and build-up land has significantly increased. From 2000 to 2010, the comprehensive dynamic outlook before the project construction was 0.16%. From 2010 to 2020, under the influence of project construction, the comprehensive dynamic attitude rose to 13.79%. In conjunction with Fig. 4, the reduction rates of farmland and grassland show almost no change. However, from 2010 to 2020, the reduction rate of forest land increased sharply. In contrast, the growth rates of water and unused land from 2010 to 2020 show a significant increase compared to the period from 2000 to 2020. Similarly, the growth rate of build-up land also shows an upward trend. It is noteworthy that the changes in land use types are not only influenced by the water diversion project but also by other factors such as urban construction, urban and rural planning, and climate change. In terms of urban construction, the acceleration of urbanization has led to an increase in build-up land area and a decrease in farmland and forest areas. Adjustments in urban and rural planning have also affected changes in land use types; for instance, some farmland may be reclassified as build-up land to meet urban development needs. The impact of climate change on land use types cannot be ignored either. For example, warming climates could lead to an increase in water area in certain regions, while drought could result in a decrease in farmland area (Table 4).

Changes in ES supply, demand, and equilibrium degree
Temporal and spatial changes of ES supply and demand
<u>Temporal and spatial evolution of ES supply.</u> From a regional perspective, the supply level of ESs was relatively low between 2000 and 2020 (Fig. 4). The southern region exhibited a higher supply capacity than the northern region. Over the past two decades, the total value of ESs experienced a decline followed by a subsequent increase, with a continuous decrease observed from 2000 to 2010. From 2010 to 2020, the total value of ESs gradually increased. Moreover, the rate of decline was faster than the rate of increase, and the final reduction was 978 million yuan. In Table 5, it is evident that the rate of change in the two time periods is consistent for most ESs. These services exhibited a gradual decrease over time, following a linear trend. Conversely, water supply service increased linearly. The decline rate of water purification services and biodiversity services from 2000 to 2010
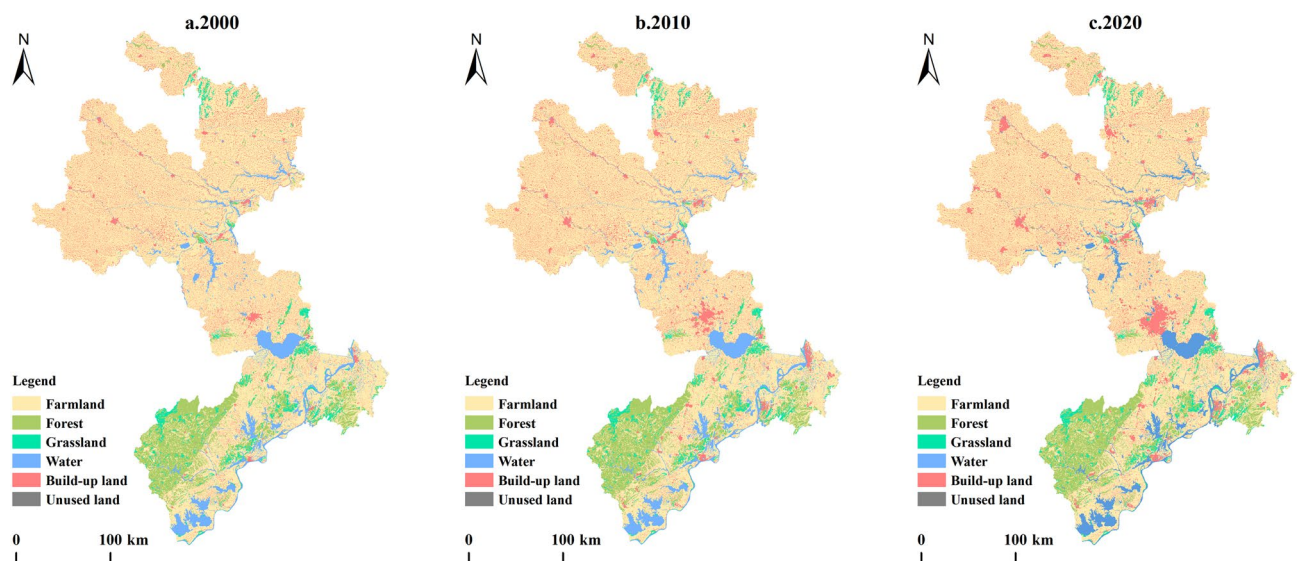

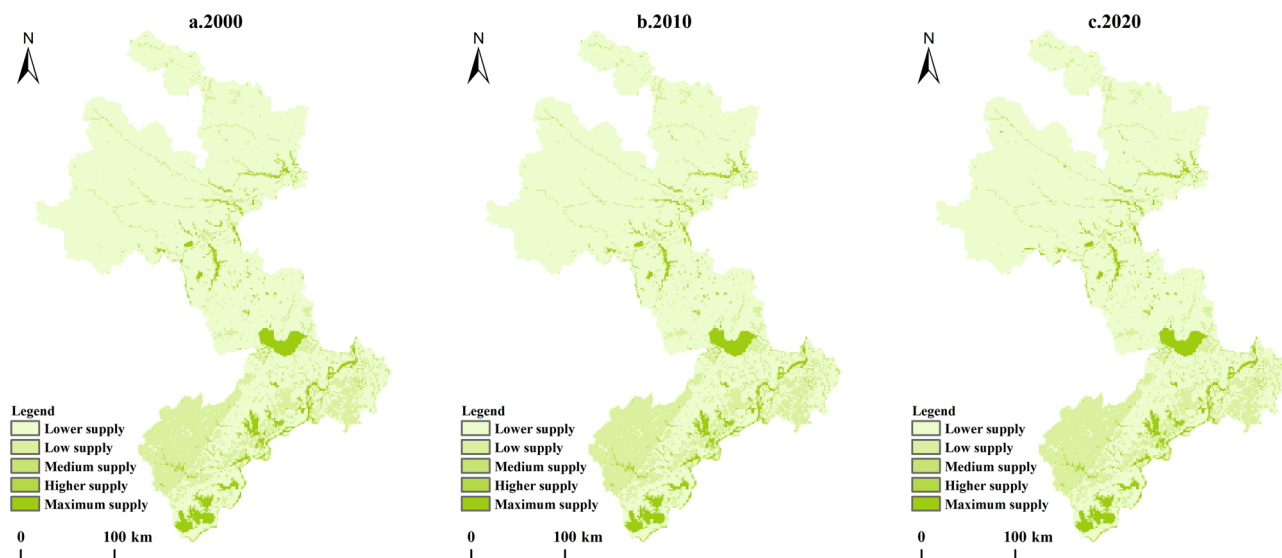**Fig. 3.** Land use status map in 2000, 2010 and 2020.

