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Original Research

Dynamic Analysis and Prediction of Water Conservation Value of the Beidagang Wetland Ecosystem in Tianjin

Rongfeng Qiao[1], Ruqing Bai[1], Bailin Zhang[1], Jinyun Gao[2]*

[1]School of Environmental Science and Engineering, Tiangong University,
No. 399 Binshui West Road, Xiqing District, Tianjin 300387, China
[2]Faculty of Geography, Tianjin Normal University,
No. 393 Binshui West Road, Xiqing District, Tianjin 300387, China

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Abstract

The purpose of this study is to explore the water conservation value of the Beidagang wetland ecosystem in Tianjin under different scenarios, to explore the scenario plan to promote the sustainable development of the Beidagang wetland, and to provide a scientific basis for the improvement of water conservation function and the formulation of a sustainable development strategy. The Beidagang wetland is the largest wetland and an important water conservation function area in Tianjin; we take Beidagang wetland and its surroundings as an example, obtain the water conservation quantity based on the correction of the InVEST model, and estimate the value by using the shadow engineering method combined with the Fixed Asset Investment Price Index. The PLUS model was used to predict land use changes under the natural development scenario, wetland protection scenario, and tourism development scenarios in 2030 and 2040 and to predict the trend of changes in its water conservation value to provide a basis for wetland protection work and ecological governance. The results show that, spatially, the areas of high-value, multi-year water conservation value are distributed in the waters dominated by artificial wetlands. In addition, mudflat wetlands, cropland, and marsh wetlands all show a strong water conservation capacity. Temporally, from 1990-2020, the overall trend of water conservation showed a decrease and then an increase, and it was the same as the trend of rainfall change. Based on the PLUS model, it is predicted that the water conservation value in 2020-2040 under the wetland protection scenario shows a steady increase. The water conservation value and wetland area under this scenario are larger than the other two scenarios, effectively curbing the trend of construction land expansion. The various land-use types have been reasonably regulated, and this scenario is conducive to restoring the ecosystems in the study area.

Keywords: water conservation, PLUS-InVEST model, value assessment, value prediction

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*e-mail: gaojinyun123@126.com
Tel.: 13114857891

Introduction

Ecosystem service function refers to the formation of ecosystems and ecological processes and can provide natural environmental conditions and utility to maintain human survival. These functions provide services that support human survival [1]. Among many service functions, water is an indispensable link between various ecosystem functions and human activities. Thus, the water conservation function and its economic value have gradually become a research hotspot in ecology, socioeconomics, environmental science, and other related disciplines at home and abroad. This function refers mainly to the ability of forest or grassland and wetland ecosystems to intercept, store, and regulate precipitation. It is an important indicator for characterizing ecosystem conditions. It is related not only to the sustainable use of regional water resources but also to the stability of the ecological environment and the protection of biodiversity. Currently, water resources in Tianjin are lacking, and per capita water availability is only one-sixth of the national average. In contrast, wetlands, which are known as "natural reservoirs", play a substantial role in water transmission, storage, and supply. Effective management of resources and sustainable use of the environment is one of the key factors in enhancing the competitiveness of regions and even countries [2]. Therefore, assessing the value of wetland water conservation services has become an important demand for water resources management decisions and is of great practical significance for developing water conservation planning, the implementation of integrated land-water conservation, and protecting regional water security. This is in line with the concept of sustainable development, i.e., meeting the needs of the present while conserving resources to ensure that the needs of future generations can be met [3].

In 1864, the German scholar Ebmayer studied the evapotranspiration dispersion of the soil surface in Bavaria [4], indicating interest in studying this field of water conservation. In 1997, Constanza [5] defined the concept of ecosystem services, after which research on water conservation gradually began to enter the development stage. As the research on water conservation has developed, academics have also constructed a variety of assessment systems and models to analyze the capacity and sustainability of water harvesting [6]; its concept has been clarified, and the evaluation methods of water conservation have been continuously enriched. These include the water storage capacity method, precipitation storage quantity method, water balance method, multimodel integration method, etc. Among them, the SCS model [7], the SWAT model [8], and the InVEST model are widely used. The InVEST model has flexible parameter adjustment and good spatial visualization ability of the assessment results. Some researchers have empirically validated the InVEST water yield ecosystem service model on a UK-wide scale. The results show that the model can accurately assess the amount of water in river catchments in the UK [9]. The model has been successfully applied to the assessment of water conservation function in the hilly areas of the Loess Plateau [10], the spatial and temporal changes of water conservation function in Sanjiangyuan National Park [11], and other related studies, and the simulation results are better. In order to better simulate the future land use change pattern, scholars have conducted a lot of research on land use simulation models [12]. The widely used prediction models include Logistic-CA [13], CA-Markov [14], FLUS [15, 16], and CLUE-S [17]. In the process of simulating land use change at the patch level, although these models can show certain characteristics of change, there are still some limitations in comprehensively analyzing the complex and multi-level driving factors behind these changes [18]. In contrast, the PLUS model, which was developed based on the FLUS model [19], can not only obtain higher accuracy and more similar landscapes but also thoroughly analyze the contribution of driving factors to land change [20]. Therefore, this paper evaluates the spatial evolution trend of land use patterns and the water conservation value of the Beidagang wetland under different scenarios in the future by coupling the PLUS-InVEST model.

The Beidagang Wetland is a nationally important ecological wetland characterized by rich biodiversity and a complete ecosystem; it was successfully listed in the List of Wetlands of International Importance in 2020. The "Tianjin Beidagang Wetland Nature Reserve Master Plan (2017-2025)" clearly indicates that it is necessary to build an important demonstration area for water conservation and biodiversity conservation and a model area for ecosystem restoration. As an important water source for the urban water supply in Tianjin, the Beidagang Wetland plays a valuable ecological role in water conservation. However, there is still a gap in research that visualizes water conservation services in this wetland ecosystem. Therefore, this study takes the Beidagang wetland and its surrounding range as the study area and, based on the estimation of water conservation value from 1990-2020 using the InVEST model, simulates the water conservation value of the Beidagang wetland under the land use conditions of the natural development scenario, wetland protection scenario, and tourism development scenario for the years of 2030 and 2040 by using the PLUS model and land use data of multiple phases, and the shadow engineering method is used to quantify and predict the value of water conservation. The purpose of this study is to reveal the spatial and temporal evolution patterns of water conservation services in the Beidagang Wetland from 1990-2020 and to explore what development scenarios would be more conducive to the enhancement of water conservation functions in the region to provide a basis for regional water resources and the establishment of an ecological compensation mechanism. Furthermore, the results can help the government propose more targeted ecological environment protection and management measures and formulate more scientific plans to protect water conservation functions.

