Journal of
Water & Climate Change

Journal of Water and Climate Change Vol 14 No 4, 1268 doi: 10.2166/wcc.2023.422

Study on the ecological water demand security assessment for the Panjin wetland based on landscape pattern

Qian Cheng, Fujiang Chen* and Tieliang Wang
College of Water Resource, Shenyang Agricultural University, Shenyang, Liaoning 110866, China
*Corresponding author. E-mail: fujiangchen1972@163.com

ABSTRACT

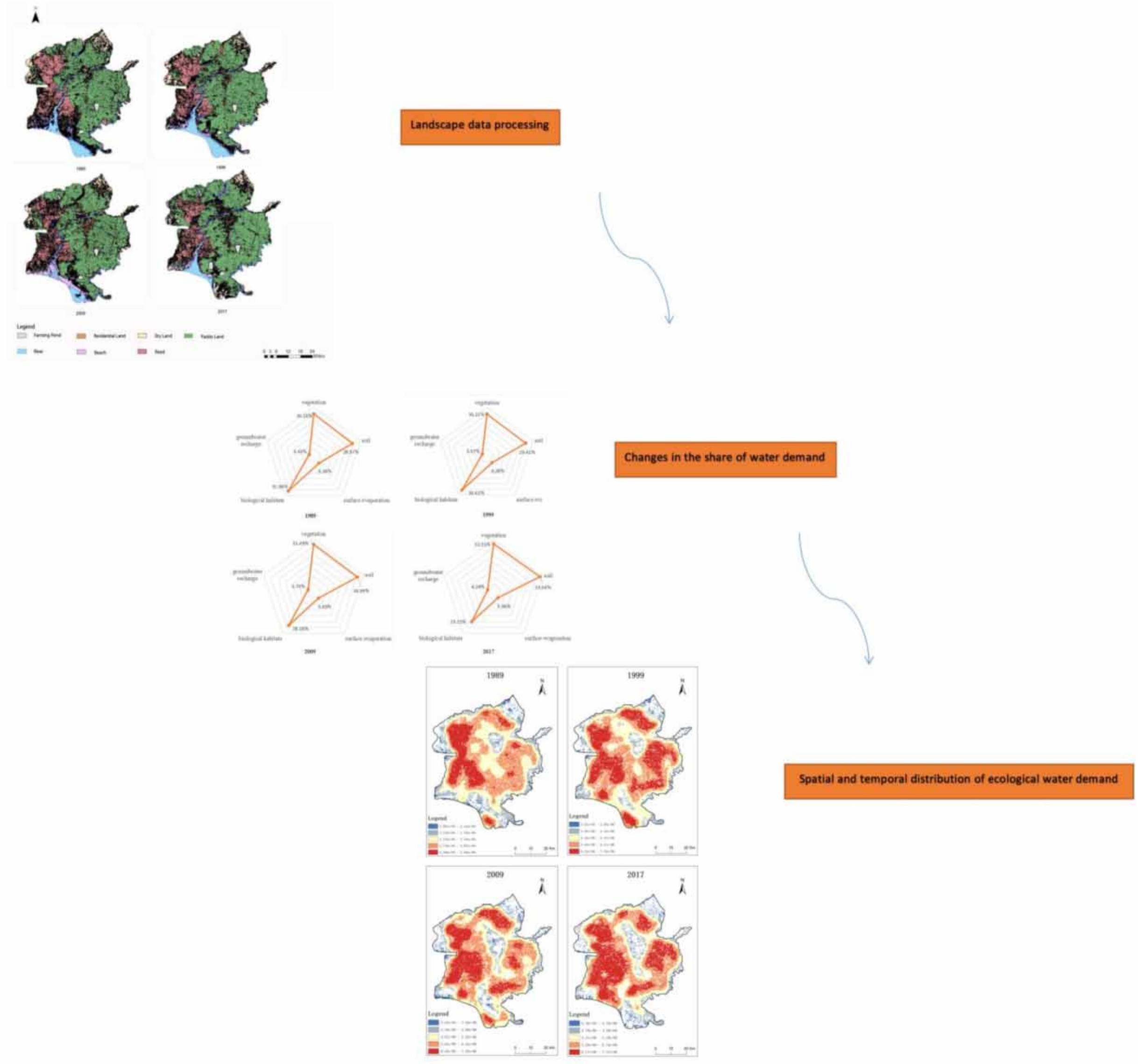
The model was used to predict and analyze the future changes in the total ecological water demand of the Panjin wetland, with a view to providing some scientific reference for the optimal allocation of regional water resources and the sustainable development of wetlands. The results showed that (1) the quality of the habitat environment in the Panjin wetland has a great influence on the change of the total water demand, and the total ecological water demand in the Panjin wetland will continue to decrease in the future. (2) There is a clear correlation between landscape pattern and ecological water demand. (3) The distribution characteristics of the landscape pattern are greatly influenced by political factors, thus affecting the total ecological water demand of the Panjin wetland.

Key words: ecological water demand, fragmentation, landscape pattern, wetland

HIGHLIGHTS

- The landscape pattern changes in the Panjin wetland from 1989 to 2017 were investigated.
- The ecological water demand of the Panjin wetland was calculated.
- The important factor affecting the ecological water demand security of the Panjin wetland was habitat quality.
- The ecological water demand of the Panjin wetland was predicted and assessed to provide a basis for scientific wetland management.

GRAPHICAL ABSTRACT



1. INTRODUCTION

For a long time, research on water supply, demand, and allocation has considered only the water needs of artificial ecosystems, ignoring the water needs of natural ecosystems, emphasizing only the water needs of production and life, and neglecting the water needs of the ecosystem itself, resulting in ecological imbalance and environmental degradation, and limiting sustainable socio-economic development. Located at the interface between land and sea, estuarine wetlands have a unique ecological structure and environmental characteristics, rich in biodiversity, sensitive to external disturbance and relatively fragile ecosystems (Mulamoottil *et al.* 1997; Keddy 2000). In recent years, with the development of aquaculture and accelerated urbanization, human activities have increasingly disturbed estuarine wetlands, causing serious water pollution and water scarcity problems in estuarine wetlands. As the problem of water pollution in wetlands intensifies, there is a growing concern about the ecological water security of estuarine wetlands (Finlayson *et al.* 2013; Zhang *et al.* 2017; Shamshirband *et al.* 2019). The ecological water demand of wetlands refers to the basic amount of water needed for wetlands to maintain their own development and ensure the performance of basic ecological functions, and a healthy wetland ecosystem requires an adequate amount of water to maintain (Zhao *et al.* 2015). Studying the ecological water demand of wetlands can make effective use of limited water resources, maximize the regulating effect of wetlands on the ecological environment, and achieve the synergistic development of ecological protection and economic construction.

Research on the wetland ecological water demand started in the 1990s, but the concept and calculation methods of the wetland ecological water demand are very different from those of riverine and terrestrial systems, and no unified standard has yet been developed (Zhang *et al.* 2019, 2021). The ecological water requirements of wetlands have been studied and estimated by various scientists. Common models used in the ecological water demand estimation process include mathematical models, water balance models, gray correlation models, and linear regression models (Gleick 1998, 2000; Schuluter *et al.* 2005; Palmer & Bernhardt 2006; Shokoohi & Amini 2014; Sajedipour *et al.* 2017). As scientists have used different models to study the water demand of wetland ecosystems for their own research purposes and perspectives, this may lead to differences in estimation results (Horne *et al.* 2017; Zhao 2020; Bayesteh & Azari 2021). Ecological, ecohydrological, and remote sensing-based simulation methods are commonly used to estimate ecological water demand (Shokoohi & Hong 2011; Kral *et al.* 2012; Agboola *et al.* 2016; Ehteram *et al.* 2018; Sharafati & Pezeshki 2020; Goorani & Shabanlou 2021). Different methods have their own advantages and disadvantages and should therefore be selected according to the actual situation in the study area. The ecological method is widely used and has good adaptability, but has the disadvantage of repeated calculations. The ecohydrological method requires high topographic data, has a limited scope and is more suitable for wetlands where the surface water level can be easily controlled. The remote sensing-based simulation analysis method has the advantages of high accuracy, real time, and wide monitoring area, and is more suitable for wetland ecological water demand calculation. With the development of RS and GIS technology, this method will be of greater value. Although some research has been conducted on ecological water demand in wetlands, the literature on ecological water demand in estuarine wetlands is less well documented. Balancing different ecological water demand objectives in estuarine wetlands and providing appropriate ecological water demand and flow processes is important to improve wetland habitat conditions, ameliorate water scarcity, and maintain biodiversity (Dong *et al.* 2011; Pan *et al.* 2015; Mao *et al.* 2016).

