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Suitable eco-environmental water requirement in Sanmenxia Reservoir wetland based on 3S technology

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ABSTRACT

Wetland is a special ecosystem formed by the interaction between water and land, which cannot be separated from the support and protection of water resources. Therefore, it is necessary to study the ecological environment water demand of wetland. This paper takes the sediment-laden river wetland-Sanmenxia Reservoir wetland as an example, constructed the calculation model of 10 indexes of consumable eco-environmental water demand and non-consumable eco-environmental water demand. At the same time, 3S technology was used to extract the area of various types of the Sanmenxia Reservoir wetland, the monthly water demand process and the annual optimal eco-environmental water demand of the Sanmenxia Reservoir wetland were calculated under the conditions of average precipitation for many years. The main conclusions are as follows: (1) On the basis of other scholar's research, increased water requirement indicators such as environmental purification water requirement, leaky water requirement, landscape protected water requirement and recreational water requirement. (2) The total water requirement for the most suitable eco-environmental in the Sanmenxia Reservoir is 16.6918.5 × 10^8 m^3. Meanwhile, considering the particularity of the operation mode of Sanmenxia Reservoir, this study gives the process of the most suitable eco-environmental monthly water demand, which provides a scientific basis for the optimal allocation of wetland water resources in the reservoir. (3) Non-consumable eco-environmental water demand in Sanmenxia Reservoir is the main type of water demand, and among all types of eco-environmental water demand indexes, environmental purification water requirement is the largest. Therefore, controlling pollutant discharge is the primary task for the ecological environment restoration of Sanmenxia Reservoir.

Keywords: 3S technology; Sanmenxia Reservoir wetland; Computation model; Water requirement process; Suitable eco-environmental water requirement

1. Introduction

In recent years, under the influence of human activities, climate change and other factors in the basin, the amount of water and sand in the Yellow River decreased significantly compared with the annual average amount of water and sand, but the Yellow River basin for the first, the second industry and living water consumption increased year by year, from a large number of eco-environmental water, leading to the ecological process of the Yellow River basin is impeded and its functions decline, fragile ecological environment, and reduce the species diversity and a series of problems.

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Wetland, as a unique ecosystem formed by the interaction between land and water, which plays an indispensable role in improving water quality, improving climate, replenishing groundwater and maintaining ecosystem balance, and eco-environmental water requirement is the most important factor to maintain the health of wetland ecosystem and its evolution [1], which involves hydrology, ecology, environmental science and other disciplines. With the deepening of people's understanding of wetland ecosystem, a large number of researchers have carried out in-depth research on wetland eco-environmental water demand.

The research on eco-environmental water demand in foreign countries is earlier and mainly focuses on river eco-environmental water demand. Firstly, in terms of water demand index calculation, Eamus et al. [2] improved the calculation method of wetland vegetation and soil water demand index, Keddy [3] improved the calculation method of water demand index of plants and animals in wetlands. Secondly, different scholars explained the key points of wetland conservation from their own research perspectives, Raskin et al. [4] pointed out that water demand of plants and animals is a key link to maintain the health of wetland ecosystem, Sajedipour et al. pointed out that the optimal allocation of wetland water resources is the most effective way for wetland restoration. In the domestic, at present, a large number of domestic scholars have also conducted in-depth research on wetland eco-environmental water demand, firstly, the classification of wetland eco-environmental water demand index is studied, Zhou et al. [6] divided wetland eco-environmental water demand into consumable eco-environmental water demand and non-consumable eco-environmental water demand. Secondly, different scholars define the concept of wetland eco-environmental water demand from their own research perspectives, Shen [7] defined the concept of wetland eco-environmental water demand in a broad sense, Cui and Yang [8] defined the concept of wetland eco-environmental water demand in a narrow sense, Guo et al. [9] defined wetland eco-environmental water demand as the amount of water needed to maintain the ecological balance of wetland ecosystem and ensure the normal functioning of wetland ecosystem services. The above research provides multiple research perspectives and references for the study of wetland eco-environmental water demand in Sanmenxia Reservoir.

Wetland eco-environmental water demand is unique, for different study areas, the calculation models are also different [10]. At present, a large number of scholars have conducted in-depth studies on the definition and calculation methods of wetland eco-environmental water demand, but its research area mainly concentrates in the general river and lake and so on wetland ecosystem, and there are few studies on the specific wetland sediment-laden river wetland ecological environment water demand. In this paper, the sediment-laden river wetland-Sanmenxia Reservoir wetland as the study area, Sanmenxia Reservoir wetland is formed under the special water and sand condition of the Yellow River, November to April of the following year, the reservoir impoundment, the wetland water level rises, the water's surface area increases, May to October, reservoir flood discharge sand, the wetland water level drops, the water's surface area decreases, the river wetland and beach wetland in the reservoir evolved alternately, the area of each type of wetland cannot be accurately measured by hand, this paper relies on 3S technology, which refers to remote sensing, geography information systems and global positioning systems, to carry out quantitative analysis on the area of various types of wetlands, it can avoid the errors caused by the uncertainty of the area of various types of wetlands to the greatest extent. At the same time, according to the characteristics of Sanmenxia Reservoir wetland, on the basis of other scholar's research, increased water requirement indicators such as environmental purification water requirement, leaky water requirement, landscape protected water requirement and recreational water requirement, the calculation model of consumption ecological environment water demand and non-consumption ecological environment water demand is established, among them, water demand for ecological environment refers to the amount of water consumed by wetland ecosystem, it includes plant evapotranspiration water demand, water's surface evaporation water demand, leakage water demand and soil water demand. Non-consumable eco-environmental water demand refers to the surface water storage to maintain the healthy development of wetland ecosystem, it includes habitat water demand, sand transport water demand, environmental purification water demand, landscape protection water demand, ecological base flow and recreational water demand. Combined with the basic data of perennial precipitation, water surface evaporation, runoff and sediment transport in the reservoir, moreover, Tennant method and key species hydraulics were used to calculate the suitable eco-environmental water demand in Sanmenxia Reservoir, and its water demand process and annual change rule are analyzed, analyze the water demand process and the law of annual change, and discuss the leading factors affecting the annual change of eco-environmental water demand in the reservoir. In terms of theory, this study has improved the eco-environmental water demand calculation model of silt river wetland, this model can meet the requirement of purifying pollutants in wetland, so as to play a guiding role in the study of eco-environmental water demand of similar wetland. In practice, the results of this study can provide scientific basis for the allocation of wetland water resources and the restoration of wetland ecological environment in Sanmenxia Reservoir.