Study Area

The Beidagang Wetland Nature Reserve is a compound wetland nature reserve that is composed mainly of marshes and shallow water reservoirs. It is located southeast of Dagang, Binhai New Area, Tianjin, approximately 6 km from Bohai Bay, with geographic coordinates of latitude 38°36′-38°57′ N and longitude 117°11′-117°37′ E. Beidagang Wetland is the largest wetland reserve in Tianjin, with a total area of 35,312.85 hm^2. Its scope covers Beidagang Nature Reserve, Shajingzi Reservoir, Qianquan Reservoir, the downstream area of the Duliujian River, Lier Bay, and its southern side and coastal mudflats in the estuary. Since the Beidagang Wetland is connected to several rivers in the vicinity and its ecological environment is closely linked, the scope of this study is defined as the Beidagang Wetland within 2 kilometers of its outward extension. The extent of the study area is shown in Fig. 1.

Beidagang Wetland is rich in biodiversity, is an important stop on the migration route of birds in East Asia, and contains a large number of coastal mudflat wetlands rarely found in the country. The protected area has a wide variety of plant species, dominated by marsh reed communities, which together constitute the diversity of the ecosystem of the Beidagang Wetland. In addition, its core area serves as an important ecological barrier between Dagang's living and industrial areas, as it mediates the entire ecosystem and regional microclimate of Tianjin. The reserve contains a variety of wetland types, including marsh wetlands, artificial wetlands, and offshore and coastal wetlands. Together, these different types of wetlands constitute the complete and unique ecosystem of the Beidagang Wetland Nature Reserve, which provides valuable habitat for biodiversity in the area and has high ecological particularity and comprehensive conservation value.

Data and Methods

Water Yield Module of the InVEST Model

The InVEST model was jointly developed by Stanford University, the Nature Conservancy (TNC), and the World Wide Fund for Nature (WWF). It is used to quantitatively and visually evaluate ecosystem service functions and weigh the impacts of human activities on ecosystems; furthermore, it is widely used as a new tool to connect ecological production functions and economic values. An important part of this model is the water yield module, which is commonly used to calculate ecosystems' water yield and water conservation. The water production function module of

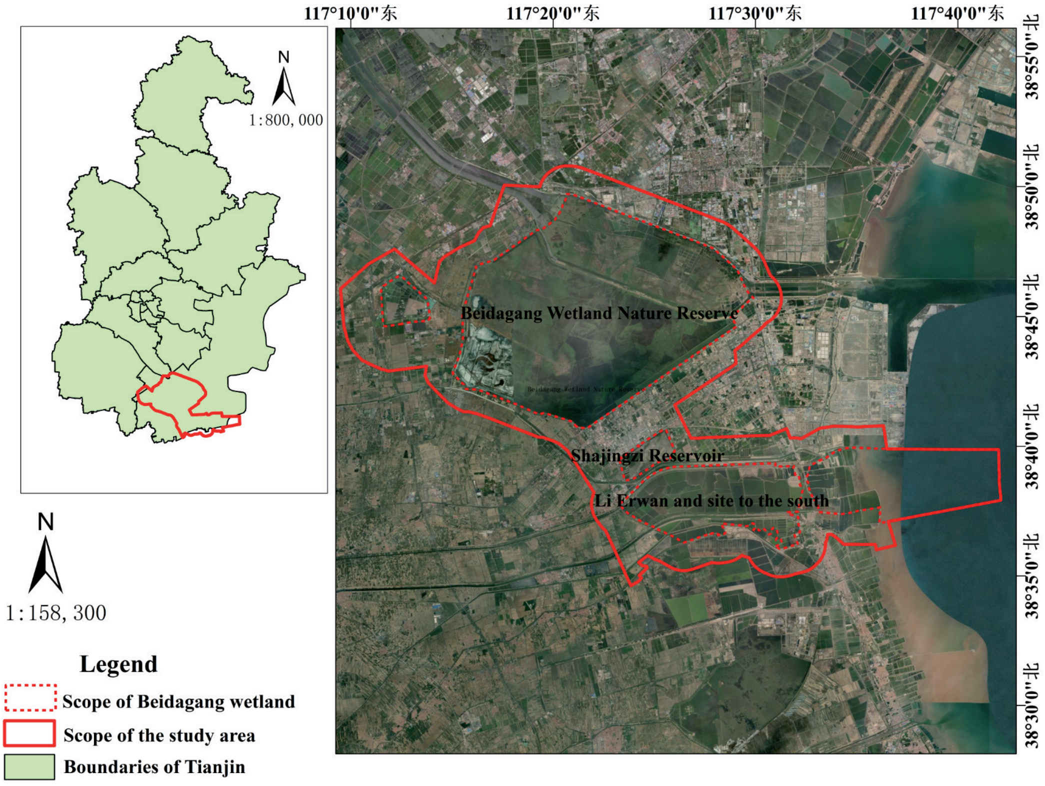

Fig. 1. Geographical map of the study area.

the model integrates the Budyko hydrothermal coupling principle and the equations of water balance and thus achieves a comprehensive assessment of the water production of each grid pixel in the region. For image x in land use type j, to determine its water yield (mm) Y_{xj}, the specific calculation principle is as follows:

$$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) \times P_x \tag{1}$$

Where AET_{xj} – The annual actual evapotranspiration of pixel x in land use type j (mm);

P_x – The annual precipitation of pixel x (mm);

$$\frac{AET_{xj}}{P_x} = \frac{1+\omega_x R_{xj}}{1+\omega_x R_{xj}+\frac{1}{R_{xj}}} \tag{2}$$

Where ω_x – Non-physical parameters characterizing natural climate-soil properties;

R_{xj} – Budyko Dryness Index, a ratio of potential evapotranspiration to precipitation

$$\omega_x = Z\frac{AWCx}{P_x} \tag{3}$$

Where AWC_x – Plant Available Water Content (mm)

Z – Zhang coefficient [21], also known as the seasonality factor;

$$R_{xj} = \frac{K_{xj}ET_{0x}}{P_x} \tag{4}$$

Where ET_{0x} – Potential evapotranspiration of pixel x (mm);

K_{xj} – Vegetation evapotranspiration coefficient;

$$AWC_x = \min\left(\text{soil\_depth}，\text{root\_depth}\right) \times \text{PAWC} \tag{5}$$

Where, Soil_depth – Soil depth;

Root_depth – The depth of the root system;

PAWC – Plant Available Water Content.

Data Sources of the Water Yield Module

The water yield module of the InVEST model was used to calculate the annual water yield of the Beidagang wetland from 1990-2020. The data required for operation include the following:

(1) Precipitation (mm) was sourced from the National Earth System Science Data Centre (http://www.geodata.cn) by Mr. Peng Shouzhang [22] for China's 1-km-resolution month-by-month precipitation dataset from 1982-2022. The monthly accumulation data were used to obtain the mean annual rainfall.