The Panjin wetland is an important part of the Liaohe Delta, and has important scientific research value and economic value. An increasing number of scholars have paid attention to this wetland and have conducted in-depth research. The research results included the spatial and temporal monitoring of wetland (Wu & Zhang 2017; Zhou *et al.* 2021), evaluation of ecological suitability of wetland (Dong *et al.* 2014; Cheng & Zhou 2018), analysis of wetland landscape pattern evolution (Song *et al.* 2016), wetland ecological functions, and wetland ecological environment (Wang & Wei 2012). The above research provides a rich scientific basis for the conservation, restoration, and planning of the Panjin wetland. However, no studies have been conducted to assess the ecological water security of the Panjin wetland. It is hoped that the results of this study will enrich the Panjin wetland in the field of wetland water demand research.

The Panjin wetland is the largest estuarine wetland in China and plays an important role in climate regulation, optimal water resource management, and biodiversity conservation. In recent years, due to the increasing disturbance of human activities, the fragmentation trend of the Panjin wetland landscape pattern is obvious, and the water quality is deteriorating, posing a threat to regional water resources and water security. In order to protect wetland resources scientifically and effectively, ecological balance should be maintained and regional water resources should be allocated rationally, this study takes the Panjin wetland as the research object, takes 3S technology as the basis, combines landscape status, precipitation and evaporation and other basic data, and divides its ecological environment water demand into two parts: consumptive ecological environment water demand and non-consumptive ecological environment water demand.

2. MATERIALS AND METHODS

2.1. Study area

The Panjin wetland is located in the core area of the Liaohe Delta, from the mouth of the Daling River in the west to the mouth of the Daliao River in the east, with a geographical location between 121°30′ to 122°31′ E and 40°45′ to 41°27′ N (Figure 1). The total area of the Panjin wetland is 39.21×10^4 hm^2. The Panjin wetland is an important waterbird habitat in China, which has rare waterbirds such as white stork, black stork, white-tailed sea eagle, white swan, and dan-top crane.

2.2. Data source and pre-processing

2.2.1. Landscape data

The remote sensing image data of Panjin wetland are mainly provided by the UCGS website with satellite remote sensing images from 1989 to 2009 (Landsat 7 TM) and 1999 (Landsat 7 ETM+) and 2017 (Landsat 8 OLI) with a resolution of

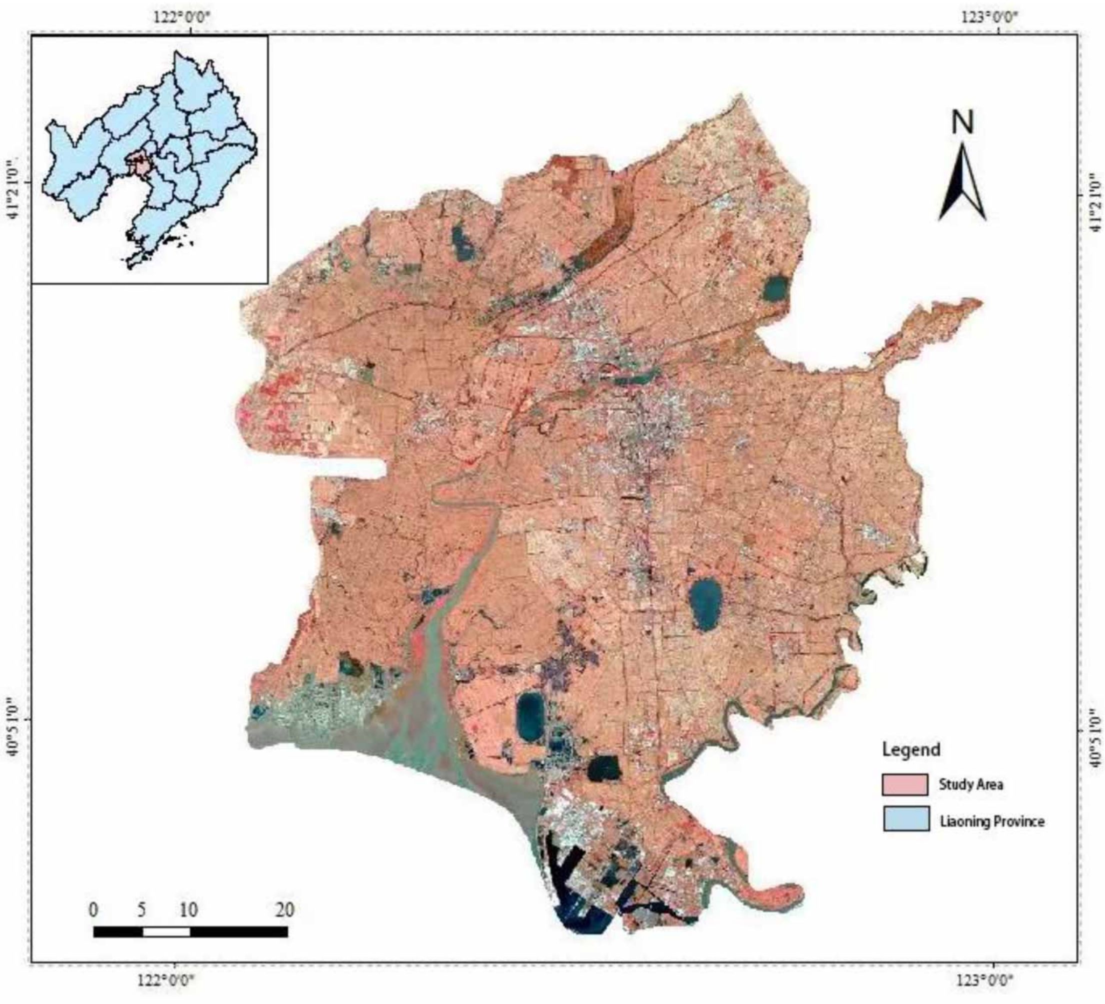


Figure 1 | Distribution map of the Panjin wetland.

30 m (Kayastha *et al.* 2012). The remote sensing software ENVI 5.0 was used to perform atmospheric correction, geometric correction, and panchromatic band fusion processing on the original images of 1989, 1999, 2009, and 2017. Using unsupervised classification and decision tree classification methods (Lin *et al.* 2018), combined with field surveys, we completed the interpretation of remote sensing images, determined the landscape types and their interpretation codes according to the Convention on Wetlands and the Liaoning Land Use Classification Code (Chopra *et al.* 2001; Liu *et al.* 2015; Zhou *et al.* 2015, 2016), established the Panjin wetland landscape classification database for 1989, 1999, 2009, and 2017, completed the landscape index analysis with the help of Fragstats 4.2 software. In this study, the overall accuracy and kappa coefficient were used as test indicators, and the results showed that the overall classification accuracy in 1989, 1999, 2009, and 2017 was 89.32, 88.79, 94.73, and 93.36%, respectively, and the decoding accuracy met the calculation requirements. Table 1 shows the Panjin wetland landscape types and their interpreted signs (Zhou *et al.* 2007). Figure 2 shows the distribution of wetland landscape types in Panjin in 1989, 1999, 2009, and 2017.