Fig. 4. Pattern of ESs' supply in 2000, 2010 and 2020.

Types of land	2000 year	2010 year	2020 year
Farmland	51,693.24	50,558.2	19,587.9
Forest	6988.08	6963	6929.81
Grassland	2050.38	2037.1	2023.84
Water	4492.22	4513.1	4552.13
Build-up land	8498.57	9651.63	10,619.18
Unused land	3.51	2.97	13.14

Table 4. Changes in land use in YHWD project types of land/km^2.

Ecosystem services	Individual ES supply 2000、2010、2020 (hundred million)		
	2000 year	2010 year	2020 year
Food production	130.34	127.74	125.53
Raw material production	41.09	40.48	39.96
Water supply	− 83.65	− 80.36	− 77.31
Gas regulation	145.84	143.65	141.77
Climate regulation	188.31	186.91	185.66
Decontaminate the environment	90.17	89.92	89.85
Hydrological regulation	825.15	824.07	825.81
Soil conservation	116.95	115.61	114.47
Maintaining nutrient cycling	21.34	20.97	20.65
Biodiversity	108.7	108.36	108.24
Landscape aesthetics	57.35	57.24	57.27
Ecosystem service supply	1641.58	1577.35	1631.9

Table 5. Changes in the supply value of individual ESs in the study area.

was significantly higher than it was from 2010 to 2020. Furthermore, hydrological regulation services decreased continuously from 2000 to 2010 and gradually increased from 2010 to 2020, with a higher rate of increase than the rate of decline.

Although the construction of the project does not significantly affect most services, it has a considerable impact on services such as water purification, biodiversity, and hydrology regulation. Among these services, hydrological regulation is most significantly affected. Additionally, in terms of supply capacity, section I > section

III > section II. The ES value of section III has increased by 138 million yuan, while that of section I has decreased by 327 million yuan.

<u>Spatial and temporal evolution of ES demand.</u>   From an overall perspective, the demand for ESs increased by 95.44% from 2000 to 2020 (Fig. 5), and the intensity of demand increased in the northern region and diminished in the southern region, contrary to the spatial pattern of supply capacity. The growth rate from 2000 to 2010 was 40.47%, while that from 2010 to 2020 was 31.8%. The growth rate of demand is declining, and the relocation activities caused by construction projects may be one of the underlying reasons. In terms of demand intensity, section III > section II > section I. Moreover, the demand intensity is consistent with population density and built-up land distribution. Sections III, II, and I increased by 22,243.5, 16,025.4, and 10,472, respectively. Due to the rapid development of Hefei, built-up land has expanded rapidly and the population has increased, resulting in the most prominent growth in demand in section II. Among them, Hefei, Bengbu, Fuyang, Bozhou, Huainan, Wuhu, and other cities have high demand intensity, which gradually decreases from the city center to the periphery. Overall, the supply and demand in the Anhui section of the YHWD Project show great differences in spatial position.

Changes in the supply and demand relationship of ESs
As can be seen from Table 6, the general balance between supply and demand for the YHWD Project in the Anhui section from 2000 to 2020 is considerable. Moreover, there is a noticeable variation in spatial distribution, with high levels in the northern region and low levels in the southern region. The overall distribution of the quality coordination area surpasses that of the completely disordered area. From 2000 to 2010, the size of completely disordered areas decreased continuously, but from 2010 to 2020, the area affected by engineering construction increased. Similarly, despite the increasing extent of areas with minor disorders, its increase from 2010 to 2020 has demonstrated a substantially higher rate compared to the pace in the preceding period. The preceding period exhibited a higher growth rate in the relative coordination area compared to the rate in the succeeding period. In contrast, the area of quality coordination experienced a continuous decrease. Interestingly, the decline rate in the latter period was relatively slower than that observed in the earlier period. Conversely, the construction of the project has a certain effect, and the most affected disordered area in section I increased significantly compared
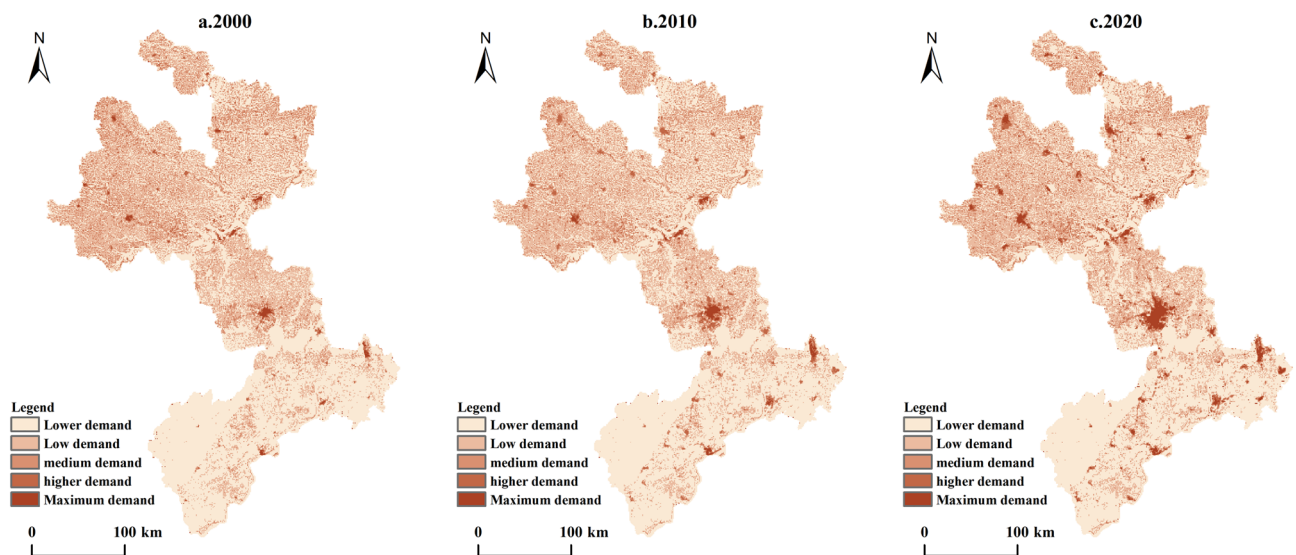