(2) Evapotranspiration (mm) data were downloaded from the National Earth System Science Data Centre (http://www.geodata.cn), and the 1-km month-by-month potential evapotranspiration dataset of China (1901-2022) was obtained via the Hargreaves potential evapotranspiration formula, which is based on the 1-km month-by-month mean, minimum, and maximum temperature datasets of China.

(3) Soil data was sourced from the World Soil Database 1.2 [23], including the soil texture and type, soil layer thickness, organic matter content, etc. The raster data were processed through masking and other steps. The following formula proposed by Zhou [24] was used to calculate vegetation's available water content data, namely, PAWC.

$$\begin{gathered}PAWC = 54.509 - 0.132 \times Sand\% - 0.003 \times (Sand\%)^2 \\ - 0.055 \times Silt\% - 0.006 \times (Silt\%)^2 - 0.738 \times Clay\% + 0.007 \\ \times (Clay\%)^2 - 2.688 \times OM\% + 0.501 \times (OM\%)^2\end{gathered}$$

Where, Sand % – Soil sand content;

Silt % – Soil fines content;

Clay % – Soil clay content;

OM % – Soil organic matter content;

(4) Land use type was based on the multi-period land use remote sensing monitoring dataset of China by Xu Xinliang [25]. Referring to wetland classification standards such as the Tianjin Wetland Conservation Plan (2022-2030) and relevant documents, eight types of land use attributes were deciphered, including cropland, grassland, construction land, riverine wetland, reservoir pits, marsh wetland, mudflat wetland, and shallow sea wetland.

(5) Watersheds were determined based on the grid data of China's 30-meter DEM (ASTER DEMv3) from the National Earth System Science Data Center (https://www.geodata.cn). The basic data were processed in ArcGIS via a series of hydrological tools, such as puddle filling, streamflow, and flow, to obtain a vector map of the watershed.

(6) The biophysical table contains land use codes, root depths, evapotranspiration coefficients, and other indicators. The specific indicators were determined by referring to existing studies [26, 27].

(7) The Z parameter, which is the seasonal constant, is commonly used to represent the precipitation characteristics within a study area; it generally ranges from 1 to 30. According to related studies [28, 29], the Z value is usually close to 1 in humid areas where summer precipitation is dominant and where the distribution of precipitation is uniform. Based on the simulated water production and Tianjin Water Resources Bulletin Binhai New Area data, the model parameters were corrected, and it was found that the simulated values were closer to the measured values when the Z value was adjusted to 1 by repeated calibration.

Water Conservation Assessment Model

The water conservation assessment model is based on the calculation results of the InVEST water yield module, and rainfall and the average surface runoff coefficient are used to calculate and correct the water conservation results [30, 31]. In this work, ArcGIS 10.8 and other spatial data processing software are used to process and calculate data and parameters to ensure the correctness of the data types and formats. The calculation formulas and methods of water conservation are as follows:

$$\mathrm{R}_{xj} = \mathrm{Y}_{xj} - Runoff_{xj}$$

$$Runoff_{xj} = P_x \times C_j$$

Where, R_{xj} – Water conservation of pixel *x* in land use type *j;*

Y_{xj} – Water yield of pixel *x* in land use type *j;*

Runoff_{xj} – Total annual surface runoff of each pixel;

C_j – Surface runoff coefficient of land use type *j;*

P_x – Annual rainfall of pixel *x* (mm)

PLUS Modeling and Data Sources

The patch-generating land use simulation (PLUS) model is a land use/land cover (LULC) change simulation model based on raster data and cellular automata (CA) technology. The model contains two core modules: first, a rule mining framework based on the land expansion analysis strategy (LEAS), which analyzes the changing parts of the two-phase land use data through the random forest algorithm (RF), excavates the driving factors of land expansion, and calculates the development probability of various types of land use landscapes; second, based on the CA model of multitype random patch seeds, a Markov chain is used to predict the quantity demand of land use, determine the changes in land use status, and finally simulate the patch-level evolution of the land use landscape [32]. By accurately simulating the nonlinear relationship changes associated with land use, this model can accurately predict land use changes under different future policy scenarios, thus providing powerful support for urban planning, ecological protection, and sustainable social development [33].

In this study, the PLUS model uses land use data from 2000, 2010, and 2020 to predict land use changes in 2030 and 2040 under the natural development scenario, the wetland protection scenario, and the tourism development scenario. A variety of factors influence the selection of land use change factors; based on the accuracy and reality of the PLUS model, the natural environment, social economy, traffic accessibility, and other factors are comprehensively considered. According to the principles of availability, quantification, and consistency of driving factors, 13 driving factors are selected, as shown in Table 1. The accuracy is verified based on 2005, 2010, and 2015 land use data; the Kappa coefficient is 0.87, which is greater than 0.75, indicating that the simulation results have a high accuracy compared to the actual situation and the simulation is good enough to be used for prediction [37]. The Markov chain is used to predict the future quantity demand of land use. According to Tianjin's wetland protection planning policy and related research [38], the transfer matrices and neighborhood weights were set for different scenarios. The Natural Development Scenario in this study is designed to explore the results of the future spatial evolution of sites in the study area under the existing policies and development trends. The wetland protection scenario is based on the Tianjin Wetland Protection Plan

Table 1. Land-use drivers and implications [34-36].

Data types	Driving factor	Source
Natural environment data	DEM	National Earth System Science Data Center (http://www.geodata.cn)
	Slope	Based on DEM data using ArcGIS analysis tools to obtain
	Water system	National Basic Geographic Information Center (http://www.ngcc.cn)
	Average annual precipitation	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (https://www.resdc.cn/)
	Average annual temperature	
	Average annual wind	
	Annual sunshine hours	
	Average annual relative humidity	
Socio-economic data	Population density	
	GDP	
	Distance to the Urban primary roads	
	Distance to the Urban secondary roads	
	Distance to the Urban three-level road	

(2022-2030), which restricts the conversion of wetlands to other land use types, and on this basis, it reduces the probability of transferring wetlands to non-wetlands by 50% while increasing the probability of transferring non-wetlands to wetlands by 20% concerning an existing study [39]. The tourism development scenario is based on the current spatial evolution of land use. It combines the requirements of the "14th Five-Year Plan for the Integrated Development of Culture and Tourism in Tianjin", which proposes to build a bird-watching study base in Beidagang based on the peripheral buildable land of the Beidagang wetland and simulates the long-term effect of the expansion of buildable land use on the spatial evolution of land use. First, the probability of transferring arable land to construction land is increased by a certain percentage, the probability of transferring construction land to other land types is reduced, and the demand for construction land in the predicted year is increased; lastly, in order to avoid the over-expansion of construction land affecting the regional ecological security, it is set that the future land demand for the total area of each type of wetland will not be less than 95% of the current status quo in 2020. The upper limit of construction land will be 15% [40].