2.2.2. Precipitation

The hydrological data used in this study include precipitation, surface evaporation, local reed in Panjin wetland, and evaporation from paddy land (Hughes 2001; Tubiello *et al.* 2015). The precipitation data of the site were obtained from the observations of Antun and Wanghuiwobao stations between 1985 and 2017. The surface evapotranspiration was obtained from the observations of Jinzhou station between 1985 and 2017. The average annual evapotranspiration of the wetland

Table 1 | Area of Panjin wetland 1989, 1999, 2009, and 2017 by the landscape type (km^2)

Year	Reed	Beach	River	Paddy land	Dry land	Residential land	Farming pond	Total
1989	884.86	213.11	244.00	1,536.86	424.89	336.31	280.51	3,920.55
1999	830.31	154.14	275.42	1,620.18	319.65	413.21	307.64	
2009	842.50	200.83	152.19	1,699.94	259.58	462.52	302.99	
2017	684.77	152.76	116.88	1,784.64	359.03	540.78	281.69	

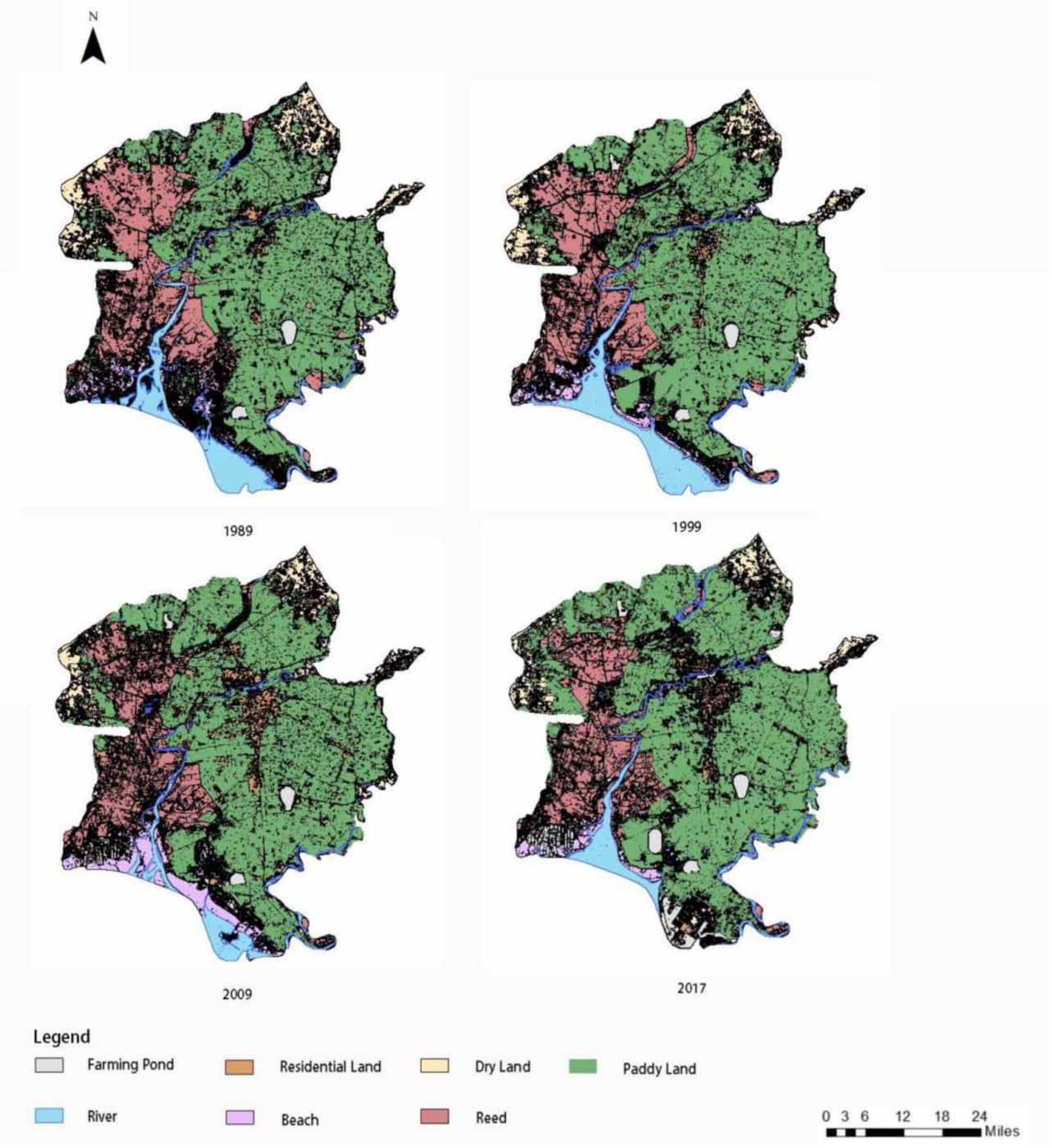


Figure 2 | Distribution of landscape types in the Panjin wetland in 1989, 1999, 2009, and 2017.

was 1,086.63 mm, and the average annual precipitation was 623.90 mm (the high precipitation period was more concentrated in summer), and the evapotranspiration was 1.7 times the precipitation. The precipitation is less than evapotranspiration, which is the more obvious characteristic of the Panjin wetland. The evapotranspiration of paddy is 650 mm from April to September, and the evapotranspiration of reed is 700 mm from April to September, as shown in Table 2.

Table 2 | Total evapotranspiration (mm) by month from paddy land and reed in the Panjin wetland

Month	4	5	6	7	8	9
Paddy land	55.99	86.3	116.43	164.79	141.37	85.12
Reed	60.3	92.94	125.39	177.46	152.24	91.67

2.3. Landscape fragmentation model

In order to more clearly analyze the changes in landscape pattern characteristics and the degree of disturbance from the outside world in the Panjin wetland during 1989–2017, PD (Patch density index), S (Landscape separation index), and SHDI (Shannon's diversity index) were selected for the study of landscape fragmentation in the Panjin wetland in this study (Zhao *et al.* 2014; Dong *et al.* 2015).

2.3.1. Patch density index

The patch density index refers to the total number of patches in a given landscape per unit area, and the higher the result, the more fragmented the landscape and the higher the degree of landscape fragmentation (Zhou *et al.* 2016):

$$\mathrm{PD} = N/A \tag{1}$$

where PD is the density of protected area patches, N is the total number of protected area patches, and A is the total area of protected area in km^2.

2.3.2. Landscape separation index

The landscape separation index is an indicator of the discrete distribution of landscapes, and the higher the result, the greater the heterogeneity between landscapes and the higher the frequency of inter-rotation between landscapes (Zhou *et al.* 2016):

$$S = \frac{D_i}{B_i}, \quad D_i = \frac{1}{2} \times (N_i/A)^{\frac{1}{2}}, \quad B_i = \frac{A_i}{A} \tag{2}$$

where S is the degree of landscape separation, N_i is the total number of patches occupied by the selected landscape type, A_i is the total area occupied by that landscape type, and A is the total area of the protected area, and the unit of area is km^2.

2.3.3. Shannon's diversity index

The higher the Shannon's diversity index score, the more exploited the ecosystem and the more fragmented the landscape pattern (Zhou *et al.* 2016):

$$\mathrm{SHDI} = -\sum_{i=1}^{m} (p_i \ln p_i) \tag{3}$$

where SHDI is the Shannon diversity of that landscape type and p_i is the proportion of the area of a given landscape type to the total area.

2.4. Ecological water demand calculation model

Dry land and residential land in the study area are mainly distributed in the test area, which are damages caused by human activities to the wetland and are not included in the calculation of ecological environment water demand. In this study, the ecological environmental water demand is divided into two parts: consumptive ecological environmental water demand and non-consumptive ecological environmental water demand. Consumptive ecological environmental water demand refers to the water consumed by the wetland, including evaporation from the water surface, plant evaporation, and seepage. Non-consumptive ecological environment water demand refers to the surface water storage to maintain the ecological balance and its normal function, including soil water demand and biological habitat water demand, the integration of the above five parts of water demand is the ecological environment water demand of the whole wetland.

2.4.1. Water demand of consumptive ecosystem

(1) Water demand from surface evaporation

Since the evaporation in Panjin is larger than the rainfall, the evaporation amount reaches about 1.7 times of the rainfall. In order to ensure the dynamic balance of the water storage area, it is necessary to calculate the water demand for surface evaporation from the protected area, as shown in the following equation (Gong *et al.* 2021):

$$W_E = \sum A(E - P) \times 10^{-3} \tag{4}$$

where W_E is the water demand for surface evaporation in the study area, in m³; A is the total area of the water landscape type, in m²; E is the total evaporation of the water landscape type, in mm; and P is the total precipitation of the water landscape type, in mm.