2. Wetland type information extraction based on 3s technology

2.1. Study area

Sanmenxia Reservoir, located at the junction of Shanxi, Shaanxi and Henan Provinces, belongs to the middle reaches of the Yellow River. Its coordinates are 34°21′-35°50′N, 108°45′-111°20′E, the controlled basin area is 688,400 km^2, accounting for 91.5% of the total area of the Yellow River basin. According to the river characteristics, Sanmenxia Reservoir can be divided into Longmen to Tongguan County, Tongguan County to Sanmenxia Dam, Weihe River to the section where Lintong meets the Yellow River, and North of Luohe River to Weihe River. In this paper, Tongguan County to Sanmenxia Dam is divided as the research area, the reservoir section is 113.2 km long, 1–6 km wide and the channel width is about 0.5 km. At present, the main tasks of Sanmenxia Reservoir are irrigation, flood control, water supply, flood prevention, power generation, water regulation and sand regulation, its application mode has gone through the stage of impoundment and sediment detention, and finally changed to impoundment and sediment discharge, the reservoir has played an important role in water and sand regulation. The concrete operation mode is from November to April of the following year, the reservoir impoundment, the reservoir water level rise, May to October, the reservoir flood discharge sand, the reservoir water level drops. The wetland in Sanmenxia Reservoir is closely related to the construction of Sanmenxia Reservoir wetland. Wetland types in the reservoir mainly include river wetland, beach wetland, marsh wetland, lake and pond wetland, etc. In the flood season and non-flood season, with the change of reservoir operation mode, the area of each type of wetland will change correspondingly. Study area location and administrative zoning map (Fig. 1).

2.2. Wetland type information extraction

According to "Wetland and Ramsar Convention" [11] and other relevant norms, combined with the results of field investigation and research purposes, the types of wetlands in the study area are divided into river wetland, beach wetland, marsh wetland, lake and pond wetland. Basic data include the data of soil type, vegetation type, climate and hydrological conditions in the study area of Landset-8 remote sensing image of earth resources with spatial resolution of 30 m in the fourth period of March, May, August and November 2017. ENVI software was used to enhance and clip the image, radiometric calibration, atmospheric correction image of the collected remote sensing image. Finally, ENVI and ArcGIS software were used for human-computer interaction interpretation to obtain the distribution characteristics of wetland types in the study area (Fig. 2) and the area of each type of wetland (Table 1). Due to the small fluctuation of each type of wetland area in adjacent months, the data of March, May, August and November respectively represent the wetland area of the reservoir from January to March, April to June, July to September, October to December.

3. Data and methodology

3.1. Basic data

The basic data required for the calculation of wetland eco-environmental water demand in Sanmenxia Reservoir include temperature, humidity, wind speed, water surface evaporation, precipitation, runoff and sediment transport. Temperature, humidity and wind speed data were collected from the Sanmenxia Meteorological Station and Tongguan

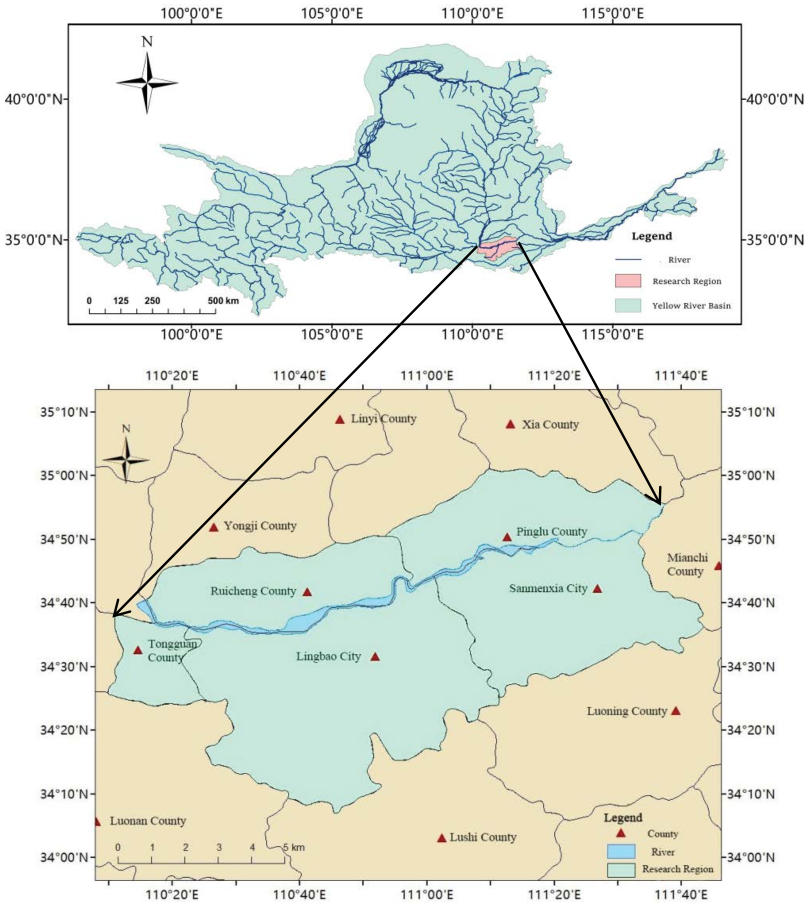

Fig. 1. Study regional location and administrative zoning map.