Results and Discussion

Temporal and Spatial Patterns of Water Conservation in the Beidagang Wetland From 1990-2020

In order to understand the direction of land use change and the structural characteristics of the Beidagang Wetland, this paper uses land use data from 1990-2020 to generate land use transfer Sankey maps at intervals of every ten years (Fig. 2). The land use type of the Beidagang wetland is mainly dominated by marsh wetland and reservoir pit pond, which occupy nearly half of the total area of the study area, and the land use transfer in this area mainly occurs between marsh wetland, mudflat wetland, and reservoir pit pond, with 3,576.48 hm^2 of marsh wetland transferred to reservoir pit pond in 1990-2000, and 7,348.35 hm^2 of marsh wetland transferred to reservoir pit pond in 2000-2010. 3,976.92 hm^2 of reservoir pit ponds were transferred to marsh wetlands, 1241.13 hm^2 of marsh wetlands were transferred to reservoir pit ponds, and 1357.91 hm^2 of mudflat wetlands were transferred to reservoir pit ponds in 2010-2020. In the past 30 years, the total amount of wetland transfer out was greater than the amount of transfer in, which was manifested in the net decrease of wetland area. Mainly because the construction of Binhai New Area has driven the transformation of regional wetlands to construction land and cropland, and the continuation of the reclamation activities in Binhai New Area has led to the conversion of a large number of coastal mudflats into construction land.

The distribution of the modified water conservation quantity based on the InVEST model is shown in Fig. 3, in which the water area, such as riverine wetland, reservoir pit pond, and shallow sea wetland, has evapotranspiration greater than precipitation so that the final water conservation quantity is calculated as 0. However, considering the actual situation, the Beidagang wetland has a sufficient water supply all year round, providing unique conditions for the water conservation of the constructed wetland. Therefore, concerning the relevant literature [30], the water area has the maximum storage capacity for precipitation. When the precipitation is directly on the water surface, the precipitation rainfall intensity and rainfall fail to reach the threshold condition of triggering the surface flow production. Then, the ecosystem will effectively retain precipitation to achieve natural storage and water regulation. Therefore, in this study, the rainfall is used to correct the water conservation quantity in the part of the water area.

Although the spatial distribution of water conservation varied greatly from year to year, its spatial distribution characteristics remained basically consistent, which is roughly the same as the distribution of land use types (Fig. 3). In addition to the water area with a water storage function, the areas with large water conservation capacity are mainly concentrated in mudflat wetland and cropland. The minimum value of water conservation depth is 0, which is mainly distributed in impervious ground such as construction land. As shown in Fig. 4, the water conservation quantity in the study area first decreased but then increased from 1990-2020, which is similar to the rainfall trend; however, due to the complex interaction mechanism within the wetland ecosystem, it is also regulated by multiple factors such as climate, soil, topography, and vegetation types. Since 2004, Tianjin has set the city's efforts to promote the construction of the South-to-North Water Diversion Management, so from 2005-2020, the water conservation quantity shows an increase that is not fully synchronized with the rainfall from 1990-1995. In 2018, the study area had the highest water conservation capacity of $19\ 885.83\times10^4$ m^3, and the average water conservation depth reached 315.84 mm. Over the 30 years of the study, the quantity of water conservation fluctuated the most from 1995-2000. With respect to the influence of drought and minimal rain in 2000, the water conservation amount in the study area experienced the most obvious decline of the study period, with a decrease of 50.51%, and the water conservation quantity reached the lowest value of 6643.22×10^4 m^3. The average depth of water conservation was only 105.51 mm. There was a greater increase in 2000-2005 and 2018-2020.

Estimation of the Water Conservation Value of the Beidagang Wetland From 1990-2020

The shadow engineering method is used to quantify the value of water conservation, and the economic value of water conservation services is estimated based on the construction cost of the corresponding reservoir capacity.

According to China's relevant technical specifications, the construction cost of China's unit reservoir capacity

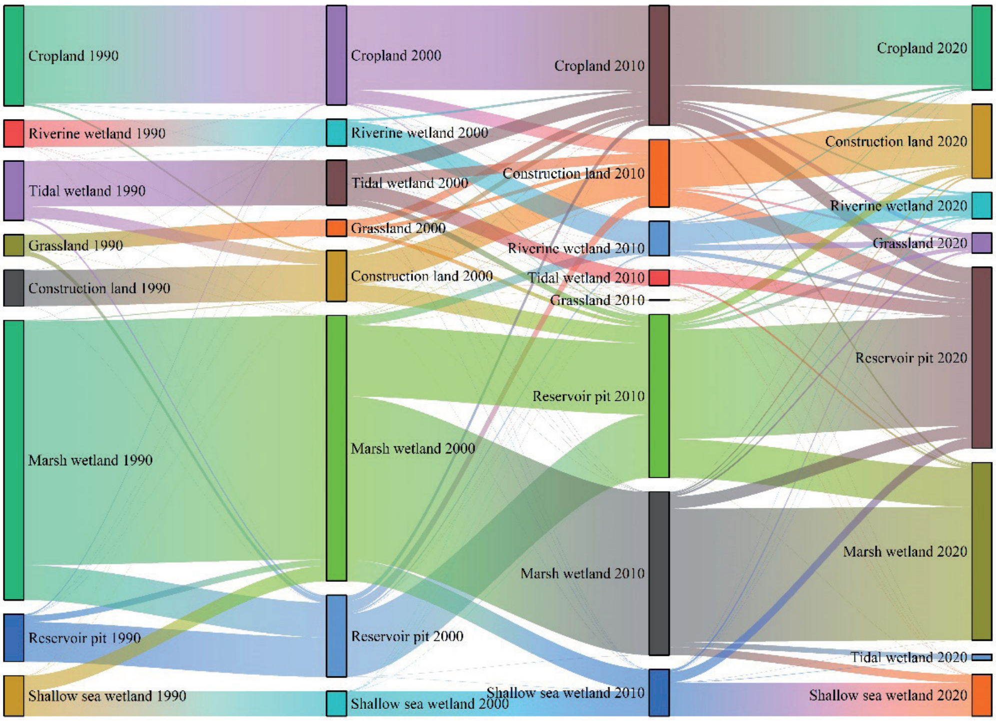

Fig. 2. The land use transfer sankey map.