(2) Evaporative water demand of vegetation

The evaporative water demand of the soil and the transpirational water demand of the vegetation roots account for approximately 99% of the total water demand of the vegetation necessary to maintain plant life and growth and for this protected area, as shown in the following equation (Ye *et al.* 2017):

$$dW_P/d_t = A(t)\mathrm{ET}_m(t) \tag{5}$$

where W_P is the ecological water demand of the vegetation of the protected area in m³, $A(t)$ is the total area of this vegetation type in m², ET_m is the evapotranspiration of this vegetation type in mm, and t is the time.

(3) Water requirements for groundwater recharge

Wetlands are resistant to flooding and are able to recharge groundwater through soil infiltration as a way of ensuring the ecological balance and stability of wetlands, as shown in the following equation (Ye *et al.* 2017):

$$W = \Phi TF \tag{6}$$

where W is the amount of groundwater recharged from the paddy land, m^3; Φ is the rate of stable infiltration in paddy land, $\Phi = 0.001$ m/d; T is the paddy growing season, d; and F is the paddy area, km^2.

2.4.2. Non-consumptive ecosystem water demand

(1) Soil water demand

The water demand of the soil in a protected area is the amount of water required to maintain a stable and balanced state of soil structure and to allow healthy growth and development of the plants that depend on it, measured by soil type, soil thickness, and soil water holding capacity, as shown in the following equation (Filgueiras *et al.* 2020; Zhao 2020):

$$Q_t = \alpha\gamma H_t A_t \tag{7}$$

where Q_t is the water demand of the soil in the wetland reserve, in m³; α can be calculated by substituting the percentage of the soil water holding capacity in the formula according to the soil type; γ is the capacity of the soil in the wetland reserve; H_t is the thickness of the soil layer in the wetland reserve, in m; and A_t is the area of the soil in the wetland reserve, in m².

(2) Biological habitat water demand

The biological habitat water demand of a wetland is the basic amount of water required to support the growth, development, and reproduction of the various species within it, as shown in the following equation (Ye *et al.* 2017):

$$dW_q/d_t = A(t)CH(t) \tag{8}$$

where W_q is the water required by organisms in the reserve to maintain their habitat, in m³; $A(t)$ is the total reserve area, in m²; C is the percentage % of the total area of the type with water surface landscape; $H(t)$ is the water depth, in m; and t is the time.

2.4.3. Total water demand of the Panjin wetland

In the Panjin wetland, the water demand of vegetation, soil, evaporation, and groundwater recharge are independent of each other and have no overlapping part, so the sum of the water demand of the five types is the total ecological water demand of the Panjin wetland according to the following formula:

$$Q = W_p + Q_t + W_E + W_q + W \tag{9}$$

2.5. Gray prediction model

Gray system theory was proposed by Chinese scholar Deng Julong in the 1980s to extract valuable information by regenerating part of the known information to obtain the system's evolutionary pattern and trend (Deng 1987; Chen 2012). Traditional gray system theory stipulates that the modeling sequence must be an equally spaced univariate first-order gray model. However, in real life, due to some irresistible factors that make the acquired data non-equally spaced, if the prediction is carried out according to the equally spaced gray model, it will disrupt the regularity of the original data and cause large deviations, which will affect the prediction results. Therefore, a non-equally spaced GM(1,1) model is used in this paper (She *et al.* 2013).

(1) Initialize the modeling raw sequence

$$X^{(0)}(k_i) = \{X^{(0)}(k_1), X^{(0)}(k_2), \Lambda, X^{(0)}(k_n)\}, \ i = 1, 2, \Lambda, n$$

(2) Initialize the modeling raw sequence

$$X^{(1)}(k_i) = \{X^{(1)}(k_1), X^{(1)}(k_2), \Lambda, X^{(1)}(k_n)\}, \ i = 1, 2, \Lambda, n$$

(3) Generate immediate mean series

$$Z^{(1)} = \frac{1}{2}\{Z^{(1)}(k_2), Z^{(1)}(k_3), \Lambda, Z^{(1)}(k_n)\}$$

(4) GM(1,1) Basic form

$$\frac{dx^{(1)}(t)}{dt} + ax^{(1)}(t) = u, t \in [0, +\infty]$$

Using least squares to find the parameters $\hat{a} = (a, u)T = (B^T B)^{-1} B^T Y$

$$Y_n = [X^{(0)}(k_2), X^{(0)}(k_3), X^{(0)}(k_4), \Lambda, X^{(0)}(k_n)]^T$$

$$B = \begin{vmatrix} -Z^{(1)}(k_2) & 1 \\ -Z^{(1)}(k_3) & 1 \\ \Lambda & \Lambda \\ -Z^{(1)}(k_n) & 1 \end{vmatrix}$$

(5) The reduced model expression

$$\hat{X}^{(0)}(k_{i+1}) = \frac{1}{\Delta(k_{i+1})}(1 - e^{a\Delta k_{i+1}})\left[X^{(0)}(k_1) - \frac{u}{a}\right]e^{-a\Delta k_{i+1}}, \ i = 1, 2, 3, \Lambda, n.$$

The evaluation results of 1989, 1999, 2009, and 2017 were used as the original data to construct a GM(1,1) gray prediction model to complete the prediction of the ecological and environmental quality status of the study area for the next 20 years.

3. RESULTS AND DISCUSSION

3.1. Analysis of landscape fragmentation

As shown in Table 3, the patch density, Shannon diversity, and separateness indices generally showed a decreasing trend, indicating that from 1989 to 2017, with the further establishment of the Panjin wetland and the successive introduction of relevant conservation policies for the reserve, the landscape pattern status of the study area was gradually restored, the landscape fragmentation was gradually improved, the ecological functions of the wetland were gradually restored, and the self-regulating capacity of the wetland was increasingly enhanced. In this study, 2017 was the year in which the ecological environment of the wetland was in the best condition during this period.

3.2. Calculation of water demand for the Panjin wetland consumptive ecosystem

(1) Surface evaporation water demand calculation

Combined with the actual situation, the types of landscapes that meet this condition in the Panjin wetland in this study are farming pond, beach, and river, and combining the rainfall, evaporation, and the corresponding total landscape area to obtain the surface evaporation ecological water demand of the reserve, as shown in Table 4.

(2) Vegetation water demand calculation

The Panjin wetland has a wide range of vegetation species and key species should be selected when calculating vegetation water demand. The reed and paddy land occupy a large area and are the key plants, so these two species were selected for the calculation (Li *et al.* 2021; Zhang *et al.* 2021). The calculated results are shown in Table 5.

Table 3 | Index values of fragmentation in the Panjin wetland

Year	PD	SHDI	S
1989	76.5	1.674	4.155
1999	64.5	1.649	3.940
2009	65.7	1.601	3.979
2017	52.3	1.576	3.678

Table 4 | Ecological water demand for evaporation from the surface of the Panjin wetland (10^9 m^3)

Year	Farming pond	Beach	River	Total
1989	0.130	0.099	0.113	0.341
1999	0.142	0.071	0.127	0.341
2009	0.140	0.093	0.070	0.304
2017	0.130	0.071	0.054	0.255

Table 5 | Water demand for vegetation in the Panjin wetland (10^9 m^3)

Year	Reed	Paddy land	Total
1989	0.999	0.619	1.618
1999	1.053	0.581	1.634
2009	1.105	0.590	1.695
2017	1.160	0.479	1.639

(3) Groundwater recharge water demand calculation

In this study, the wetland groundwater recharge water demand of the paddy land was mainly investigated, where Φ was taken as 0.001 m/d and T was taken as 120 days, to obtain the groundwater recharge demand of the Panjin wetland in 1989, 1999, 2009, and 2017 as shown in Table 6.

3.3. Calculation of the water demand of non-consumptive ecological environment in the Panjin wetland

(1) Soil water demand calculation

According to the relevant data, it is known that the soils of the Panjin wetland can be classified as rice soils and swamp soils according to the characteristics of moisture content and nutrients. The main part of the paddy soil is the paddy field, whose volume percentage reaches 60–70%, and in this study, the data were selected as 65%, and the soil thickness of its root system was selected as 1.2 m for calculation. The reed is the main species in the swamp soil and its volume percentage reaches 45–55%, and in this study, the data were selected as 50%, and the soil thickness of the plant root system can be determined according to the relevant literature, and its calculation data was selected as 0.8 m. The calculations were carried out to obtain the soil water demand of the Panjin wetland in 1989, 1999, 2009, and 2017, as shown in Table 7.