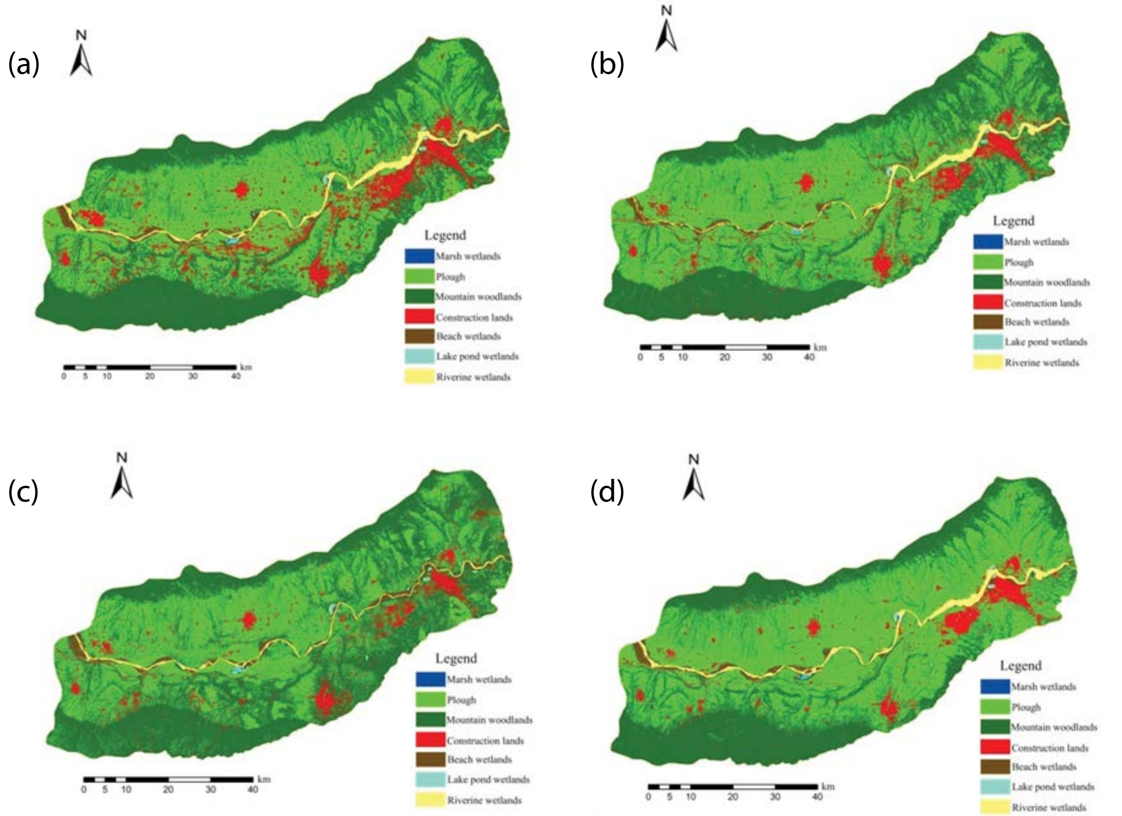

Fig. 2. Wetland type map of Sanmenxia Reservoir in 2017: wetland types in (a) March, (b) May, (c) August and (d) November.

Table 1
Area of various types of wetlands in Sanmenxia Reservoir in 2017 (km^2)

Month	River wetland	Beach wetland	Lake and pond wetland	Marsh wetland	Total area
3	115.82	81.36	15.61	3.16	215.95
5	103.62	88.24	13.42	3.29	208.57
8	53.21	134.89	10.87	2.86	201.83
11	93.35	101.72	12.98	3.32	211.37

Meteorological Station in each month from 1981 to 2017. Data of water surface evaporation and precipitation were collected from each month of Sanmenxia Meteorological Station and Tongguan Meteorological Station from 1972 to 2017. Runoff and sediment discharge data were collected from the Sanmenxia Hydrological Station and Tongguan Hydrological Station in each month from 2008 to 2017.

3.2. Calculation method of wetland eco-environmental water demand index

3.2.1. Water requirement for evapotranspiration of vegetation

Vegetation evapotranspiration water demand mainly refers to vegetation surface transpiration water consumption and soil evaporation water consumption. There are many types of wetland vegetation in Sanmenxia Reservoir, among which reed is the dominant species of wetland in the reservoir. In this study, the evapotranspiration amount of reed community is generalized into the evapotranspiration amount of wetland vegetation in the reservoir. The calculation formula is as follows:

$$W_{\mathrm{ml}} = 0.001 A_i \cdot \mathrm{ET}_C \tag{1}$$

In the formula, W_{ml} is the vegetation evapotranspiration water demand (m^3); A_i is the vegetation area (m^2); ET_C is the evapotranspiration (mm).

The calculation formula of actual evapotranspiration of reed community is as follows:

$$\mathrm{ET}_C = K_C \cdot \mathrm{ET}_0 \tag{2}$$

In the formula, ET_C is the actual evapotranspiration (mm/d); ET_0 is the reference crop evapotranspiration (mm/d); K_C is the crop coefficient [12], because there is no measured data, the wetland reed crop coefficient K_C in the reservoir was obtained by using the recommended value of FAO-56 and through adjustment.

The FAO Penman–Monteith formula [13,14] is used to compute amount of Sanmenxia Reservoir wetland reference crop evapotranspiration ET_0, the formula considers the factors affecting evapotranspiration comprehensively, and the simulation results are good and the accuracy is high. The calculation formula is as follows:

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \frac{900}{T+273}\gamma U_2\left(e_s - e_d\right)}{\Delta + \gamma\left(1 + 0.34U_2\right)} \quad (3)$$

In the formula, ET_0 is the reference evapotranspiration refer to evapotranspiration (mm); G is the soil heat flux (MJ/m^2/d); R_n is the net canopy surface radiation (MJ/m^2/d); e_s is the saturation vapor pressure (KPa); e_d is the actual vapor pressure (KPa); γ is the hygrometer constant (KPa/°C); Δ is the slope of saturation vapor pressure and temperature curve (KPa/°C); U_2 is the wind speed at 2 m height (m/s); T is the average temperature (°C).

3.2.2. Water demand for surface evaporation

Water surface evaporation plays an important role in wetland water cycle. Therefore, water surface evaporation demand must be taken into account when calculating ecological environment water demand. The calculation formula is as follows:

$$W_e = 0.001A \cdot T \quad (4)$$

In the formula, W_e is the evaporation requirements (m^3); A is the area of water surface (m^2); T is the average evaporation of water surface (mm).