Fig. 5. Demand pattern of ESs in 2000, 2010 and 2020.

Equilibrium pattern of supply and demand	Equilibrium pattern of supply and demand of ESs in 2000, 2010, 2020		
	2000 year	2010 year	2020 year
Severely dislocated	23,086	22,624	22,708
Less severe disorders	1874	1999	2221
Basic equilibrium	3111	3534	3820
Higher coordination	1904	9105	9279
High-quality coordination	39,648	38,363	37,624

Table 6. Equilibrium pattern of supply and demand of ESs in 2000, 2010 and 2020.

to the corresponding size of the area before the construction of the project. Research conducted revealed that low supply-high demand (LS-HD) and low supply-low demand (LS-LD) significantly dominate the research area, constituting approximately 34.5% and 40.9% of the area, respectively.

From a regional perspective, the alteration of supply and demand equilibrium is consistent with the trend of change in the demand index (Fig. 6). The regions with high-quality coordination and relative coordination are concentrated in sections III and II, while the regions with complete disorder and relative coordination are mainly concentrated in section I. The proportion of LS-HD and LS-LD in section III is relatively high, being 55% and 38.5%, respectively, and the distribution of supply index and demand index is relatively coordinated. Among them, the section of Yangtze River to Huaihe communication is dominated by LS-HD, accounting for approximately 41% of communication. Due to the low supply index and population agglomeration, the demand intensity has increased, and the demand is greater than the supply. Section II has superior natural conditions in the research area, and HS-LD dominate there, accounting for approximately 52% of land use, and the overall supply surpasses demand. With the rapid development of surrounding towns and cities, the built land is gradually intensifying, and the demand for ESs continues to improve, resulting in the constant improvement of the supply and demand equilibrium.

Correlation between land use change and the balance between ES supply and demand

The Moran's I index test indicates a significant correlation between the current state of land use and the balance of ecosystem services (ES) supply and demand across different study periods (Fig. 6). The findings indicate that alterations in the supply–demand balance exhibited a linear association, with changes observed in various land categories. Variations in the extent of different land use types will consequently induce modifications in the equilibrium of ES supply and demand.

Further examination of the heat map depicting correlation (Fig. 7) shows that the degree of correlation between various land use types and the supply–demand balance corresponds to the following sequence: arable land holds the highest proportion, followed by forest land, water area, built-up land, grassland, and unused land. There is a positive association between the balance of supply and demand and the proportion of farmland and built-up land. Conversely, a negative correlation is observed between the proportion of forest land, grassland,
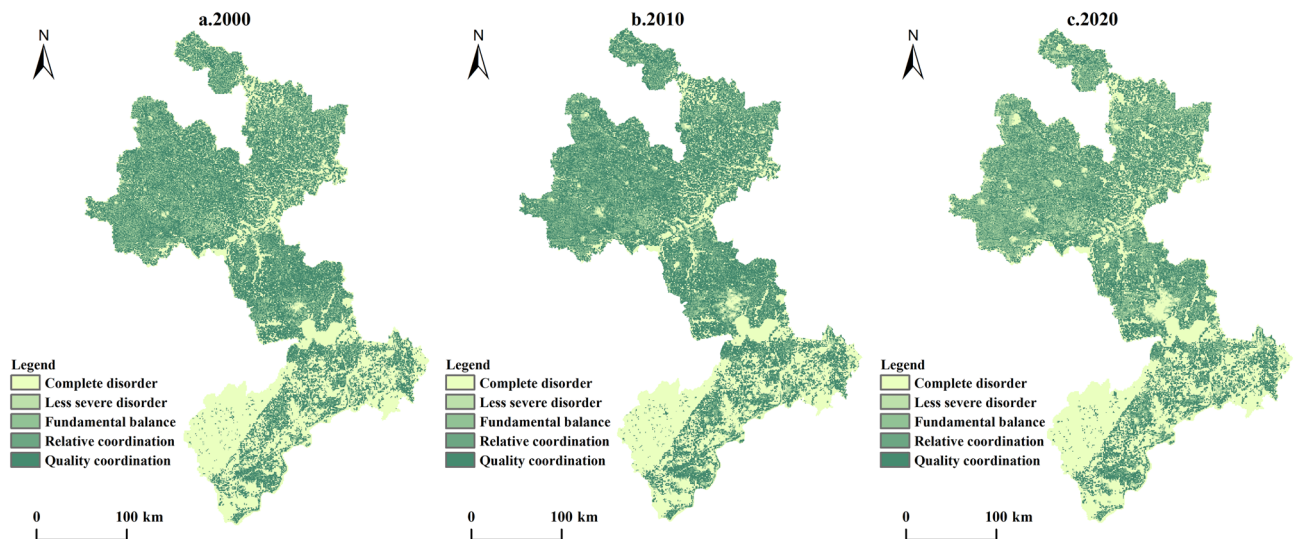