(2) Biological habitat water demand calculation

The calculation of the biological habitat water demand in Panjin wetland is mainly based on various necessary biological activities of fish, birds, and other organisms in the area, and the amount of water required by them for these activities is the biological habitat water demand in the area. Black-billed gulls, cranes, and other national key protected animals mainly inhabit the reed and beach, where the water depth is around 0.5–1.0 m, and 0.8 m was chosen for this calculation. As for fish, shrimps, and plankton, they mainly live in farming pond and river, and 1.5 m was chosen for this calculation, the water demand of biological habitats in Panjin wetland in 1989, 1999, 2009, and 2017 can be obtained, as shown in Table 8.

3.4. Total water demand of the Panjin wetland

The total water demand of the Panjin wetland ecosystem is the sum of five types of ecological water demand, and the calculation results are shown in Table 9.

As shown in Table 9, the overall upward trend in the total ecological water demand between 1989 and 1999 was due to the arrival of large numbers of people in the area, resulting in the increased demand for agricultural land and the development of

Table 6 | Ecological water demand for groundwater recharge in the Panjin wetland (10^9 m^3)

Year	Total
1989	0.184
1999	0.194
2009	0.204
2017	0.214

Table 7 | Soil water requirement of the Panjin wetland (10^9 m^3)

Year	Swampy soil	Rice soil	Total
1989	0.354	1.199	1.553
1999	0.332	1.264	1.596
2009	0.337	1.326	1.663
2017	0.274	1.392	1.666

Table 8 | Ecological water demand of biological habitats in the Panjin wetland (10^9 m^3)

Year	Reed and beach	Farming pond and river	Total
1989	0.878	0.787	1.665
1999	0.788	0.875	1.662
2009	0.835	0.683	1.517
2017	0.670	0.598	1.268

Table 9 | Total water demand of the ecosystem in the Panjin wetland (10^9 m^3)

Year	Vegetation	Soil	Surface evaporation	Biological habitats	Groundwater recharge	Total
1989	1.618	1.553	0.341	1.665	0.184	5.362
1999	1.634	1.596	0.341	1.662	0.194	5.428
2009	1.695	1.663	0.304	1.517	0.204	5.383
2017	1.639	1.666	0.255	1.268	0.214	5.042

some of the reed into paddy land. In addition, people were driven by economic interests and the increasing number of small-scale individual ponds resulted in continuous encroachment and pollution of the beach resource, which led to the continuous deterioration of the ecological environment within the wetland, the degradation of ecological functions, the reduction of autogenous supply capacity and the increasing demand for ecological water. This phenomenon was alleviated after 1999, with the completion of the second phase of the Panjin wetland restoration project and the introduction of related conservation measures and policies, the ecological environment of the Panjin wetland has been improved to a certain extent and its internal ecological functions have been enhanced.

As shown in Figure 3, the proportion of vegetation water demand, soil water demand, and biological habitat water demand to the total water demand is relatively large, which shows that the quality of the habitat environment within the Panjin wetland has a strong influence on the changes of the total water demand. Between 1989 and 2017, the biological habitat water demand changed the most, accounting for 31.06% of the total water demand in 1989, 30.62% of the total water demand in 1999, 28.18% of the total water demand in 2009, and 25.15% of the total water demand in 2017, with the proportion decreasing year by year and decreasing more significantly than other water demands, mainly due to the local government adjusted the industrial structure after 2009 in order to achieve the synergistic development of economic benefits and ecological protection, which led to the increasing improvement of the habitat environment of Panjin wetland and the gradual recovery of the wetland's internal self-regulation ability.

In this study, a 100 × 100 grid was established under the ArcGIS10.2 platform, and the spatial interpolation was performed based on the total ecological water demand of the reserve after converting the landscape distribution map into a grid to obtain a spatial and temporal distribution map of the ecological water demand of Panjin wetland. The spatial and temporal distribution of the total ecological water demand within the Panjin wetland varies significantly (Figure 4). The areas with high ecological water demand are mainly distributed in the reed in the western area of Panjin wetland and the paddy land in the eastern area. In terms of temporal distribution, before 1999, the irrational industrial structure led to the proliferation of private aquaculture farms, resulting in the destruction of natural wetland resources, which to some extent increased, and the total ecological water demand during this period. After 1999, the local government introduced relevant policies to adjust the industrial structure and protect wetland resources, during which the ecological environment of wetlands improved and ecological functions were restored year by year, and the total ecological water demand of the Panjin wetland also decreased year by year. In terms of spatial distribution, the total ecological water demand gradually decreases from the western and eastern regions to the peripheral areas. In the eastern region, the ecological water demand has increased due to the increase in the number of paddy field and dry land, the more frequent anthropogenic disturbances, the more fragmented and degraded natural wetland landscapes, and the weakening of self-sufficiency.

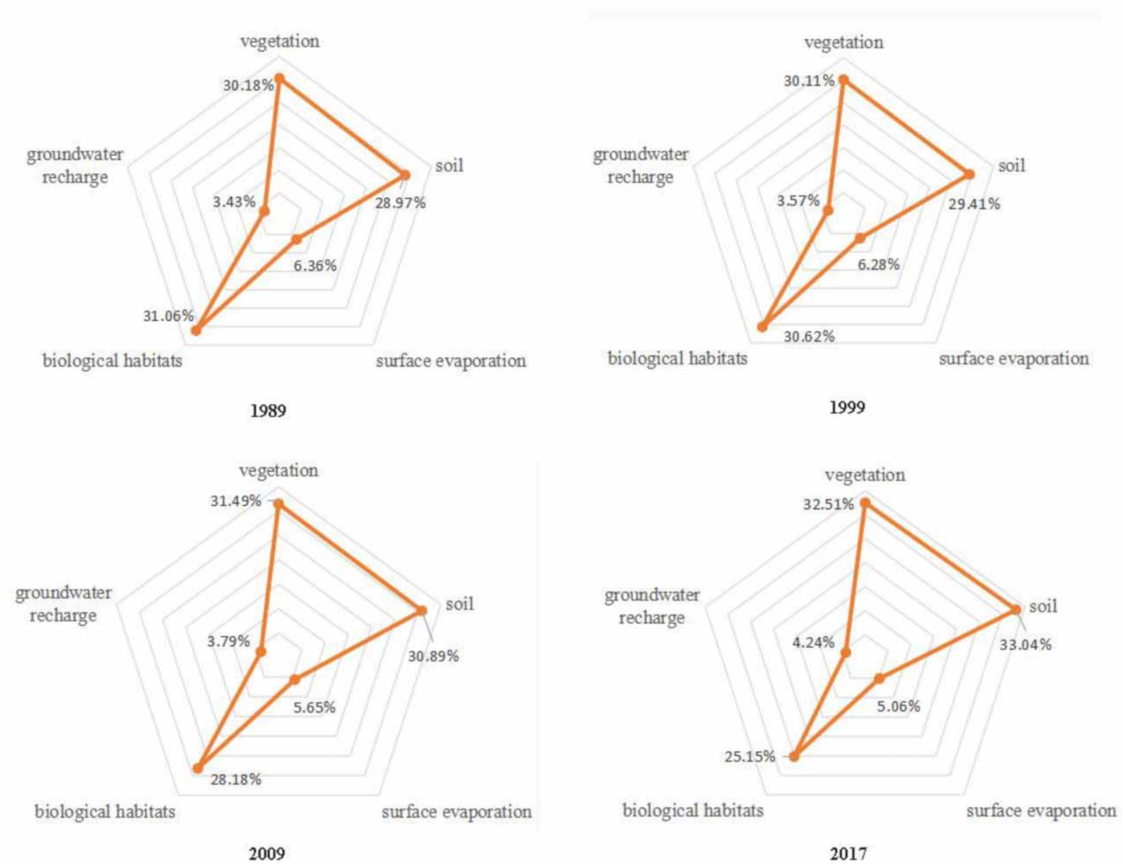


Figure 3 | Changes in the share of water demand by category in 1989, 1999, 2009, and 2017.

