ISSN:2372-0743 print
ISSN:2373-2989 on line
International Journal of Ground Sediment & Water
Vol. 22
2025

◆ Research paper
DOI: 10.5281/zenodo.15033706

Water Ecological Demands and Supplementary Water Supply in the Yongding River Basin, China

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Abstract: With the intensification of global environmental change, variations in runoff patterns have profoundly impacted the natural environment. This study focuses on the Yongding River Basin, analyzing the runoff change trends from 1962 to 2020 and calculating the ecological water demand and ecological replenishment curves for the basin. The research finds that changes in water resources have significantly affected the ecosystem, exacerbating the water resource shortage in the basin. By calculating the minimum, suitable, and maximum ecological flow, the study ensures that the hydrological needs of the basin's ecosystem are met. The minimum ecological water demand in the Yongding River Basin is 63 million m3, the maximum ecological water demand is 378 million m3, and the optimal ecological water demand is 297 million m3. Additionally, the ecological replenishment demand exhibits significant seasonal and interannual fluctuations, especially in years of water scarcity, where replenishment demand fluctuates greatly. The study provides important scientific evidence for water resource management and ecological restoration in the basin, and proposes recommendations for dynamically adjusting replenishment measures to ensure the stability and sustainable development of the ecosystem. Future efforts should focus on strengthening water resource monitoring and management to ensure the successful achievement of ecological restoration goals.

Keywords: Yongding River Basin, runoff change, ecological water demand, ecological replenishment, water resource management

1. Introduction

Global environmental changes have had a profound impact on runoff patterns (Wu et al., 2019; Döll & Schmied, 2012; Piao et al., 2007). The fluctuations in runoff and the increase in extreme weather events directly affect the availability and distribution of water resources, which in turn influence soil properties, vegetation growth, and ecosystem functions within the basin (Shrestha et al., 2017). This can even trigger geological disasters, such as changes in expansive soil properties, leading to landslides and other natural hazards (Zhang & Sun, 2024; Sun et al., 2009). Furthermore, the increasing shortage of runoff has exacerbated water resource issues, gradually revealing the growing imbalance between supply and demand within various river basins (Jury & Vaux, 2005). Since the 20th century, runoff in several major river basins, such as the Hai River, Heihe River, Yellow River, and Yangtze River, has significantly decreased compared to historical periods (Zhang et al., 2020). Water resources, as a fundamental element for ecological security and human development, are becoming increasingly scarce, and the pressures on the ecological environment have become major constraints on regional development and social stability (Zhang et al., 2012; Feng et al., 2019).

The Yongding River Basin is an important component of the Hai River Basin, with significant water supply and ecological barrier functions. Since the mid-20th century, the runoff in the Yongding River Basin has sharply decreased, and the growing imbalance between water supply and demand has severely restricted ecological restoration and economic development in the basin (Ding & Liu, 2011; Zeng et al., 2013). The impact of changes in water resources on the basin's ecosystem is particularly important. Against this backdrop, ecological water demand and ecological replenishment have become critical aspects of water resource management. Ecological water demand refers to the amount of water required for the normal functioning of the basin's ecosystem, while ecological replenishment refers to the additional water provided to the ecosystem when water resources are insufficient. As climate change intensifies and water resources become increasingly scarce, calculating ecological water demand and ecological replenishment has become a key issue in water resource management and ecological restoration.

To address this challenge, this study systematically analyzes the runoff change trends in the Yongding River Basin and calculates the ecological water demand and ecological replenishment within the basin. The research provides scientific evidence for water resource management, ecological restoration, and supplementary water strategies, aiming to ensure the sustainable development of the ecosystem under water scarcity conditions