Fig. 6. Area changes in the balance between supply and demand for ESs between 2000, 2010 and 2020.
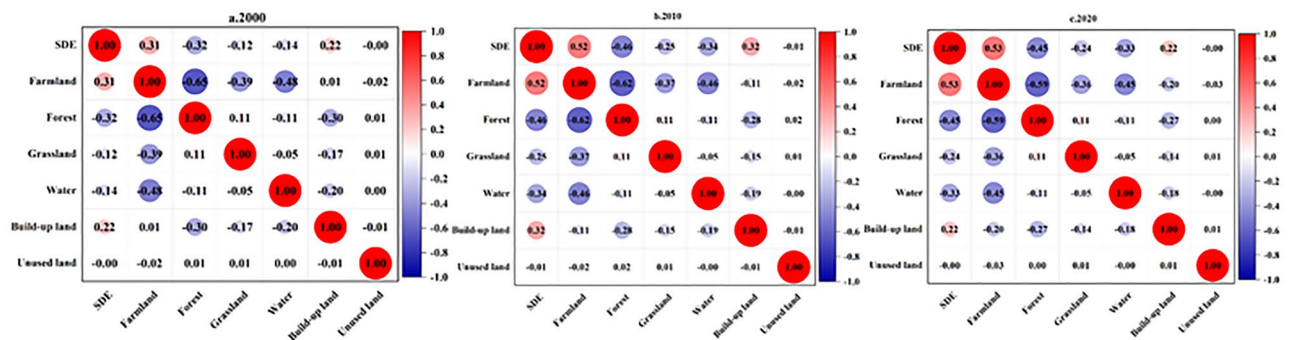

Fig. 7. The correlation between land use proportions and the supply–demand equilibrium from 2000, 2010 and 2020.

and water area. In 2000, the correlation coefficients of forest, farmland, built-up land, water area, grassland, the proportion of unused land, and supply and demand equilibrium were 0.32, 0.31, 0.22, 0.14, 0.12, and 0.004, respectively. In 2010, the correlation coefficients were 0.52 for farmland, 0.46 for forest, 0.34 for water, 0.32 for built-up land, 0.25 for grassland, and 0.007 for unused land. In 2020, the correlation coefficients were 0.53 for farmland, 0.45 for forest, 0.33 for water area, 0.24 for grassland, 0.22 for built-up land, and 0.002 for unused land.

The quality coordination of the research area is mainly in sections III and II and mostly consists of farmland and built-up land, dominated by LS-HD areas. The coordination and LS-HD suggest that the difference between supply and demand in this region is minimal: most of the seriously disordered areas are located in section I. Hence, while ensuring an equilibrium between supply and demand, it is essential to uphold harmony between cultivated and built-up land to curtail the surge in demand. Section III has a large difference between supply and demand and, owing to its substantial supply of natural materials, can be properly developed to increase demand.

Forecast of supply and demand of ESs in 2030

Based on the above research, the PLUS model was implemented to estimate future supply and demand modes by predicting land use. The prediction results show that in 2030, farmland and built-up land will dominate the research area, with farmland accounting for the largest proportion (65.99%). Compared with 2020, the area of farmland and forest in the research area in 2030 will decrease by 935.65 km^2 and 23.58 km^2, respectively, with farmland area showing the most significant decrease.

In terms of supply (Table 7), the ES value of the YHWD Project in the Anhui section will be 162,989 billion yuan in 2030, with the water area accounting for the highest proportion. Farmland will be second, accounting for 24.54% of the ES value. Compared with 2020 figures, the ES value of the research area will decrease by 1.52% in 2030. Moreover, in 2030, the ES of farmland, forest, and grassland will experience a decline, whereas the ES of water and unused land will witness an increase. The continuous transformations in land use, caused by engineering construction, have led to significant ecological changes, particularly regarding farmland and water.

The demand index of the research area in 2030 evaluates the population and economic densities for that year, taking into account the population and GDP growth rates in 2000, 2010 and 2020. Additionally, the index determines the percentage of built-up land by analyzing the projected land use data for 2030. As a consequence of the ongoing progress in urban infrastructure, there has been a noticeable rise in the allocation of land for construction purposes. Furthermore, the growth in GDP resulting from economic advancement will fuel the escalating demand for ESs relative to 2020. Specifically, the maximum demand areas will still be primarily located in urban areas, and the overall ES demand will be low in section I due to increased forest and water area (Fig. 8). Section III has many small and medium-sized cities, the construction land density is largely dense, and the overall ES demand is high. With Hefei city as a core, the demand for ESs in section II is highest, and the demand gradually decreases from the core to the outside.

According to scientific research, land use has a substantial impact on supply and demand. A comparison between the ES balance in 2020 and projections for 2030 reveals significant improvements in the overall ES balance and a noticeable shift in equilibrium. LS-HD and LS-LD still dominate supply and demand.