3.5. Correlation analysis between landscape pattern index and total ecological water demand

Figure 5 shows a plot of the correlation between the landscape index and the total ecological water demand in the Panjin wetland over the past 30 years, and it is easy to see that the landscape index is significantly correlated with the ecological water demand, and ecological water demand is significantly and positively correlated with the PD, SHDI, and S index. This indicates that during the period of 1989–2017, the trend of landscape fragmentation in the Panjin wetland gradually improved and the landscape pattern gradually recovered while the total ecological water demand required in the reserve decreased.

3.6. Panjin wetland water demand risk assessment

In this study, MATLAB software was used for predictive analysis, and the total ecological water demand of the Panjin wetland in 1989, 1999, 2009, and 2017, 5.362×10^9 m^3, 5.428×10^9 m^3, 5.383×10^9 m^3, and 5.042×10^9 m^3, respectively, were used as raw data for the predictive analysis. The total ecological water demand of the Panjin wetland in 2027, 2037, 2047, and 2057 is 4.913×10^9 m^3, 4.738×10^9 m^3, 4.570×10^9 m^3, and 4.408×10^9 m^3, respectively. Simulated values and simulation errors are shown in Table 10.

4. CONCLUSION

In this study, the Panjin wetland was selected as the research object, and the landscape pattern of the Panjin wetland was analyzed based on the landscape classification data in 1989, 1999, 2009, and 2017, with patch density, Shannon diversity index, and separation degree as indicators. The results showed that the landscape fragmentation and ecological functions of the Panjin wetland have been improved between 1989 and 2017, and the whole ecosystem is developing in a better direction. This study also used the ecological water demand calculation model to calculate the total ecological water demand for

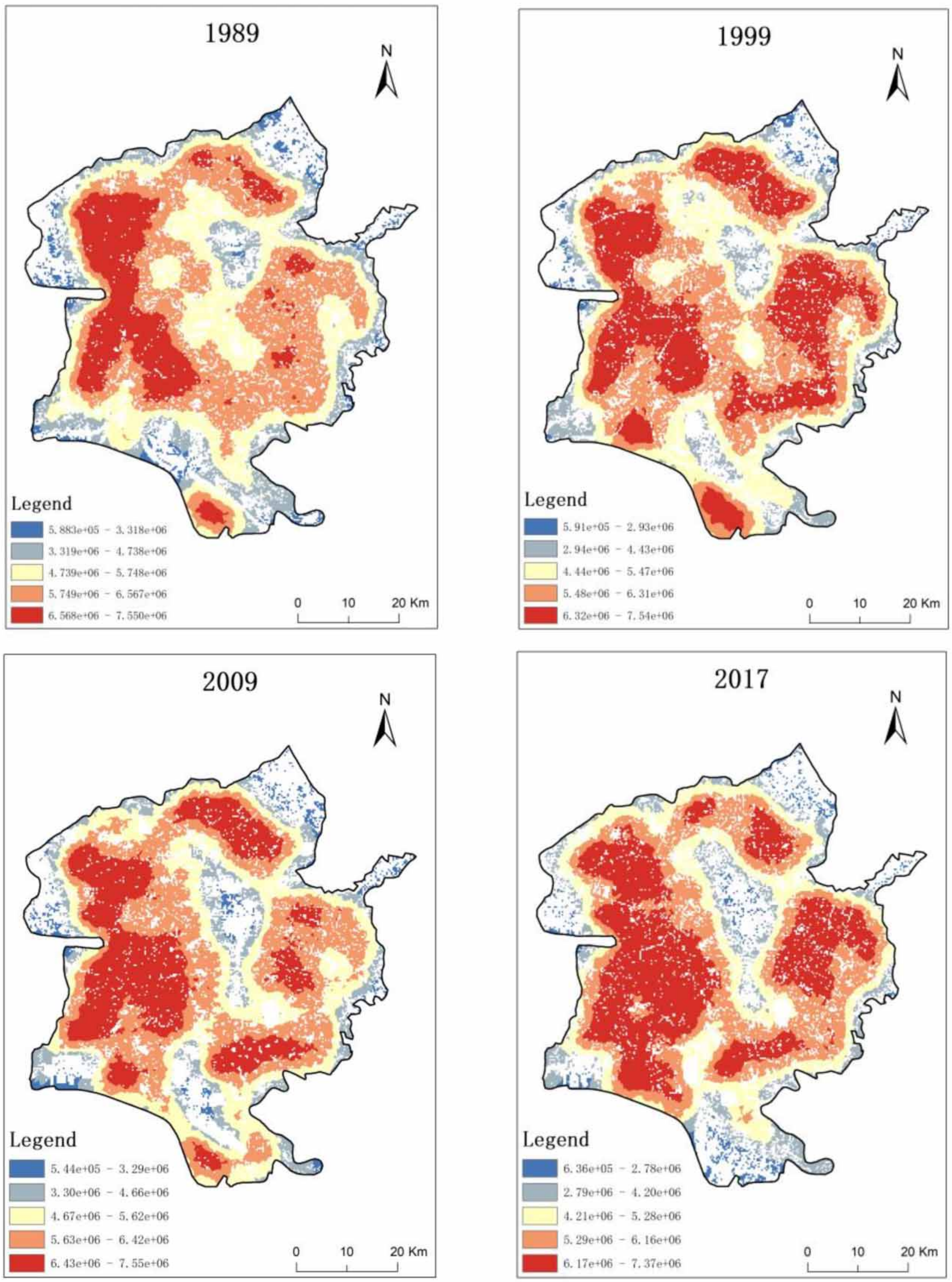
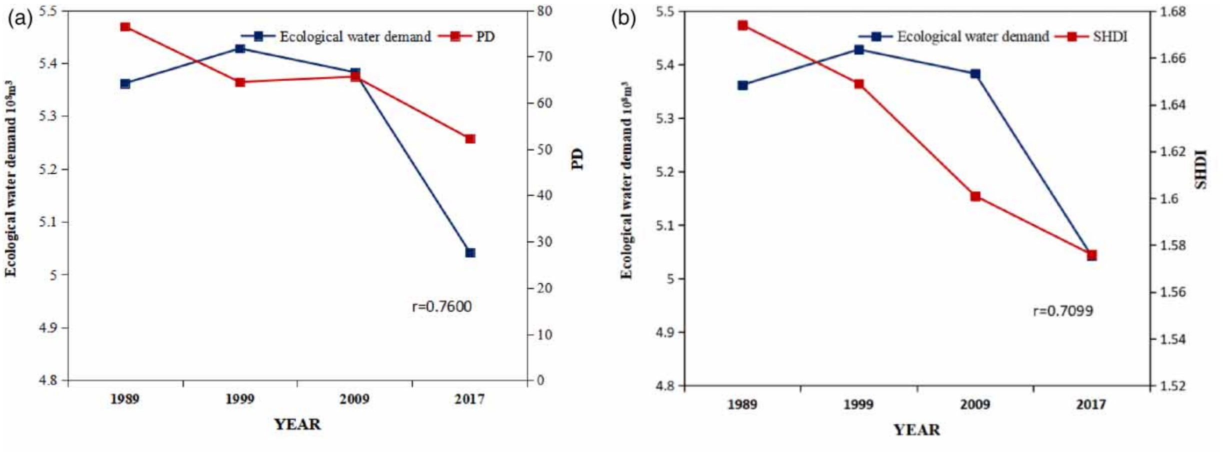


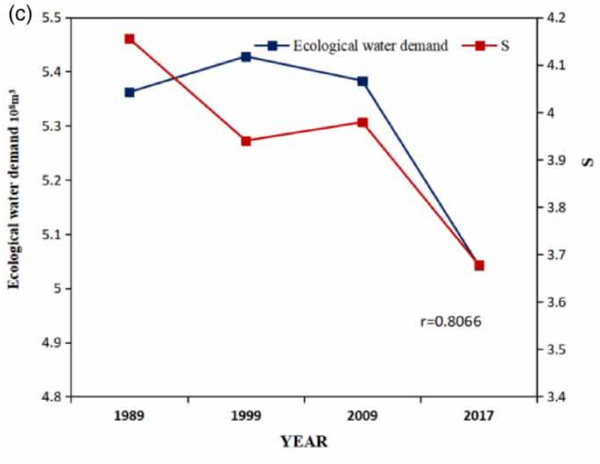
Figure 4 | Spatial and temporal distribution of the ecological water demand in Panjin wetland in 1989, 1999, 2009, and 2017.