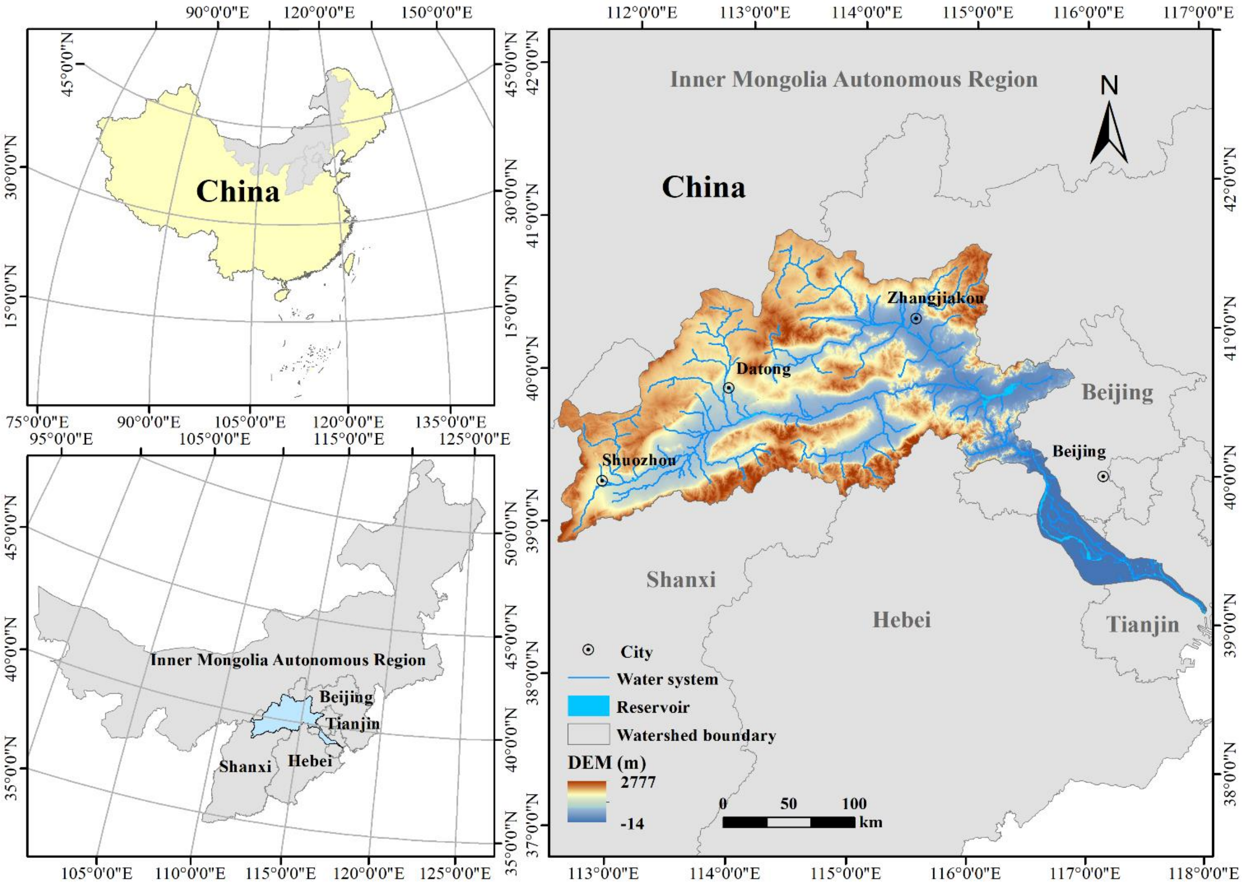

Fig.1 Geographical location of the Yongding River Basin

2. Material and methods

2.1. Study areas

The Yongding River is one of the seven major river systems in the Hai River Basin (Fig.1). It is located between longitudes 112°00′-117°45′ and latitudes 39°00′-41°20′, spanning five provinces (autonomous regions and municipalities): Shanxi Province, Inner Mongolia Autonomous Region, Hebei Province, Beijing Municipality, and Tianjin Municipality (Yang et al., 2023). The river originates from Ningwu County in Shanxi Province and Xinghe County in the Inner Mongolia Autonomous Region. After merging with Hebei, it forms the Yongding River. The total area of the Yongding River Basin is approximately 47,000 km^2, accounting for 14.7% of the total area of the Hai River Basin. Of this, 40.7% of the basin area is in Hebei Province, 39.6% in Shanxi Province, 12% in Inner Mongolia Autonomous Region, 6.8% in Beijing Municipality, and 0.9% in Tianjin Municipality.