Discussion

Impact and forecast of water and heating engineering on ES supply and demand

Due to extensive resettlement and population migration, the implementation of the YHWD Project has not only resulted in a substantial rise in water area and built-up land but also has a notable impact on land use transformation[61]. Between 2000 and 2010, land use change was characterized by a decrease in farmland and forest and an increase in built-up land. This situation occurred before the project was constructed, and urban development may have been the primary driving factor[62]. From 2010 to 2020, the predominant land use change involved the transition from other land use types to water and built-up land. This period witnessed a swift expansion of water, with unconventional interference projects being the likely primary driving factor[63]. Compared with other relevant studies, there are similar research results on the impact of engineering construction on land use change[64].

The construction of the Anhui section of the YHWD project has both positive and negative impacts on ES supply. The project has increased water production and improved hydrological regulation[65], but services such as environmental purification and biodiversity continue to decline (Fig. 9). The influence of engineering projects on water production and hydrological regulation is greater than the influence of other factors, consistent with

Types of land	2020 year		2030 year		2020–2030 years	
	Value/billion yuan	Contribution ratio/%	Value/billion yuan	Contribution ratio/%	Trends	Variable/billion yuan
Farmland	407.73	24.99	400.04	24.54	Decline	− 7.69
Farmland	331.73	20.33	330.61	20.28	Decline	− 1.12
Grassland	50.82	3.11	50.51	3.10	Decline	− 0.31
Water	841.60	51.57	848.71	52.07	Rise	7.11
Build-up land	0	0	0	0	Rise	0
Unused land	0.02	0	0.02	0	Rise	0
Total	1631.90	100	1629.89	100	Decline	− 2.01

Table 7. Changes in the value of ESs in the study area in 2020 and 2030.
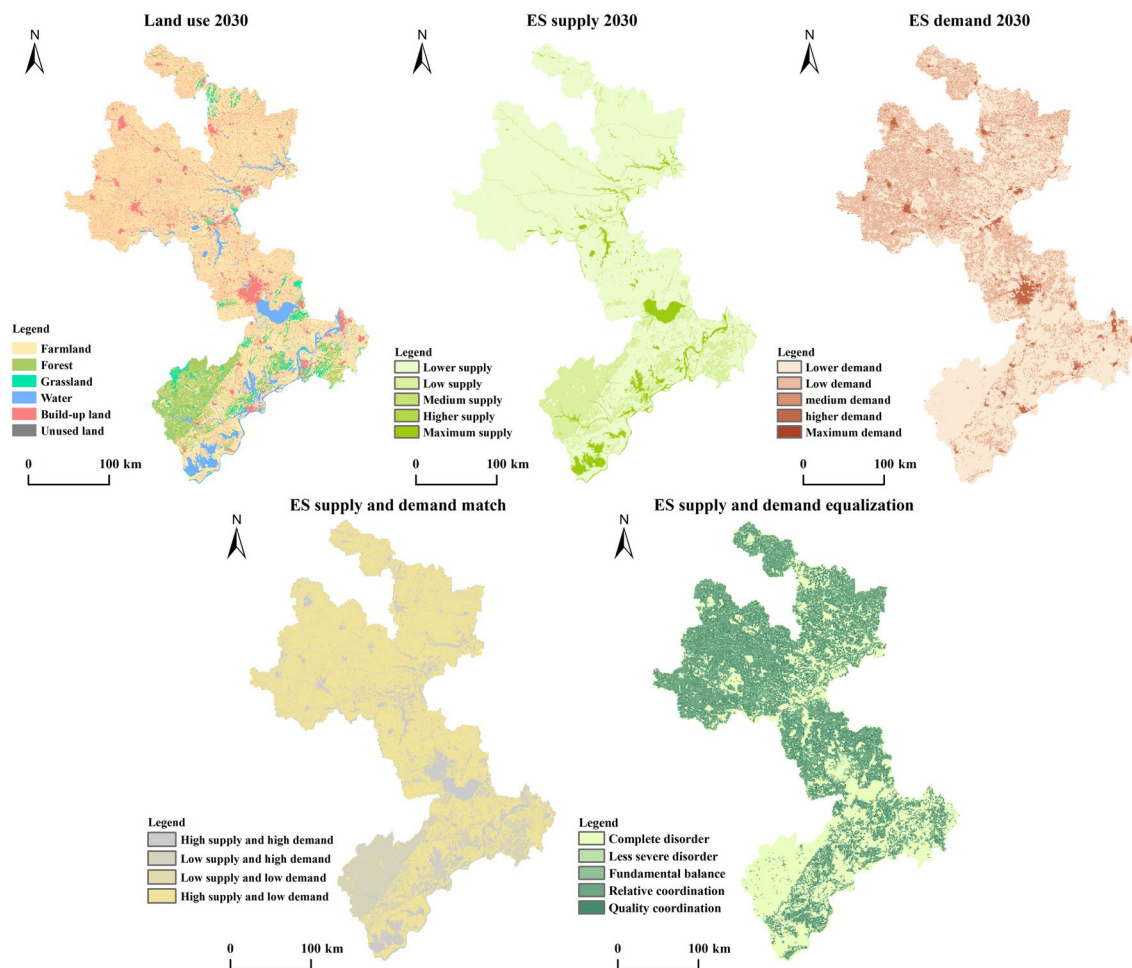
Fig. 8. Map of ESs' projections for 2030.

research findings on the Three Gorges reservoir area and other related studies. According to the research findings, an alteration of land use patterns resulting from engineering construction leads to spatio-temporal variations in supply and demand. The influence of the engineering project on demand primarily stems from a rise in built-up land proportion and changes in demand due to population migration. At the initial construction phase, the area of serious imbalance increased and the area of quality coordination decreased. Furthermore, the intricate nature and diverse composition of human and environmental systems typically result in the transmission of supply–demand of ESs[66]. Consequently, conducting dynamic temporal evolution studies becomes imperative to effectively comprehend the magnitude of supply–demand within the designated research vicinity.