1989, 1999, 2009, and 2017 for Panjin wetland as 5.362×10^9 m^3, 5.428×10^9 m^3, 5.383×10^9 m^3, and 5.042×10^9 m^3, respectively, based on the landscape pattern classification data. A gray prediction model was used to obtain the future. The ecological water demand of the Panjin wetland in 2027, 2037, 2047, and 2057 is 4.913×10^9 m^3, 4.738×10^9 m^3,



Correlation of ecological water demand and PD

Correlation of ecological water demand and SHDI



Correlation of ecological water demand and S

Figure 5 | Correlation analysis between landscape index and total ecological water demand in the Panjin wetland. (a) Correlation of ecological water demand and PD. (b) Correlation of ecological water demand and SHDI. (c) Correlation of ecological water demand and S.

Table 10 | Simulated values and simulation errors

Serial number	Actual data	Simulation data	Residuals	Relative simulation error
1	5.362	5.362	0	0
2	5.428	5.476	−0.048	0.886%
3	5.383	5.282	0.101	1.885%
4	5.042	5.094	−0.052	1.028%

4.570×10^9 m^3, and 4.408×10^9 m^3, which shows an overall decreasing trend and indicates that the overall ecological environment of the Panjin wetland is improving.

This study investigated the ecological water demand of the Panjin wetland and used gray models to predict the future ecological water demand of the Panjin wetland, enriching the research results in the field of ecological assessment of the Panjin wetland, providing a basis for scientific management of wetlands, and providing a scientific reference for other regional estuarine wetlands research. However, the low resolution of the remote sensing images, with a resolution of only 30 m, can have an impact on the analysis results. In addition, the small number of samples chosen to carry out the prediction analysis will also have a certain bias on the prediction results. There are many factors affecting the ecological environment of wetlands, and in the process of practical application, the impact of social and economic factors on the ecological water demand security of wetlands should also be taken into account.

FUNDING

This study was funded and supported by the National Natural Science Foundation of China (No. 31570706).

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Agboola, J. L., Ndimele, P. E., Odunuga, S., Akanni, A., Kosemani, B. & Ahove, M. A. 2016 Ecological health status of the Lagos wetland ecosystems: implications for coastal risk reduction. *Estuarine, Coastal and Shelf Science* **183**, 73–81. https://doi.org/10.1016/j.ecss.2016.10.019.

Bayesteh, M. & Azari, A. 2021 Stochastic optimization of reservoir operation by applying hedging rules. *Journal of Water Resources Planning and Management* **147**, 04020099.

Chen, H. 2012 Assessment of hydrological alterations from 1961 to 2000 in the Yarlung Zangbo River. *Ecohydrology & Hydrobiology* **12**, 93–103. https://doi.org/10.2478/v10104-012-0009-z.

Cheng, Q. & Zhou, L. F. 2018 Landscape pattern evolution and habitat suitability evaluation of the Panjin wetland. *Water Saving Irrigation* **9**, 42–50. https://doi.org/10.3969/j.issn.1007-4929.2018.09.009.

Chopra, R., Verma, V. K. & Sharma, P. K. 2001 Mapping, monitoring and conservation of Harike wetland ecosystem, Punjab, India, through remote sensing. *International Journal of Remote Sensing* **22**, 89–98. https://doi.org/10.1080/014311601750038866.

Deng, J. L. 1987 Properties of gray forecasting models GM(1,1). *Journal of Huazhong University of Science and Technology* **15**, 1–6. https://doi.org/10.13245/j.hust.1987.05.001.

Dong, W. J., Cao, X. Z. & Hu, L. L. 2011 Calculation of ecological water demand in Baiyangdian wetlands. *China Science and Technology Information* **11**, 23–25. https://doi.org/10.3969/j.issn.1001-8972.2011.11.005.

Dong, Z. Y., Liu, D. W., Wang, Z. M., Ren, C. Y., Zhang, L., Tang, X. G., Jia, M. & Ding, Z. 2014 Assessment of the habitat suitability for waterfowls in the Panjin, Liaoning with GIS and remote sensing. *Acta Ecologica Sinica* **34**, 1503–1511. https://doi.org/10.5846/stxb201210281494.

Dong, L. Q., Zhang, G. X. & Zhang, K. 2015 Analysis and prediction of wetland ecological water requirements in the Nenjiang Basin. *Acta Ecologica Sinica* **35**, 6165–6172. https://doi.org/10.5846/stxb201401100077.

Ehteram, M., Mousavi, S. F., Karami, H., Farzin, S., Saeed, F., Vijay, P. S., Kwok-wing, C. & Ahmed, E. S. 2018 Reservoir operation based on evolutionary algorithms and multi-criteria decision-making under climate change and uncertainty. *Journal of Hydroinformatics* **20**, 332–355. https://doi.org/10.2166/hydro.2018.094.

Filgueiras, R., Almeida, T. S., Mantovani, E. C., Dias, S. H. B., Fernandes-Filho E, I., Da Cunha F, F. & Venancio L, P. 2020 Soil water content and actual evapotranspiration predictions using regression algorithms and remote sensing data. *Agricultural Water Management* **241**, 106346. https://doi.org/10.1016/j.agwat.2020.106346.

Finlayson, C. M., Davis, J. A., Gell, P. A., Kingsford, R. T. & Parton, K. A. 2013 The status of wetlands and the predicted effects of global climate change: the situation in Australia. *Aquatic Sciences* **75**, 73–93. https://doi.org/10.1007/s00027-011-0232-5.

Gleick, P. H. 1998 Water in crisis: paths to sustainable water use. *Ecological Applications* **8**, 571–579. https://doi.org/10.2307/2641249.

Gleick, P. H. 2000 The changing water paradigm: a look at twenty first century water resource development. *Water International* **25**, 127–138.

Gong, Z. N., Lu, L., Jin, D. D., Qiu, H. C., Zhang, Q. & Guan, H. R. 2021 Remote sensing estimation of evapotranspiration and ecological water demand in Zhalong wetland under land use/cover change. *Acta Ecologica Sinica* **41**, 3572–3587. https://doi.org/10.5846/stxb202003060431.

Goorani, Z. & Shabanlou, S. 2021 Multi-objective optimization of quantitative-qualitative operation of water resources systems with approach of supplying environmental demands of Shadegan wetland. *Journal of Environmental Management* **292**, 112769. https://doi.org/10.1016/j.jenvman.2021.112769.

Horne, A. C., Webb, J. A., Stewardson, M. J., Richter, B. & Acreman, M. 2017 Water for the environment from policy and science to implementation and management. *Journal of Environmental Management* **237**, 215–216. https://doi.org/10.1016/j.jenvman.2019.02.056.

Hughes, D. A. 2001 Providing hydrological information and data analysis tools for the determination of ecological instream flow requirements for South African river. *Journal of Hydrology* **24**, 140–151. https://doi.org/10.1016/S0022-1694(00)00378-4.

Kayastha, N., Thomas, V., Galbraith, J. & Banskota, A. 2012 Monitoring wetland change using inter-annual Landsat time-series data. *Wetlands* **32**, 1149–1162. https://doi.org/10.1007/s13157-012-0345-1.

Keddy, P. A. 2000 *Wetland Ecology: Principles and Conservation*. Cambridge University Press, Cambridge, pp. 124–238. https://doi.org/10.1002/ldr.1135.

Kral, F., Corstanje, R., White, J. R. & Veronesi, F. 2012 A geostatistical analysis of soil properties in the Davis Pond Mississippi freshwater diversion. *Soil Science Society of America Journal* **76**, 1107–1118. https://doi.org/10.2136/sssaj2011.0206.

Li, X. Y., Zhu, C. G., Ma, Y. Q., Wang, X. Y., Wang, J. Z. & Chen, Y. N. 2021 Ecological base flow and natural vegetation water requirement of Konqi River Basin, Xinjiang. *Arid Land Geography* **2**, 337–344. https://doi.org/10.12118/j.issn.1000-6060.2021.02.05.