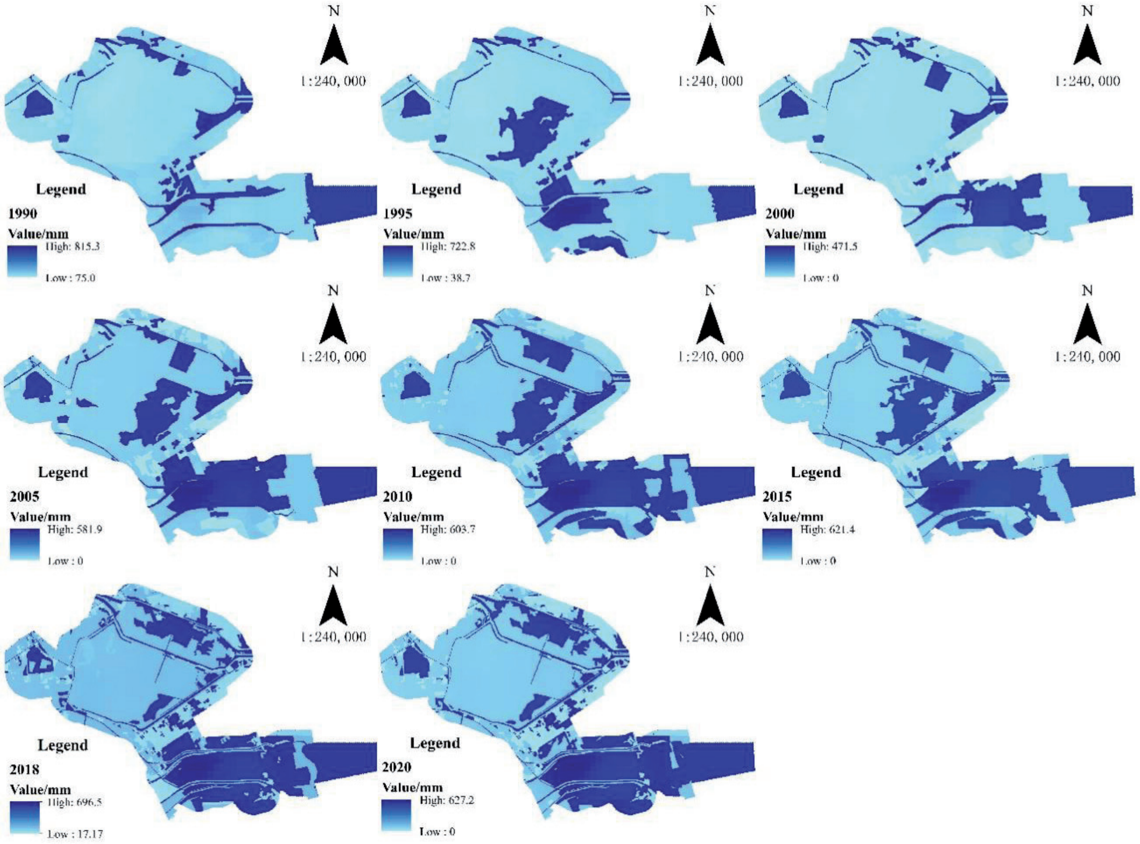

Fig. 3. The annual spatial distribution of water conservation from 1990-2020.

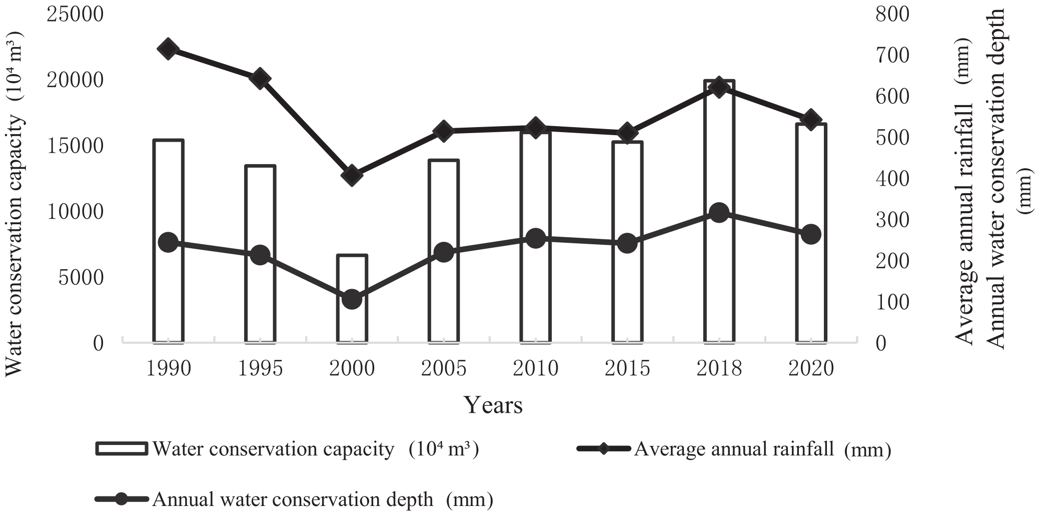

Fig. 4. Trend chart of water conservation and precipitation from 1990-2020.

Table 2. Water conservation capacity and value in 1990-2020.

Years	Water conservation capacity (10^4 m^3)	Unit storage cost (yuan/m^3)	The value of water conservation (10^4yuan)	Water conservation value per unit area (10^4yuan/hm^2)
1990	15374.90	2.79	42895.97	0.68
1995	13423.66	5.32	71413.86	1.13
2000	6643.22	5.65	37534.17	0.60
2005	13848.52	6.11	84614.43	1.34
2010	15955.82	7.09	113126.75	1.80
2015	15226.34	7.57	115263.41	1.83
2018	19885.83	8.40	167040.96	2.65
2020	16607.33	8.86	147140.91	2.34

in 2005 was 6.1107 yuan/m^3, accounting for the large period of the study. To avoid the impact of monetary inflation, with reference to the Fixed Asset Investment Price Index [41], the unit reservoir capacity construction price was corrected for each year based on 2005 (Table 2); the calculation formula is as follows:

$$V_{wr} = Q_{wr} \times P_{wr}$$

Where, V_{wr} – Ecosystem water conservation value (yuan/a);

Q_{wr} – Ecosystem water conservation capacity (m^3/a);

P_{wr} – The project cost per unit of reservoir capacity (yuan/m^3).

By further analyzing the contribution of each land use type to the water conservation value of wetland ecosystems (Table 3), it was found that water area and marsh wetlands were the main contributors to the total water conservation value of the study area. In addition, mudflat wetlands showed strong water conservation capacity except for water area, and the water conservation value per unit area of cropland, marsh wetland, and grasslands was close.