Factors influencing the supply and demand of ESs in the YHWD project

When examining factors influencing the supply and demand of ESs and land use changes beyond the construction of the YHWD project (Anhui section), it is crucial to recognize that the dynamics of land use are the result of the interaction of multiple factors. Analyzing the sensitivity of various land uses to eight driving factors not only unveils the intrinsic mechanisms of land use change but also validates the effectiveness of the PLUS model in predicting and simulating land use dynamics. The sensitivity of different land uses to these driving factors varies: farmland is most sensitive to population density and GDP, forests to temperature and population density, grasslands to temperature and elevation, water to population density and distance from rivers, built-up land to population density and distance from major roads, and unused land to temperature and GDP[67]. The construction of the YHWD Project (Anhui section) has had significant impacts on forest, water, build-up land, and unused land, while its effects on farmland and grassland are relatively weaker. This can be attributed to factors such as land acquisition during the construction process, resettlement of residents, and related policy directives. For instance, from 2010 to 2020, the area of water bodies increased by 0.86%, partially due to the implementation of the water diversion project. However, it is important to note that this impact is not caused by a single factor, but is the result of the combined effects of other human activities and natural factors. With the acceleration of urbanization, the types of land use in urban fringe areas have undergone significant changes. We observed that the area of build-up land increased by 10.02% from 2010 to 2020, which is significantly higher than the growth rate from 2000 to 2010 (Fig. 10). This change is mainly due to urban expansion, where farmland and forest have been converted to build-up land to meet the demand for residential and commercial facilities. For example,
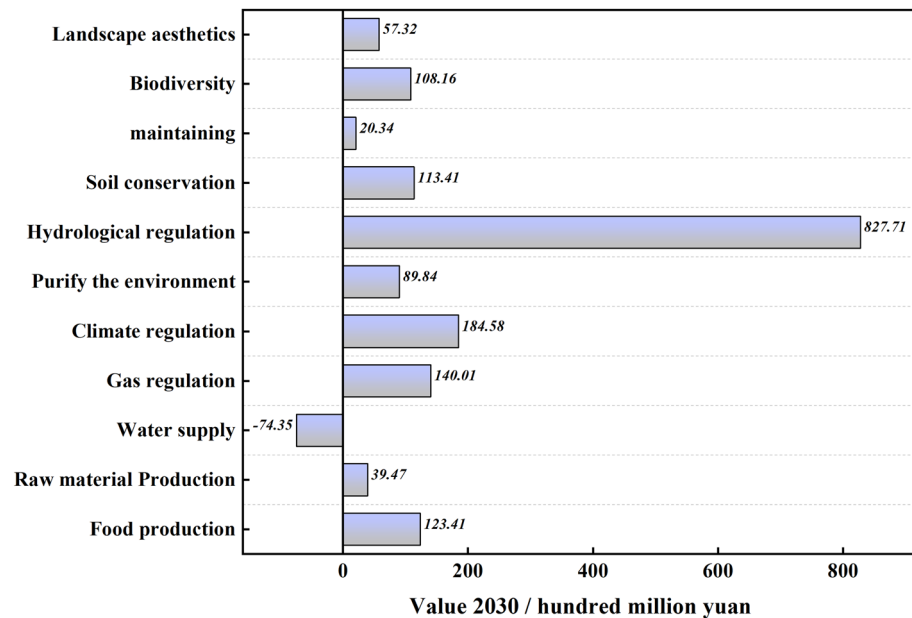
Fig. 9. Changes in the supply value of individual ESs in the study area.

Hefei, the capital of Anhui Province, experienced rapid urbanization during this decade, resulting in a large amount of farmland being converted into build-up land. Adjustments in urban and rural planning policies also significantly influenced changes in land use types. To promote balanced regional development, some areas may have implemented new land use plans, such as establishing industrial parks or new urban districts, leading to large-scale land use transformations. For instance, the urban master plan implemented in Chuzhou during this period likely led to the conversion of suburban farmland into build-up land.

In addition to the aforementioned human activities, other factors also influence land use changes. Economic growth and industrial structure adjustments are significant factors affecting land use changes. Farmland and unused land are most sensitive to GDP changes. With the rapid economic development in Anhui Province, the expansion of the secondary and tertiary industries may have led to more land being utilized for industrial and service sectors. Changes in population density significantly impact various types of land use, especially farmland, forest, and build-up land. Population growth and urbanization have accelerated the expansion of build-up land while also increasing pressure on farmland. Climate factors, particularly temperature changes, have a significant impact on forest and grassland. Climate warming may lead to changes in vegetation cover in certain areas, thereby affecting land use types. Changes in agricultural policies, such as land transfer policies and agricultural subsidy policies, may also lead to changes in farmland types and intensified land use. For example, the agricultural modernization policies implemented in Anhui Province may have promoted the formation of large-scale agricultural land, altering the traditional small-scale farming model. The land use changes observed in 2000, 2010, and 2020 are the result of the combined effects of multiple factors. While the implementation of the YHWD Project has indeed impacted land use in the study area, it is only one of many influencing factors. Urban construction, urban and rural planning, economic development, population changes, and climate change all shape the land use patterns in the study area. This complex interaction has ultimately led to the observed trends in land use changes and has profoundly impacted the supply–demand balance of ESs. Future research should aim to further quantify the relative contributions of these factors to better understand the driving mechanisms of land use changes, providing more precise scientific evidence for regional sustainable development and ecosystem service management.