Lin, W. P., Li, Y., Xu, D. & Zeng, Y. 2018 Changes in landscape pattern of wetland around Hangzhou bay. *ISPRS Annals of Photogrammetry. Remote Sensing and Spatial Information Science* **IV** (3), 153–159. https://doi.org/10.5194/isprs-annals-IV-3-153-2018.

Liu, Y. J., Zhu, S. R. & Lu, Y. 2015 Valuation of ecosystem services of Dayingjiang river wetland in Yunan. *Wetland Science & Management* **11** (2), 50–53. https://doi.org/10.3969/j.issn.1673-3290.2015.04.07.

Mao, J., Zhang, P., Dai, L., Dai, H. & Hu, T. 2016 Optimal operation of a multi-reservoir system for environmental water demand of a river-connected lake. *Nordic Hydrology* **7**, 206–224. https://doi.org/10.2166/nh.2016.043.

Mulamoottil, G., Warner, B. G. & McBean, E. A. 1997 *Wetlands: Environmental Gradients, Boundaries, and Buffers*. CRC Press Inc., Boca Raton, pp. 2274–2275. https://doi.org/10.2307/2265970.

Palmer, M. A. & Bernhardt, E. S. 2006 Hydroecology and river restoration: ripe for research and synthesis. *Water Resources Research* **42**, W03S07. https://doi.org/10.1029/2005WR004354.

Pan, B. Z., Wang, H. Z., Ban, X. & Yin, X. A. 2015 An exploratory analysis of ecological water requirements of macroinvertebrates in the Wuhan branch of the Yangtze River. *Quaternary International* **380**, 256–261. https://doi.org/10.1016/j.quaint.2014.10.011.

Sajedipour, S., Zarei, H. & Oryan, S. 2017 Estimation of environmental water requirements via an ecological approach: a case study of Bakhtegan Lake, Iran. *Ecological Engineering* **100**, 246–255. https://doi.org/10.1016/j.ecoleng.2016.12.023.

Schuluter, M., Savitsky, A. G., Mckinney, D. C., Savitsky, A. G. & Lieth, H. 2005 Optimizing long-term water allocation in the Amudarya River delta: a water management model for ecological impact assessment environmental. *Modeling & Software* **20**, 529–545. https://doi.org/10.1016/j.envsoft.2004.03.005.

Shamshirband, S., Ehsan, J. N., Jason, E. A., Azizah, A. M., Amir, M. & Kwok-wing, C. 2019 Ensemble models with uncertainty analysis for multi-day ahead forecasting of chlorophyll a concentration in coastal waters. *Engineering Applications of Computational Fluid Mechanics* **13**, 91–101. https://doi.org/10.1080/19942060.2018.1553742.

Sharafati, A. & Pezeshki, E. 2020 A strategy to assess the uncertainty of a climate change impact on extreme hydrological events in the semi-arid Dehbar catchment in Iran. *Theoretical and Applied Climatology* **139**, 389–402. https://doi.org/10.1007/s00704-019-02979-6.

She, D., Xie, S. F., Peng, J. D. & Liu, Y. F. 2013 Application of non-equal interval GM (1,1) in deformation forecast. *Science of Surveying and Mapping* **5**, 85–86,111. https://doi.org/10.16251/j.cnki.1009-2307.2013.03.029.

Shokoohi, A. & Amini, M. 2014 Introducing a new method to determine rivers' ecological water requirement in comparison with hydrological and hydraulic methods. *International Journal of Environmental Science and Technology* **11**, 747–756. https://doi.org/10.1007/s13762-013-0404-z.

Shokoohi, A. & Hong, Y. 2011 Using hydrologic and hydraulically derived geometric parameters of perennial rivers to determine minimum water requirements of ecological habitats. *Hydrological Processes* **25**, 3490–3498. https://doi.org/10.1002/hyp.8076.

Song, W. D., Yang, D., Li, E. B., Zhao, Q. H. & Zhang, Y. N. 2016 Wetland information extraction and dynamic monitoring of Panjin. *Science of Surveying and Mapping* **41**, 60–65, 79. https://doi.org/10.16251/j.cnki.1009-2307.2016.09.013.

Tubiello, F. N., Salvatore, M., Ferrara, F., House, J., Federici, S., Rossi, S., Biancalani, R., Golec, R. D. C., Jacobs, H. & Flammini, A. 2015 The contribution of agriculture, forestry and other land use activities to global warming, 1990-2012. *Global Change Biology* **21**, 2655–2660. https://doi.org/10.1111/gcb.12865.

Wang, L. W. & Wei, Y. X. 2012 Variation analysis about net primary productivity of the wetland in Panjin region. *Acta Ecologica Sinica* **32**, 6006–6015.

Wu, J. W. & Zhang, Y. S. 2017 Daily evapotranspiration estimation of Panjin wetland based on SEBAL model and its distribution characteristics. *Science of Soil and Water Conservation* **15**, 8–15. https://doi.org/10.16843/j.sswc.2017.05.002.

Ye, Z. X., Li, W. H., Chen, Y. N., Qiu, J. J. & Aji, D. L. 2017 Investigation of the safety threshold of eco-environmental water demands for the Bosten Lake wetlands, western China. *Quaternary International* **440**, 130–136. https://doi.org/10.1016/j.quaint.2016.12.030.

Zhang, W. S., Zhou, L. F. & Cheng, Q. 2017 Research on eco-environmental water requirement in Liaohe Estuary wetlands based on 3S technology. *Water Saving Irrigation* **3**, 84–93. https://doi.org/10.3969/j.issn.1007-4929.2017.07.018.

Zhang, H., Chang, J., Gao, C., Wu, H., Wang, Y., Lei, K., Long, R. & Zhang, L. 2019 Cascade hydropower plants operation considering comprehensive ecological water demands. *Energy Conversion and Management* **180**, 119–133. https://doi.org/10.1016/j.enconman.2018.10.072.

Zhang, A. M., Hao, T. P., Zhou, H. P., Ma, Z. B. & Cui, S. S. 2021 Analysis on characteristics of Baiyang River Basin and water requirement of ecological vegetation in Xinjiang. *Acta Ecologica Sinica* **5**, 1921–1930. https://doi.org/10.5846/stxb201911092362.

Zhao, C. 2020 Study on the ecological water demand of Yinjiang National Wetland Park. *Journal of China Hydrology* **5**, 67–71. https://doi.org/10.19797/j.cnki.1000-0852.20190242.

Zhao, X. Y., Yang, P. L., Ren, S. M. & Xu, T. W. 2014 Research on eco-environmental water demand of Hetao Irrigation District in Inner Mongolia. *Journal of Irrigation and Drainage* **33** (2), 126–129. https://doi.org/10.7631/j.issn.1672-3317.2014.02.032.

Zhao, J. H., Qin, W. & Shen, G. H. 2015 Research on paddy artificial wetland ecological environment water demand. *Water Resources Development and Management* **4**, 48–50. https://doi.org/10.16616/j.cnki.10-1326/TV.2015.04.015.

Zhou, L. F., Xu, S. G., Li, Q. S. & Liu, D. Q. 2007 Safety threshold of eco-environmental water requirement in wetland. *Journal of Hydraulic Engineering* **38**, 845–851. https://doi.org/10.13243/j.cnki.slxb.2007.07.013.

Zhou, W. B., Li, Y. P., Wang, S. Y. & Yang, H. 2015 Estimation of ecological water demand in Sanmenxia reservoir wetland. *South-to-North Water Transfers and Water Science & Technology* **13**, 877–882. https://doi.org/10.13476/j.cnki.nsbdqk.2015.05.013.

Zhou, L. F., Xu, H. T. & Zhang, J. 2016 Landscape pattern change and division of function zones in Linghekou wetland nature reserve. *Wetland and Science* **14**, 403–407. https://doi.org/10.13248/j.cnki.wetlandsci.2016.03.015.

Zhou, W. C., Zhang, W., Hu, X. Y., Fu, T. & Shi, Y. H. 2021 Evaluation of wetland ecosystem service value in Hubei Province. *Bulletin of Soil and Water Conservation* **41**, 305–311, 364. https://doi.org/10.3969/j.issn.1004-3020.2010.03.003.

First received 31 October 2022; accepted in revised form 12 March 2023. Available online 31 March 2023