Multi-Scenario Simulation Projections of Land Use

Based on the PLUS model, the land use under the natural development scenario, wetland protection scenario, and tourism development protection scenario was simulated and predicted for 2030 and 2040. Taking 2020 as the base year, the predicted land use data will be imported into the InVEST model, and the methods described in the previous section will be followed to simulate and predict the value of water conservation services under three different scenarios in 2030 and 2040. A unit capacity cost of 8.856 yuan/m³ in 2020 was used to ensure comparability between the predicted water conservation values.

The prediction results are graphically displayed (Fig. 5 and Table 4) to analyze the changes in land use structure under different scenarios. Compared with 2020, the area change characteristics of each land use

Table 3. Water conservation value of different land-use types from 1990-2020.

Land-use type		1990	1995	2000	2005	2010	2015	2018	2020
Cropland	V_t	4228.88	3952.03	1168.58	4381.91	7207.90	6273.35	9298.61	6171.76
	V_u	0.41	0.46	0.11	0.45	0.59	0.53	1.16	0.71
Grassland	V_t	765.49	589.07	30.75	390.13	31.40	25.32	3191.98	1455.31
	V_u	0.35	0.34	0.02	0.30	0.43	0.35	1.02	0.70
Construction Land	V_t	1375.62	1692.02	0.00	422.41	1482.58	583.46	4599.06	1462.66
	V_u	0.37	0.47	0.00	0.07	0.22	0.08	0.55	0.19
Marsh Wetland	V_t	10509.91	9738.93	4018.94	8850.58	9528.84	7729.90	19528.60	12850.92
	V_u	0.36	0.43	0.15	0.44	0.56	0.49	1.10	0.70
Mudflat Wetland	V_t	2385.02	5590.31	718.05	1940.06	993.36	1445.50	1404.98	506.67
	V_u	0.39	0.48	0.15	0.48	0.63	0.59	1.29	0.87
Water area	V_t	23631.05	49851.50	31597.86	68629.34	93882.68	99205.88	129017.73	124693.58
	V_u	2.01	3.44	2.30	3.17	3.72	3.89	5.23	4.86

Note: V_t for the total value of water conservation (10^4 yuan); V_u for water conservation value per unit area (10^4 yuan/hm^2)

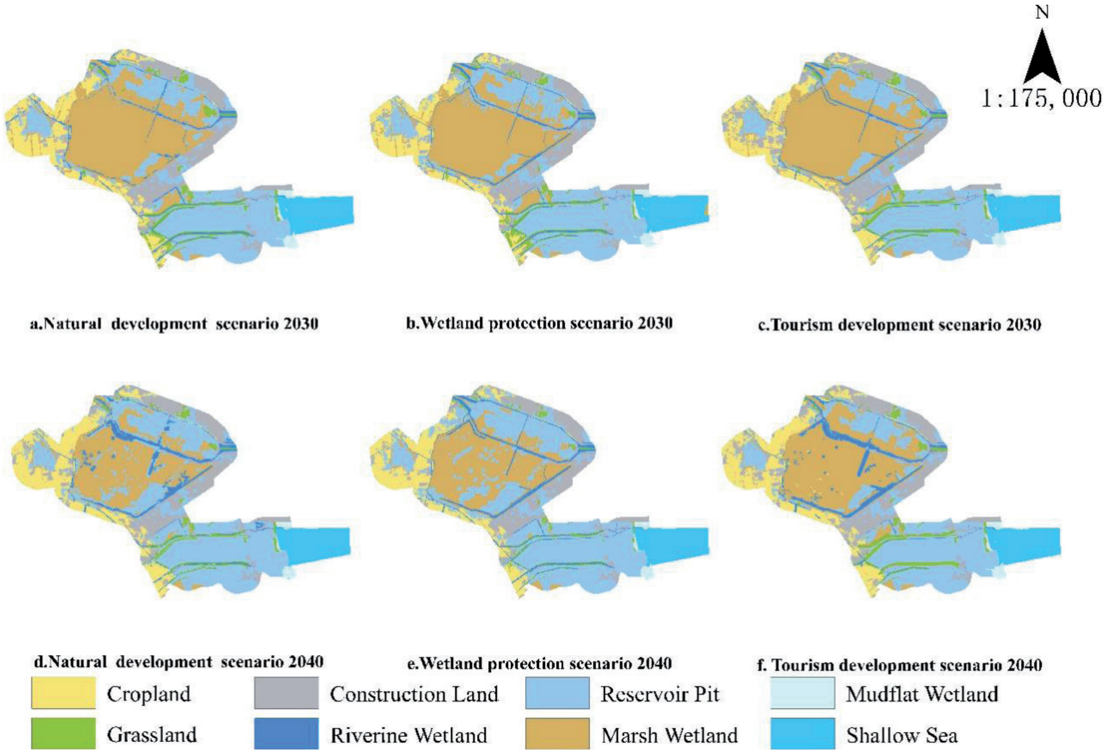

Fig. 5. Land-use distribution map under different scenarios in 2030 and 2040.

type under the three scenarios in 2030 and 2040 have both similarities and differences. Marsh wetlands and mudflat wetlands will still be dominant in the study area over the next 20 years under all three scenarios. Under the natural development scenario, the reservoir pit ponds and marsh wetlands in the study area have the most obvious changes, and the marsh wetlands are transformed into reservoir pit ponds in irregular blocks based on 2020. By 2040, the cropland area will be reduced by 996.24 hm^2 compared with 2020, and the construction land will expand slightly. Under the wetland protection scenario, the area of reservoir pit ponds shows a significant increase in the next 20 years compared to 2020, with an increase of 2,383.49 hm^2 in 2030 and 7,088.34 hm^2 in 2040, whose main sources are marsh wetland, cropland, and grassland, and the trend

Table 4. 2020-2040 changes in the area of land-use types under the three scenarios.

Land use type	2020	Natural development scenario		Wetland protection scenario		Tourism development scenario	
		2030	2040	2030	2040	2030	2040
Cropland	8693.15	6761.89	7696.91	6310.03	6981.27	6279.01	7602.96
Grassland	2069.34	2545.99	1929.90	2358.53	1317.08	2383.40	2421.01
Construction land	7581.17	7853.72	8575.69	7581.17	7581.17	9379.68	9104.51
Riverine land	2728.02	2177.22	3527.67	2496.43	2994.05	2152.90	3596.75
Reservoirs pits	18691.81	19641.75	23346.83	21074.30	25780.15	18675.62	18657.54
Marsh wetland	18380.56	19168.99	13089.56	18378.30	13493.50	19277.06	16755.30
Mudflat wetland	583.17	626.03	532.98	634.26	551.70	626.03	625.94
Shallow sea wetland	4232.73	4184.35	4260.40	4126.93	4261.03	4186.25	4195.92

of expansion of construction land has been effectively controlled. Under the tourism development scenario, the degree and trend of construction land expansion become more obvious. The area of construction land in 2030 and 2040 increases by 1798.51 hm^2 and 1523.34 hm^2, respectively, compared with that in 2020, and the area of marsh wetland and cropland decreases slightly, which poses a certain threat to ecological security.