Changes in the supply and demand of ESs are also influenced by multiple factors. As an illustration, ES supply first decreased and then increased from 2000 to 2020, which may be associated with factors such as agricultural policy adjustments, climate change, and biodiversity reduction[68]. Moreover, adjustments in agricultural policies may lead to a decrease in food and raw material production, while climate change may affect the supply of climate regulation services. For example, global warming can impact the distribution of water resources, thereby affecting the supply of hydrological regulation services. Furthermore, the decline rates of water purification services and biodiversity services were significantly higher from 2000 to 2010 compared to their levels from 2010 to 2020, which may be related to the implementation of pollution control measures and the strengthening of ecological protection policies.

ES demand is higher in the north and lower in the south—opposite to the spatial pattern of supply capacity. This phenomenon may be associated with factors such as population growth, urban expansion, and economic development. For example, the rapid development of cities such as Hefei has led to a rapid expansion of construction land and a concentrated increase in population, significantly raising ES demand. Moreover, the migration activities of residents due to construction projects may be one of the reasons behind the decrease in demand growth rates. The changes in the equilibrium of supply and demand align with the trends in demand index changes, with high-quality and high coordination areas concentrated in sections where water is sent north and the
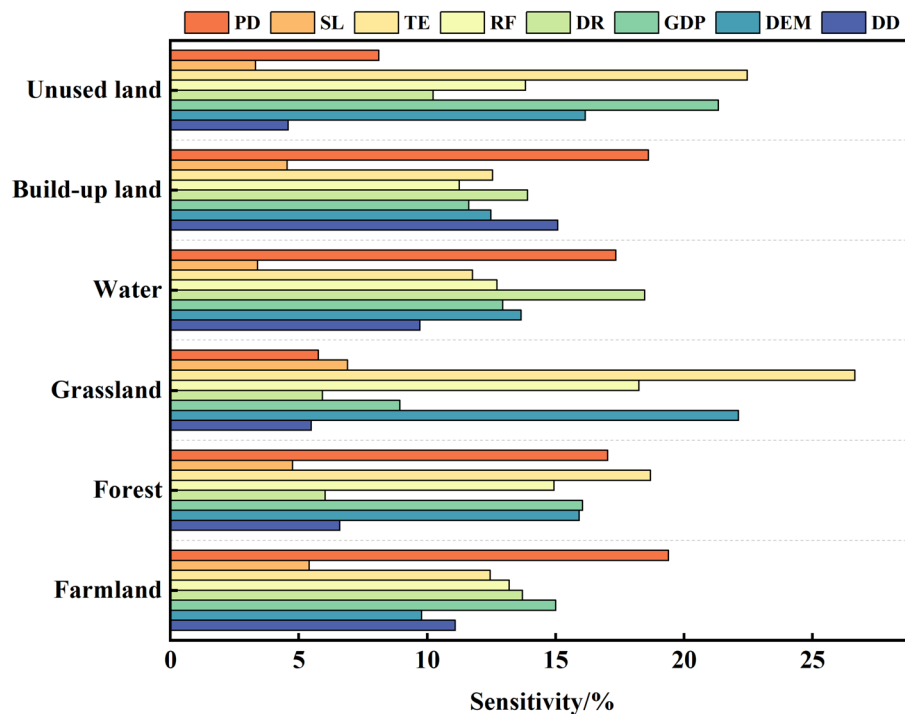
Fig. 10. Sensitivity of various land uses to drivers.

section where the Yangtze and Huaihe rivers are connected, while areas of complete disorder and low coordination are mainly concentrated in sections where water is diverted to Lake Chaohu. This outcome may be related to factors such as regional economic development levels, population density, and distribution of construction land. For example, sections where water is sent north and where the Yangtze and Huaihe rivers are connected have high economic development levels and large population densities, leading to high ES demand and relatively low supply capacity, resulting in patterns of high demand with low supply and low demand with low supply. In contrast, in the section where water is diverted to Lake Chaohu, there are more favorable natural conditions and stronger ES supply capacity but relatively lower demand, resulting in a pattern of high-supply with low demand.

The changes in ES supply and demand in the middle and lower reaches of the Yangtze and Huaihe rivers are the result of the combined effects of multiple factors. In assessing these changes, we need to comprehensively consider factors beyond the construction of the Anhui section in the YHWD Project, such as urban development, agricultural policies, natural disasters, and socioeconomic changes as well as their interactions to gain a comprehensive understanding of the dynamic changes in ES supply and demand and provide a scientific basis for sustainable regional development.

Coping strategies for ES supply and demand in the YHWD Project

Although the construction of water diversion projects cannot compensate for the damage caused by natural ecosystems, it can reduce the damage[69]. When a decision is made to build a water diversion project, policy measures should be attempted to minimize threats. During the establishment of the region covered in this research, the conversion of arable land and forest land into built-up land and water areas led to a notable decrease in the availability of ESs. Consequently, there was a substantial increase in demand, resulting in a significant misalignment . When a decision is made to build a water diversion project, policy measures should be attempted to minimize threats. During the establishment of the region covered in this research, the conversion of arable land and forest land into built-up land and water areas led to a notable decrease in the availability of ESs. Consequently, there was a substantial increase in demand, resulting in a significant misalignment between supply and demand. The ecological and environmental monitoring system established during the construction of the Three Gorges Project can serve as a reference, and the monitoring report can be used as a comprehensive evaluation basis for policy regulation. To build a sound monitoring and evaluation system for ES supply and demand, local governments must cover the entire project basin, including areas with HS-HD, HS-LD, LS-LD, and LS-HD for ecological supply and demand monitoring and specific assessment[69]. Firstly, this comprehensive approach aims to capture the impact and changing trends of the project on ES supply and demand. Moreover, the quality and stability of ES supply should be improved[70]. The local government should continue to promote the protection and restoration of the ecosystem. They should refer to Hu's research and use the matching degree of supply and demand to classify the priority level of ecological restoration, formulate restoration zones and optimization strategies[71], and prioritize the protection of areas severely impacted by major engineering construction[18].