2.2. Data source

The digital elevation model (DEM) data used in this study comes from the Geospatial Data Cloud, with a resolution of 30 meters. To ensure the accuracy and applicability of the data, the original DEM data was clipped to the boundary of the study area using the mosaic and clipping tools in ArcGIS software. The monthly flow data of Guanting Reservoir from 1956 to 2020, selected for this study, is sourced from the "Hai River Basin Hydrological Yearbook." These flow data provide reliable support for water resource analysis in the study area

2.3. Research method

2.3.1. Linear regression method

The application of the linear trend estimation method in hydrology is based on long time series of hydrometeorological data (Ji et al., 2024; Xu et al., 2022; Ye et al., 2023). The formula for the simple linear regression equation is as follows:

$$\hat{x}_i = a + bt_i, (i = 1, 2, ..., n) \tag{1}$$

$$\left\{ \begin{array}{l} a = \bar{x} - b\bar{t} \\ b = \dfrac{\sum_{t=1}^{n} x_i t_i - \dfrac{1}{n}\left(\sum_{i=1}^{n} x_i\right)\left(\sum_{t=1}^{n} t_i\right)}{\sum_{t=1}^{n} t_i^2 - \dfrac{1}{n}} \end{array} \right\} \tag{2}$$

In the formula: x_i is the precipitation amount; t_i is the year; a is the regression constant; b is the regression coefficient.

2.3.2. Penman-Monteith equation

The Penman-Monteith formula comprehensively considers both the aerodynamic and thermodynamic factors among meteorological elements. It is a widely used model for calculating potential evapotranspiration (Portela et al., 2019; Tegos & Efstratiadis, 2013; Rampisela et al., 1990). The specific calculation method is as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \Upsilon \dfrac{900}{T + 273} W_{S2}(e_s - e_a)}{\Delta + \Upsilon(1 + 0.34 W_{S2})} \tag{3}$$

In the formula: ET0 represents potential evapotranspiration, (mm/d); Δ is the slope of the saturation vapor pressure curve, (kPa/°C); Rn is the net radiation, (MJ/(m2·d)); G is the soil heat flux density, (MJ/(m2·d)); γ is the psychrometric constant, (kPa/°C); T is the average air temperature, (°C); es is the saturation vapor pressure, (kPa); ea is the actual vapor pressure, (kPa); Ws2 is the average wind speed at 2 meters, (m/s).

2.3.3. Ecological baseflow calculation

Tennant method is a commonly used approach for calculating ecological water demand (Zhang et al., 2024; Zheng et al., 2015; Wang et al., 2020). This method establishes an empirical relationship between river flow and the ecological status within the river channel, calculating the ecological water demand as a certain percentage of the multi-year average flow. It is simple and convenient to use. The flow percentages corresponding to different ecological water demand conditions in river channels are detailed (Table 1).

Table 1 Flow percentage corresponding to the ecological and environmental status

ecological environment level	Percentage of the multi-year average natural flow during the same period	
	in the drier periods of the year	in the wetter periods of the year
Maximum	200	200
Optimal range	60-100	60-100
Excellent	40	60
Very good	30	50
Good	20	40
Average	10	30
Poor	10	10
Very poor	<10	<10

3. Results

3.1. Hydrological situation analysis

Based on the measured monthly runoff data from Guanting Reservoir spanning from 1956 to 2020 (a total of 65 years), a trend analysis of the long-term runoff data in the Yongding River Basin was conducted using methods such as linear regression and 5-year moving averages (Fig.2). The results show that the average annual runoff of Guanting Reservoir is 621 million m^3, with the historical maximum reaching 2.044 billion m^3 and the minimum dropping to 28 million m^3. Overall, the runoff in the basin shows a significant decreasing trend, with this trend being highly statistically significant.