The total area of the five types of wetlands was 44 616.28 hm^2 in 2020. The total area of wetlands in 2030 and 2040 under the natural development scenario is 45 798.34 hm^2 and 44 757.43 hm^2, respectively. The wetland area is gradually decreasing after a brief increase, indicating that although the conservation measures under the existing policies help slow down the rate of wetland degradation, it does not mean that they can completely reverse the trend of wetland reduction. The wetland area in 2030 and 2040 under the tourism development scenario is 44,917.85 hm^2 and 43,831.46 hm^2, respectively, which shows that construction land expansion is not conducive to wetland protection and restoration due to anthropogenic interference. In contrast, the wetland area in 2030 and 2040 under the wetland protection scenario is 46,710.22 hm^2 and 47,080.43 hm^2, showing a steady growth trend compared with 2020, and the wetland area under the wetland protection scenario is larger than that of the natural development scenario and the tourism development scenario, so the wetland has been protected to a certain extent.

Comparative Analysis of Water Conservation Values Under Different Scenarios

According to Fig. 6 and Table 5, it is possible to visualize changes in the water conservation value under different future scenarios. Under the natural development scenario, the value of water conservation is 148 173.30×10^4 yuan in 2030 and 168 586.86×10^4 yuan in 2040. The total value has increased slightly, compared with 147 140.91×10^4 yuan in 2020. The increases are 0.70% and 14.58%, respectively. The water conservation value under the wetland protection scenario is 155 224.91×10^4 yuan in 2030 and 177 010.47×10^4 yuan in 2040; the increases are 5.49% and 20.30%, respectively. The water conservation

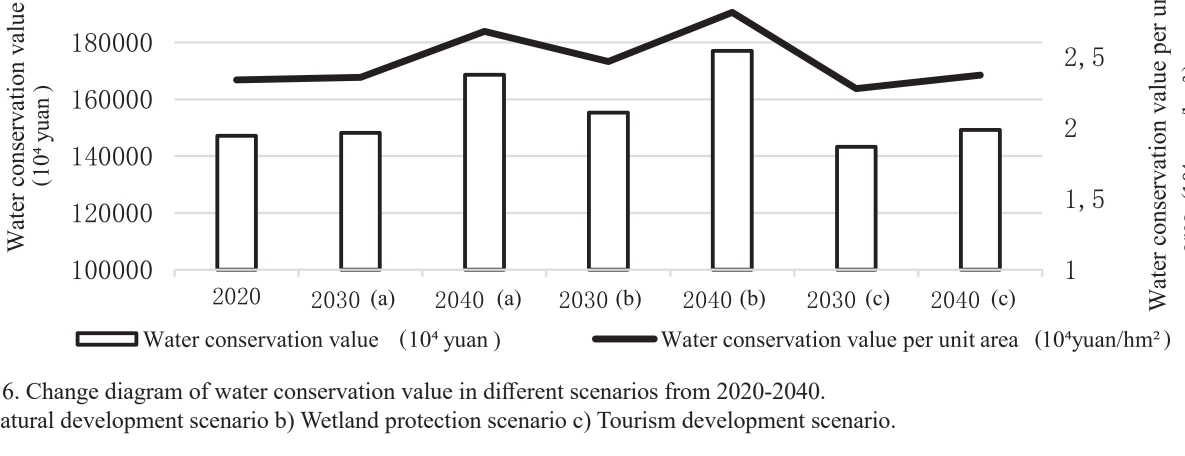

Fig. 6. Change diagram of water conservation value in different scenarios from 2020-2040.
a) Natural development scenario b) Wetland protection scenario c) Tourism development scenario.

Table 5. 2020-2040 changes in water conservation value of land-use types under three scenarios.

Land use type	Year		Cropland	Grassland	Construction Land	Marsh Wetland	Mudflat Wetland	Water area
	2020	V_t	6171.76	1455.31	1462.66	12850.92	506.67	124693.58
		V_u	0.71	0.70	0.19	0.70	0.87	4.86
Natural development scenario	2030	V_t	4747.37	1743.38	1469.92	13399.60	543.91	126269.12
		V_u	0.70	0.68	0.19	0.70	0.87	4.86
	2040	V_t	5424.12	1361.03	1528.15	9085.27	463.07	150725.22
		V_u	0.70	0.71	0.18	0.69	0.87	4.84
Wetland protection scenario	2030	V_t	4403.89	1596.19	1462.66	12858.57	551.06	134352.55
		V_u	0.70	0.68	0.19	0.70	0.87	4.85
	2040	V_t	4893.72	915.00	1462.66	9413.04	479.33	159846.72
		V_u	0.70	0.69	0.19	0.70	0.87	4.84
Tourism development scenario	2030	V_t	4458.01	1678.54	1521.40	13449.35	543.91	121567.03
		V_u	0.71	0.70	0.16	0.70	0.87	4.86
	2040	V_t	5375.40	1715.67	1568.33	11683.40	543.83	128366.61
		V_u	0.71	0.71	0.17	0.70	0.87	4.85

Note: V_t for the total value of water conservation (10^4yuan); V_u for water conservation value per unit area (10^4 yuan/hm^2)

value in 2030 and 2040 under the tourism development scenario is 143 218.23 ×10^4 yuan and 149 253.23×10^4 yuan, respectively, slightly increasing after decreasing. Compared with the natural development scenario and the tourism development scenario, the water conservation value under the wetland protection scenario increases significantly, which also indicates that the size of the water conservation value is closely related to the wetland area change.

The change in land use pattern mainly affects the process of water conservation directly or indirectly by changing the type and structure of the underlying surface [42]; it is considered an important driving factor for the change of ecosystem service function, especially water conservation function. A summary and analysis of the above research results and a comparison of the water conservation values of different land use types revealed obvious differences in different ecosystems' water conservation service values. Based on the three scenarios, the contribution of each land use type to the overall water conservation value of the study area in 2020-2040 is analyzed, and the order is as follows: water area > marsh wetland > cropland > grassland > construction land > mudflat wetland. Further analysis of the value of water conservation per unit area of each land use type is arranged in the following order: water area > mudflat wetland > cropland > marsh wetland > grassland > construction land. The water area has the highest value of water conservation service due to its strong water storage capacity under manual intervention. Although mudflat wetland accounts for a relatively small area and has the lowest overall contribution, its value of water conservation per unit area is second only to the water area, and the value of water conservation per unit area of cropland, marsh wetland, and grassland is relatively close.