3.2.3. Soil water demand

Soil water demand refers to the water quantity first met when the wetland in the reservoir restores water, which is mainly affected by soil bulk density, soil layer thickness and wetland soil area, etc. In this paper, soil weight moisture content method is used to calculate soil water demand [15]. The calculation formula is as follows:

$$W_t = \frac{\left(\gamma\alpha_s A_s H_s + \gamma\alpha_f A_f H_f\right)}{\rho} \quad (5)$$

In the formula, W_t is the soil water demand (m^3); γ is soil bulk density (g/cm^3); A_s is the area of water's surface (m^2); α_s is the percentage by weight of water in a soil at saturation (%); H_s is the thickness of the soil layer on the water's surface of wetlands (m); ρ is the density of water (g/cm^3); A_f is the non-water's surface area of wetlands (m^2); α_f is the percentage water content by weight when the soil reaches the field capacity (%); H_f is the thickness of the soil layer in a wetland non-water's surface area (m).

3.2.4. Leakage water demand

Wetlands mainly supply groundwater through leakage. Therefore, leakage water demand must be considered in the calculation of eco-environmental water demand [16]. The calculation formula is as follows:

$$W_i = KA_iT \quad (6)$$

In the formula, W_i is the leakage water demand (m^3); K is the permeability coefficient (m/d); A_i is the seepage profile area (m^2); T is the calculated period length (d).

3.2.5. Habitat water requirement

The Sanmenxia Reservoir wetland is rich in animal and plant resources. The habitat water requirement is the habitat needed to maintain the survival of animals and plants, and the basic water quantity to protect biodiversity, which is related to the habitat area and the water depth required for the survival of organisms. The calculation formula is as follows:

$$W_{\text{hml}} = A_j \cdot H_i \quad (7)$$

In the formula, W_{hml} is the habitat water requirement (m^3); A_j is the water's surface area of the habitat (m^2); H_i is the average water depth (m).

3.2.6. Environmental purification water requirement

Wetland has the ecological service function of degrading pollutants and purifying water quality. Therefore, the water demand for environmental purification must be considered in the calculation of eco-environmental water demand.

Due to the lack of water quantity and water quality data such as sewage and reclaimed water discharged from reservoirs, it is impossible to use water quality prediction model to calculate environmental purification water demand, but the lowest monthly average flow rate method in the last decade can be used [17]. At present, this method is widely used in China, which can estimate the flow rate and environmental purification water demand meeting the general river pollution prevention and control. The calculation formula is as follows:

$$W_Z = \frac{T}{n}\sum_{i=1}^{n} Q_{i\min} \quad (8)$$

In the formula, W_Z is the environmental purification water requirement (m^3); $Q_{i\min}$ is the driest monthly average flow in the i year (m^3); n is the number of years counted; T the calculated period length (d).

3.2.7. Ecological base flow

Ecological basal flow is the basic flow that maintains the river ecosystem. In this study, Tennant method [18,19] was used to estimate the basal flow in the reservoir (Table 2).

The calculation formula is as follows:

$$W_j = \alpha \cdot Q_j \quad (9)$$

In the formula, W_j is the ecological basal flow (m^3); α is the average flow percentage (%); Q_j is the average monthly runoff (m^3).

Table 2
Tennant method recommended flow rate criteria

Qualitative description of flow and corresponding habitat	Recommended base flow rate (average flow percentage) (%)	
	General water use period (October to March of the next year)	Spawning period of fish (April to September)
Maximum	200	200
Best range	60–100	60–100
Best	40	60
Very good	30	50
Good	20	40
Medium	10	30
Poor or minimum	10	10
Serious degradation	<10	<10

3.2.8. Sand transport water requirement

Sediment transport is not only an important ecological service function of wetland ecosystem, but also an important task of wetland management. Therefore, sediment transport water demand must be considered when calculating the eco-environmental water demand of wetland in sediment-laden rivers. In this paper, sediment transport capacity method [20] is adopted to calculate sediment transport water demand of wetlands in the reservoir. The calculation formula is as follows:

$$W_x = \eta^{\alpha} \cdot W_{\omega} \tag{10}$$

$$W_{\omega} = \frac{W - W_s}{\gamma_s} \tag{11}$$

$$\eta = \frac{W_{s\,\mathrm{in}}}{W_{s\,\mathrm{out}}} \tag{12}$$

In the formula, W_x is the sand transport water requirement (m^3); η is the sediment transport efficiency, α is the index (Its value according to determine the efficiency of sediment transport, when the sediment transport efficiency is less than 1, take $\alpha = 1$; When the sediment transport efficiency is greater than or equal to 1, take $\alpha = 0$); W_{ω} is the clean water (m^3); W is the volume of runoff (m^3); W_s is the amount of sand transported (t); γ_s is the weight per unit volume of sediment (Generally take 2.65 t/m^3); $W_{s\,\mathrm{in}}$ and $W_{s\,\mathrm{out}}$ are the amount of sand transported of import and export stations respectively (t).

3.2.9. Landscape protection water requirement

Wetland natural landscape and cultural landscape in Sanmenxia Reservoir is rich, among which water, marsh, reed and lotus is the most important part of Sanmenxia Reservoir landscape. The calculation formula is as follows:

$$W_{\mathrm{lc}} = H_{\mathrm{lc}} \cdot A_{\mathrm{lc}} \tag{13}$$

In the formula, W_{lc} is the landscape protection water requirement (m^3); H_{lc} is the water level of landscape protection (m); A_{lc} is the area of landscape protection (m^2).

3.2.10. Recreational water requirement

In recent years, the Sanmenxia Reservoir wetland has been developed on a large scale, and the number of tourists is increasing year by year. Recreational water demand refers to the basic amount of water needed to ensure the landscape and traffic conditions for tourists' entertainment. The calculation formula is as follows:

$$W_d = H_d \cdot A_d \tag{14}$$

In the formula, W_d is the recreational water requirement (m^3); H_d is the recreational water level (m); A_d is the area of the entertainment area (m^2).