Supply and demand should serve as the basis for the supervision and evaluation of the planning and implementation of ecological restoration in engineered river basins[55]. Additionally, the alterations in hydrology

resulting from the project's construction may affect the spawning grounds and migration routes of fish in the Yangtze River Basin, resulting in a decline of biodiversity in the basin. Consequently, local governments need to formulate strategic plans and action plans for biodiversity protection in water diversion projects and improve the policy and institutional framework for biodiversity protection[54]. Furthermore, focus should be placed on high-supply areas, and the construction of the biodiversity conservation network system should be accelerated[53], incorporating biodiversity indicators into the monitoring and evaluation system of water diversion projects between basins.

Contribution and limitation of the study

This study effectively bridges the gap between theory and reality through specific case analyses. At the theoretical level, this research deepens an understanding of the supply and demand dynamics of ESs, particularly in the context of land use changes under cross-basin water diversion projects. By examining the Anhui section of the YHWD project, we have unveiled the concrete relationships between different land use types (e.g., farmland, forest, and water areas) and the dynamics of ES supply and demand. These findings not only enrich existing theories but also provide new perspectives on understanding the impact of land use management strategies on ESs.

Compared to previous studies[51,52], our research places greater emphasis on the quantitative relationship between land use changes and the balance of ES supply and demand, providing empirical support for theoretical models. The use of the PLUS model to predict future land use changes, with a high kappa coefficient of 0.939 for simulation validation, further confirms the scientific validity of our results. The integrated application of EFM and the GeoDa model to analyze the relationship between ES supply and demand enhances the accuracy and reliability of the study. Compared to single models or methods[72], our research is more comprehensive in methodology.

Considering the complex interactions of multiple factors such as climate change and human activities, our research provides a scientific basis for the development of adaptive management strategies. Unlike studies that focus solely on theoretical analysis[50], our research emphasizes practical applications, providing direct guidance for sustainable regional development. By revealing the impact of water diversion projects on the balance between ES supply and demand, this study provides a scientific basis for public participation in environmental protection and decision-making, thereby positively impacting society and human well-being. Unlike studies that focus solely on academic contributions[49], our research emphasizes social impact, contributing to the advancement of society and environmental protection.

Although this study has made a preliminary contribution to an analysis of the balance between ES supply and demand in the YHWD Project (Anhui section) and provided a scientific basis and decision support for sustainable regional development, we are acutely aware of the limitations in our research. For instance, due to data source constraints, we were unable to obtain continuous land use data from 2000 to 2020 and instead used discrete data points from the years 2000, 2010, and 2020. This discontinuity in data may affect a comprehensive understanding of land use change trends. Moreover, in the selection of driving factors for the PLUS model, our consideration of climatic factors was not sufficiently comprehensive. The impact of climate change on ESs is complex, and future research should place great emphasis on the role of climatic factors to enhance the predictive accuracy and explanatory power of the model. We look forward to overcoming these limitations in future research and providing an in-depth analysis.

Conclusion

This study focuses on the YHWD Project as an empirical research area. Moreover, this research utilizes EFM and the GeoDa model to analyze the influence of the supply and demand relationship in the Anhui section of the YHWD Project. Additionally, this study predicts the future matching pattern of supply and demand by incorporating the PLUS model to provide theoretical support for the sustainable and healthy development of the basin ecosystem. The results are as follows: (1) The comprehensive dynamic attitude before construction was 0.16% from 2000 to 2010. During construction, from 2010 to 2020, the comprehensive dynamic attitude increased to 13.79%. Project construction had a significant impact on the change in land use patterns. The influence of engineering construction on farmland and grassland is weak but on forest, water area, build-up land, and unused land, it is strong. (2) Engineering construction has a great impact on water purification, biodiversity, and hydrological regulation; notably, the impact on hydrological regulation services is greatest. The migration of residents and economic development resulting from construction may be one of the reasons for the change in demand. (3) The significance test results of ES supply–demand balance and land use reveal a correlation between the matching degree of supply and demand and land use. The proportion of arable land and building land consistently shows a positive correlation with the balance between supply and demand. Conversely, the proportion of forest, grassland, and water area exhibits a negative correlation. Nevertheless, the land use factor merely constitutes a single component that impacts the equilibrium. Hence, it is crucial to integrate this research with the prevailing circumstances for a comprehensive analysis. The construction of the river diversion project is primarily responsible for causing environmental change in the Jianghuai River Basin. Additionally, other practices related to land use and management are part of the driving forces behind environmental change. Therefore, the ecological environment impact caused by the project is intricate and uncertain.

As global climate patterns continue to evolve, it is anticipated that significant changes will occur in rainfall patterns, temperatures, and extreme weather events. These changes will further impact the ecosystem services within the YHWD Project area. Therefore, future research should consider incorporating additional climate factors into models to accurately predict and assess the impacts of these factors on the supply and demand dynamics of ESs. This incorporation will not only help to foster an understanding of the potential effects of climate change on the ESs in the YHWD Project area but also provide a scientific basis for developing adaptive management

strategies to mitigate the negative impacts of climate change and promote the sustainable and healthy development of ecosystems.

Data availability

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Wenqing Ding: supervision, writing—review and editing, investigation, resources. Guangzi Shi: conceptualization, investigation, writing—original draft, data curation. Hui Zha: resources, validation. Haojie Miao, Mengmin Lu: formal analysis. Jing Jin: supervision, writing—review and editing.

Competing interests

The authors declare no competing interests.

Additional information

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