The surface of construction land is usually covered with concrete and cement to form an impermeable layer, and all precipitation is completely consumed through evaporation and surface runoff, which may lead to a situation where the water conservation value is zero. The grassland and cropland soil aggregates have a stable structure, small weight capacity, high porosity, high infiltration performance, high initial infiltration rate, and high degree of intercepted precipitation [43]. Wetlands have ecological functions such as intercepting part of precipitation, enhancing soil infiltration, inhibiting evaporation, and reducing surface runoff and water retention. Therefore, wetlands have a relatively high water conservation capacity under the same hydrological conditions.

To summarize, this study calculates water conservation based on the water yield module of the InVEST model and the water balance method, and it accounts for the value of water conservation services using the shadow engineering method. The results indicated that the water conservation value of the artificial wetland water area was at the highest level. At the same time, the construction land had the worst water conservation capacity, which was similar to the results of Chen's study on the Bosten Lake Basin [44]. Mudflat wetlands and marsh wetlands possess strong water conservation capacity, which was similarly confirmed by Gao Yue [45] in his study on wetland degradation assessment in Tianjin. By analyzing the effect of land use change on water conservation value, it can be seen that the change is mainly due to the change of wetland area, especially the water area of artificial wetland, and this view was further verified in Reheman's study on the prediction of water yield in the Urban Agglomerations on the Northern Slopes of the Tianshan Mountains [46]. It was further found that the fluctuation of interannual precipitation was significantly consistent with the trend of water conservation, and the areas of high water conservation and high precipitation were highly spatially coincident, which was consistent with the findings of Luo's study [47]. Moreover, compared with other regional wetland water conservation value evaluation studies in China, the water conservation value of the Yuhuan Xuanmen Bay National Wetland Park [48] was 1.36×10^4 yuan/hm^2, that of Upper Reaches of Minjiang River [49] was 1.82×10^4 yuan/hm^2, and that of Guangxi Beihai Coastal National Wetland Park [50] was 1.32×10^4 yuan/hm^2. The average water conservation service value of the Beidagang wetland from 1990-2020 was 1.55×10^4 yuan/hm^2, which is on par with all other wetlands in the literature. The findings of this study are consistent with the ideas of previous studies[51, 52], all of which are rational.

Conclusions

The purpose of this study is to quantitatively evaluate the water conservation value of the Tianjin Beidagang wetland from 1990-2020 via the PLUS-InVEST model and to predict the water conservation value under the scenarios of natural development, wetland protection, and tourism development scenarios in 2030 and 2040. The resulting data are used to propose relevant suggestions to provide theoretical support and references for the sustainable improvement of the wetland water conservation service function. The main conclusions are as follows: Spatially, areas of high water conservation value are distributed in water areas, with the exception of artificially intervened water areas. The areas with large water conservation are distributed in marsh wetlands, and the multi-year water conservation of construction land is the least. From the perspective of time, water conservation showed a trend of decreasing first and then increasing, which was the same as the fluctuation trend of rainfall, and the lowest value appeared in 2000. Based on the results of the PLUS prediction of land use data simulation and evaluation of water conservation value, the land use type with the largest value of water conservation service in each year from 1990-2040 is the water area. In addition, mudflat wetlands show strong water conservation capacity, and marsh wetlands, cropland, and grasslands have similar water conservation values per unit area. From 2020-2040, the value of water conservation decreased. It then increased slightly under the natural development scenario and the tourism development scenario, while the value of water conservation under the wetland protection scenario showed a steady increase trend, and the wetland protection scenario > natural development scenario > tourism development scenario. Under the wetland protection scenario, the expansion trend of construction land has been effectively curbed, and the wetland area is larger than the natural development scenario and the tourism development scenario. Therefore, future work should focus on strengthening the protection of wetland ecological environments and reducing the conversion of wetlands to non-wetlands to improve regional water conservation capacity.

When the water conservation volume is calculated, the surface runoff volume of some construction land exceeds the actual water yield, which leads to negative results when the water balance method and runoff coefficient method are used to simultaneously calculate the water conservation volume. To avoid this situation, referring to the relevant research of Zhang Changshun [53], the water conservation volume of the region is 0 when the calculated surface runoff volume is greater than the water yield. In addition, this study's limitation is that the PLUS model's prediction process relies on certain assumptions that may not fully reflect the actual situation on the ground. In the calculation of water conservation, external water transfer is neglected, and although the InVEST model can reflect the spatial distribution of water conservation, its simplification of ecological processes may not fully capture the complexity and dynamics of the ecosystems. The models' predictions may be somewhat biased, especially under rapidly changing environmental conditions. In addition, the assessment process involves a large amount of data, and parameters may lead to a certain error in the results. Fieldwork and monitoring projects can be added in the future to obtain more accurate data support and improve the accuracy of the evaluation results.

Overall, the InVEST-PLUS model has a good simulation effect in this study, quantitatively assessing the spatial and temporal distribution and changes in the water conservation value of the Beidagang wetland in the last 30 years and predicting the changes in the water conservation value of the region under different scenarios in the future. Compared with most previous studies that used the InVEST model to simulate the amount of water conservation in different regions or ecosystems and used the price per unit of storage capacity in a single year for the assessment of water conservation value, the main innovation of this study is that the Price Indices of Investment in Fixed Assets was used to correct the unit storage price in different years, which effectively eliminated the impact of price changes in the period, improved the results from a scientific perspective, and realized the accurate quantification of the economic value of water conservation services in the Beidagang wetland. This method provides a solid scientific basis for formulating regional water resource management and ecological protection strategies. In addition, the value of water conservation is an important indicator for evaluating the sustainable development of ecosystems.

Compared with the traditional value equivalent method for predicting the future water conservation value, the InVEST-PLUS model can assess the change of water conservation value under multiple scenarios and can analyze the impacts of different land use decisions on the value of water conservation services by combining with the scenarios of land use changes, which can reflect the general trend of water conservation value transfer in the Beidagang wetland in a certain application, which is important for maintaining the water balance and promoting the sustainable development of water resources. It can quantitatively reflect the general trend of the transfer of water conservation value in the Beidagang wetland, which has certain applicability and is highly important for maintaining the water balance and promoting sustainable development in the future.

Combined with the prediction results of land use change trends and water conservation values in the study area from 2020-2040, the wetland protection scenario is ideal for future land use change. The prediction results indicate that the reduction in wetland area is effectively curbed under the wetland protection scenario, and the main direction of wetland protection, restoration, and rational utilization proposed by the "Wetland Conservation Plan of Tianjin Municipality (2022-2030)" has been well realized. Therefore, it is necessary to adopt a comprehensive approach to further strengthen the management of wetland reserves based on existing wetland protection policies, strictly control wetland occupation, and ensure regional ecological supply.

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Conflict of Interest

The authors declare no conflict of interest.

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