3.3. Calculation method of optimal total eco-environmental water demand

The above eco-environmental water requirements exist cross-repetition, simple addition is not reasonable. Therefore, this paper adopts the following methods to determine the optimal total amount of eco-environmental water demand in each month and year. The calculation formula is as follows:

$$Q = \sum_{n=1}^{12} Q_n \tag{15}$$

$$Q_n = \max\left\{W_{\mathrm{hml}}, W_z, W_j, W_x, W_{\mathrm{lc}}, W_d\right\} + W_{\mathrm{ml}} + W_e + W_t + W_i - P \tag{16}$$

$$P = 0.001p \cdot A \tag{17}$$

In the formula, Q is the annual optimal total eco-environmental water demand (m^3); Q_n is the optimal amount of eco-environmental water demand in the n-th month (m^3); W_{hml} is the habitat water requirement (m^3); W_z is the environmental purification water requirement (m^3); W_j is the ecological base flow (m^3); W_x is the sand transport water requirement (m^3); W_{lc} is the landscape protection water requirement (m^3); W_d is the recreational water requirement (m^3); W_{ml} is the plant evapotranspiration water requirement (m^3); W_e is the water's surface evaporation water requirement (m^3); W_t is the soil water requirement (m^3); W_i is the leaky water requirement (m^3); P is the total precipitation (m^3); p is the precipitation (mm); A is the wetland area (m^2).

4. Results and discussion

4.1. Calculation of consumable ecological environment water demand

4.1.1. Plant evapotranspiration water requirement

According to the calculation method in section 3.2.1, combined with the existing meteorological data, calculate the amount of vegetation evapotranspiration ET_C. The vegetation in the reservoir mainly grows in the marsh wetland and beach wetland, and the sum of the area of marsh wetland and beach wetland is set as the vegetation area. The water demand level is divided according to the vegetation growth status (early growth (March), middle growth (April to August), late growth (September to October) and non-growth (November to February of the following year). The results are calculated according to the vegetation evapotranspiration ratio of 0.5, 0.9, 0.8 and 0.5 respectively (Table 4).

4.1.2. Water's surface evaporation water requirement

According to the calculation method in section 3.2.2, combined with the existing monthly average evaporation data of Sanmenxia Meteorological Station and Tongguan Meteorological Station from 1972 to 2017, the monthly average water surface evaporation volume and annual average water surface evaporation demand of the Sanmenxia Reservoir wetland are counted and calculated (Table 4).

4.1.3. Soil water requirement

Based on field investigation and relevant literature research [21], comprehensive determine the Sanmenxia Reservoir wetland main soil types for swamp soil. Soil bulk density and density of water are 1.3 g/cm^3 and 1 g/cm^3 respectively. When the soil reaches saturated water content, set α_S to 50%. When the soil reaches the amount of water held in the field, set α_f to 30%. The thickness of soil layer on the surface of wetland is 1.5 m. The thickness of the soil layer in the non-surface area of the wetland was 2.5 m. The water surface area of the reservoir is the sum of the average monthly area of river wetlands, lakes, ponds and marshes, while the average monthly area of beach wetlands is taken from the non-surface area. By using Eq. (5), the soil water demand of the reservoir wetland in 2017 is 2,041.9 million m^3.

4.1.4. Leaky water requirement

According to the research of Gong [22], Tongguan–Sanmenxia reach is an underground river, which shows groundwater recharge surface water. The recharge of surface water to groundwater only occurs in the season of abundant water, and the supply amount is very small. Therefore, the leakage water demand of the Sanmenxia Reservoir wetland can be neglected from the perspective of the whole year (Fig. 3).

4.2. Calculation of non-expendable eco-environmental water demand

4.2.1. Habitat water requirement

Sanmenxia Reservoir is rich in wetland bird resources, which is an important wintering place for whooper swans. According to the research of Zhou et al. [23], the living water depth of wetland birds (whooper swans) in the reservoir (Table 3).

The Sanmenxia Reservoir wetland is rich in fish resources, mainly grass carp and silver carp. In this paper, the carp living in the bottom of the water body as an example. Studies on fish at home and abroad show that the minimum depth required for fish life is three times the length of fish. In this paper, the length of carp was set at 35 cm, and the water depth required for carp survival was 1.05 m.

Comparing the water depth required by fish and birds, the larger values of the two were set as 1.05 m for the average water depth required by habitat. Since fish generally live in rivers, lakes and reservoirs, the surface area of habitat is the sum of the area of river wetlands, lake and pond wetland. Because habitat water demand is non-consumptive water demand, annual water demand is the average of monthly water demand, formula (7) can be used to calculate the habitat water demand of wetlands in the reservoir in each month (Table 4).

4.2.2. Environmental purification water requirement

According to the calculation method in section 3.2.6 and combined with the existing monthly average runoff data of Sanmenxia Hydrological Station and Tongguan

Table 3
Water depth requirement of birds in Sanmenxia Reservoir wetland (m)

Time	Average depth of water required	Range of water requirements	Cause of water demand
April to June	0.1	0.1–0.5	Breeding
July to October	0.5	0.2–0.8	Birds grow and reproduce
November to March of the following year	0.2	0.1–1	Birds wintering

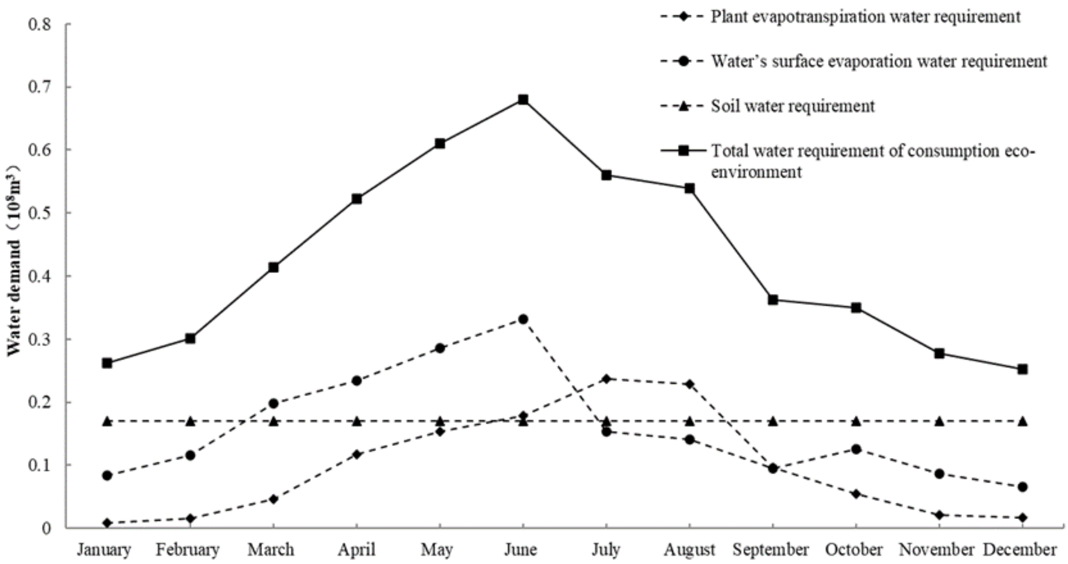

Fig. 3. The annual variation trend of the total water demand of consumption-oriented eco-environment and the water demand of various indicators in the Sanmenxia Reservoir wetland in each month.

Hydrological Station from 2008 to 2017, the average monthly runoff and water demand for environmental purification of the Sanmenxia Reservoir wetland in recent ten years were calculated and counted (Table 4).

4.2.3. Ecological base flow

According to the calculation method in section 3.2.7, during the normal water use period (October to March of the following year), the percentage of the average flow was 20%, and during the spawning period (April to September), the percentage of the average flow was 40%. Based on the monthly average runoff data of Sanmenxia Hydrological Station and Tongguan Hydrological Station from 2008 to 2017, the monthly average runoff and ecological base flow of Sanmenxia Reservoir wetland in recent ten years are calculated and counted (Table 4).

4.2.4. Sand transport water requirement

According to the calculation method in Section 3.2.8 and the monthly average runoff and sediment transport data of Sanmenxia Hydrological Station and Tongguan Hydrological Station in 2017, the water demand for wetland sediment transport in Sanmenxia Reservoir is calculated (Table 4).

4.2.5. Landscape protection water requirement

Reed and lotus are the most important components of the natural landscape in Sanmenxia Reservoir. Among them, the optimum water depth for reed growth is 0.5–1 m, and the optimum water depth for lotus root growth is 0.05–1 m [24]. In view of the wetland vegetation condition in Sanmenxia Reservoir, the water level for landscape protection is 0.8 m. Because reed and lotus mainly concentrate on marsh wetland and beach wetland, but beach wetland does not consider water level, so the area of landscape protection is set as marsh wetland area. Because reed and lotus are mainly concentrated in marsh wetland and beach wetland, but beach wetland does not consider water level, so the area of landscape protection is set as marsh wetland area. Moreover, the water demand for landscape protection belongs to non-consumable water demand, so the annual water demand is equal to the average water demand of each month, the water requirement for landscape protection in each month of wetland in reservoir can be calculated by formula (13) (Table 4).

4.2.6. Recreational water requirement

Boats can be rowed on a surface with a depth greater than 0.7 m, the water depth greater than 2 m is suitable for mechanical vessels to navigate [24]. Considering the actual situation of wetland in Sanmenxia Reservoir, the recreational water level should be 1 m. Because the flow velocity of the main channel of the Yellow River is too high to be suitable for recreation, the recreation area is set as the area of lakes and reservoirs [25,26]. Moreover, recreational water demand belongs to non-consumable water demand, so the annual water demand takes the average of water demand in each month, the water requirement for landscape protection in each month of wetland in reservoir can be calculated by formula (14) (Fig. 4).

4.3. Calculation of the optimum total eco-environmental water demand

4.3.1. Calculating the total precipitation of wetland

Based on the monthly average evaporation data of Sanmenxia Meteorological Station and Tongguan Meteorological Station from 1972 to 2017, the monthly average precipitation and total monthly average precipitation of the Sanmenxia Reservoir wetland are calculated by formula (17) (Table 4).

Table 4
Water demand of each index in each month and the total amount of water demand of the most suitable ecological environment in each month in the Sanmenxia Reservoir wetland (10^8 m^3)

Month	Plant evapotranspiration water requirement	Water's surface evaporation water requirement	Soil water requirement	Habitat water requirement	Sand transport water requirement	Environmental purification water requirement	Landscape protection water requirement	Ecological base flow	Recreational water requirement	Total precipitation	Total eco-environmental water requirement in months
1	0.0087	0.0832	0.1702	1.3800	0	10.1246	0.0253	2.3033	0.3122	0.0093	10.3774
2	0.0156	0.1152	0.1702	1.3800	0	9.1448	0.0253	2.8484	0.3122	0.0168	9.4290
3	0.0466	0.1974	0.1702	1.3800	0	10.1246	0.0253	4.4121	0.3122	0.0424	10.4964
4	0.1175	0.2343	0.1702	1.2289	0	9.7980	0.0263	7.5068	0.2684	0.0822	10.2378
5	0.1539	0.2858	0.1702	1.2289	0	10.1246	0.0263	4.7682	0.2684	0.1227	10.6118
6	0.1787	0.3316	0.1702	1.2289	0	9.7980	0.0263	5.9584	0.2684	0.1232	10.3553
7	0.2366	0.1537	0.1702	0.6728	5.9731	10.1246	0.0229	9.2472	0.2174	0.2279	10.4572
8	0.2287	0.1403	0.1702	0.6728	16.6942	10.1246	0.0229	10.734	0.2174	0.1777	17.0557
9	0.0969	0.0953	0.1702	0.6728	27.9240	9.7980	0.0229	16.0432	0.2174	0.1864	28.1000
10	0.0544	0.125	0.1702	1.1165	29.1682	10.1246	0.0266	4.4818	0.2596	0.1139	29.4039
11	0.0208	0.0861	0.1702	1.1165	0	9.7980	0.0266	3.3603	0.2596	0.0487	10.0264
12	0.0165	0.0658	0.1702	1.1165	0	10.1246	0.0266	2.8758	0.2596	0.0095	10.3676

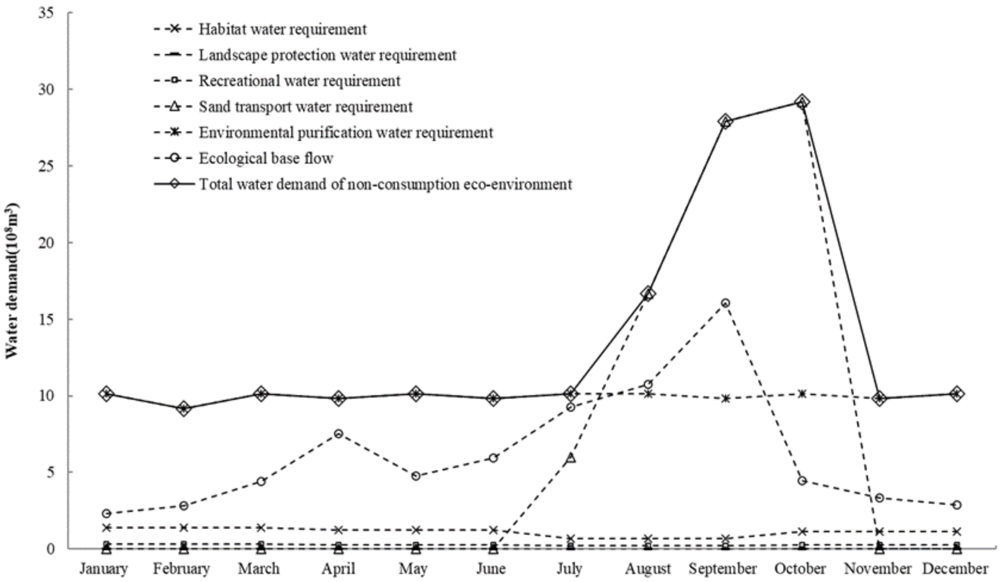

Fig. 4. The variation trend of the total water demand of non-consumption-oriented eco-environment and the water demand of various indicators in the Sanmenxia Reservoir wetland in each month.

4.3.2. The most suitable water requirement process of eco-environment monthly

According to the calculation results of various ecological and environmental water demand indexes of wetlands, the optimal monthly water demand process of the Sanmenxia Reservoir wetland can be obtained by using formula (16) (Table 4).

4.3.3. Total water requirement for the best ecological environment in the year

According to the calculation results of water demand process of the most suitable ecological environment in each month in section 4.3.2, and using Eq. (15), the total water demand of the Sanmenxia Reservoir wetland is 166.9185 billion m^3.

4.4. Discussion

- The area of marsh wetlands, lake and pond wetland in Sanmenxia Reservoir is small and has little change in the year. The area of river wetlands decreases first and then increases with time and the area of beach wetland increases first and then decreases with time (Table 1). Combining with Fig. 2, it is found that there is an obvious conversion between river wetland and beach wetland in the year. Through field investigation and research, it is found that the main reasons for this phenomenon are different operation modes of Sanmenxia Reservoir in the year, reservoir impoundment in non-flood season, rising water level of wetlands, flooding of a large number of beaches, flood discharge and sand discharge of reservoirs in flood season, decline of water level of wetlands, gradual bareness of beaches and increase of beach area.
- The total wetland area in Sanmenxia Reservoir decreases first and then increases with time (Table 1). Through field investigation, it is found that the main reason for this phenomenon is the interference of human activities. In the non-flood season, some beach wetlands were reclaimed as farmland, while in the flood season, the reclaimed farmland was submerged and turned into wetland again.
- The variation range of the most suitable eco-environmental water requirement of the Sanmenxia Reservoir wetland is 94,290–294,039 million m^3, with the minimum value occurring in February and the maximum value occurring in October. During the non-flood season, the water requirement of ecological environment changed little in each month. The main water requirement types were the water requirement of environmental purification and ecological basic flow, and the water requirement was stable at about 1 billion m^3 [27]. The main reason for the increase of water demand for ecological environment in flood season is the influence of sand transport water requirement. The most suitable water demand for ecological environment dropped sharply in November (Fig. 5, Table 4), the reason for this phenomenon is the operation mode of Sanmenxia Reservoir. In November, the gate of Sanmenxia Dam closed and the reservoir began to store water and retain sediment.
- The total water demand of different ecological environment indexes varies greatly in the whole year. Among them, the water demand for environmental purification is the largest (11.921 billion m^3), followed by the water demand for sediment transport (7.976 billion m^3) and the ecological base flow (7.454 billion m^3) (Fig. 6). It shows that the most important factor affecting the healthy development of the Sanmenxia Reservoir wetland is the pollution caused by human activities.
- The total water demand and precipitation of consumptive eco-environment of the Sanmenxia Reservoir wetland changed little in each month, and the water demand

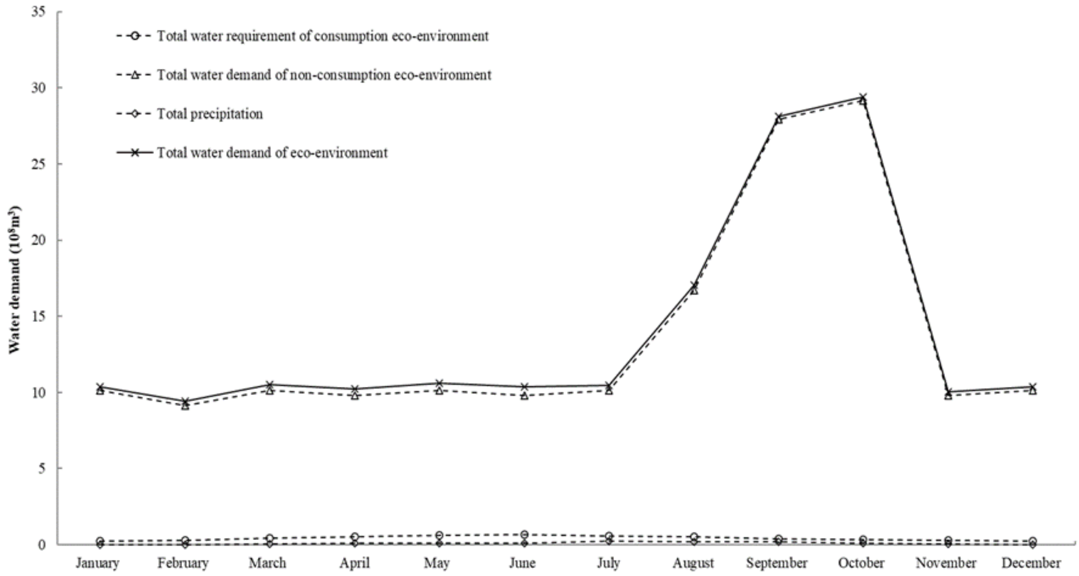

Fig. 5. The variation trend of the consumptive eco-environment water demand, non-consumptive eco-environment water demand, total water demand of eco-environment and total precipitation of the Sanmenxia Reservoir wetland in each month.

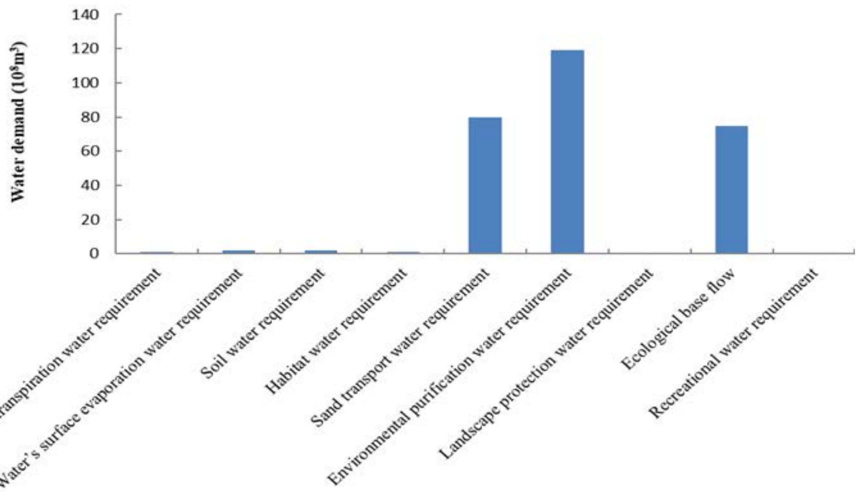

Fig. 6. Annual water demand for each indicator of the Sanmenxia Reservoir wetland.

in each month was small. However, the trend of total ecological and environmental water demand is basically the same as that of non-expendable ecological and environmental water demand, and the total water demand in each month is very close (Fig. 5), which shows that non-consumable ecological and environmental water demand is absolutely dominant.

- Compared with Zhou et al. [23] and others' calculation results on the suitable eco-environmental water demand of the Sanmenxia Reservoir wetland in 2005, the research results in this paper increased by 2.285 billion m^3. The reasons for this increase are as follows: (a) On the basis of Weibo Zhou's index system, this study increased the water demand for leakage, environmental purification, landscape protection and entertainment. Compared with the previous index system, the index system constructed in this study is more comprehensive and scientific. (b) The calculation methods of the total amount of water demand for the most suitable ecological environment for the whole year are different. Zhou made the consumptive water demand plus non-consumptive water demand equal to the most suitable total eco-environmental water demand for the whole year. However, this study considered that the operation mode of Sanmenxia Reservoir led to different trends of water demand for each ecological environment in the year. Therefore, in this paper, the maximum value of monthly consumption water demand plus non-consumption water demand is equal to the total amount of suitable eco-environmental water demand per month, and then the total amount of eco-environmental water demand in each month is equal to the optimal eco-environmental water demand in the whole year. Compared with the previous research methods, the calculation method adopted in this study has improved the accuracy and credibility of the research results.

5. Conclusion

- Although domestic and foreign scholars have done a lot of research on the water demand of wetland ecological environment, there are differences between the ecological and hydrological processes of different wetland ecosystems. Taking the Sanmenxia Reservoir wetland as an example, based on the research of other scholars and combined with the characteristics of the wetland in sediment-laden rivers, this study increased the environmental purification water requirement, leaky water requirement, landscape protection water requirement and recreational water requirement, and improved the calculation model of the eco-environmental water demand of the wetland in sediment-laden rivers. This model can satisfy the requirement of purifying pollutants in wetlands, so as to play a guiding role in the study of ecological and environmental water demand of similar wetlands.
- The results show that the optimum total water requirement of the Sanmenxia Reservoir wetland is 166.9185×10^8 m^3. Because of the particularity of the operation mode of Sanmenxia Reservoir, this study gives the most suitable monthly water requirement process for the ecological environment, which provides a scientific basis for the optimal allocation of wetland water resources in the reservoir.
- The non-consumable eco-environmental water demand of the Sanmenxia Reservoir wetland is the main type of water demand. Among all kinds of eco-environmental water demand indicators, the environmental purification water demand is the largest. Therefore, the control of pollutant discharge is the primary task of the current wetland ecological environment restoration. It is suggested that the relevant departments should strengthen the protection of wetlands from many aspects. Firstly, relevant laws and regulations should be perfected, supervision strengthened and publicity strengthened to make the concept of wetland protection popular; secondly, point source pollution should be controlled and enterprises should adopt measures combining rewards and punishments to promote enterprises to actively reduce pollutant emissions; finally, non-point source pollution should be controlled and wetlands in the occupied reservoir should be completely protected. To stop agricultural production and other activities, and then indirectly reduce the pollution of chemical fertilizer to wetland in reservoir, improve the coverage of forest and grass in wetland, restore vegetation buffer zone on both sides of the reservoir, and give some ecological compensation to farmers who have returned farmland from wetland in reservoir.

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