3.2. Ecological water demand calculation

This article calculates three types of ecological flow in rivers: minimum ecological flow, suitable ecological flow, and maximum ecological flow (Table 2). The minimum ecological flow is calculated using conservative methods (Tennant method 10%, minimum flow method, Q90 method) to ensure the ecosystem meets its lowest hydrological requirements. The suitable ecological flow is determined by synthesizing the results of the Tennant method (30%), Texas method, and Tessman method, selecting the most appropriate method to ensure biodiversity and water quality needs of the ecosystem. The maximum ecological flow is determined by using the Tennant method (60%), frequency curve method (90%), or Q90_Q50 method to ensure that the river ecosystem receives adequate water in high-flow conditions to maintain its ecological functions.

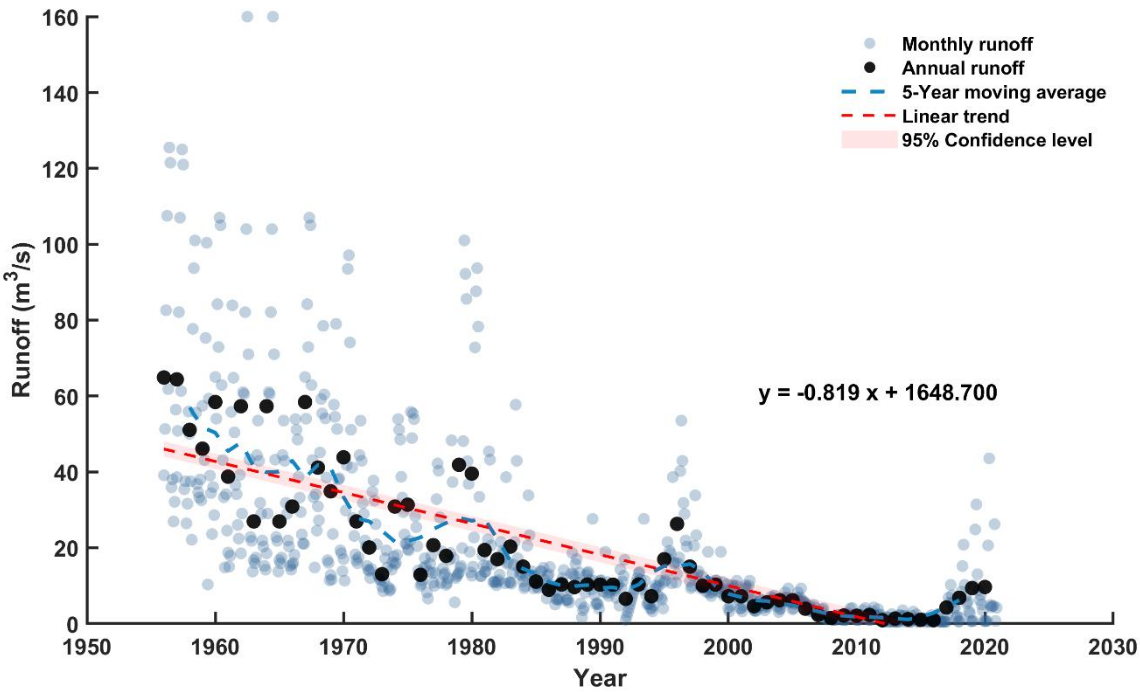

Fig.2 Annual runoff trend changes of Guanting Reservoir

The flow based on the Tennant method reduces, especially the 10% flow, which remains between 1.2 m3/s and 1.3 m3/s throughout the year, far below the natural levels. The demand for 30% and 60% flow also significantly decreases. The water demand calculated using the Texas method remains almost constant, ranging between 0.45 m3/s and 0.50 m3/s, with an annual average of 0.47 m3/s. This greatly reduces the seasonal fluctuation of water demand throughout the process. The flow calculated using the Tessman method generally remains around 8.0 m3/s, with a slight increase during spring and summer, peaking at 14.1 m3/s in June. The flow calculated using the minimum flow method remains very stable, mostly between 0.45 m3/s and 0.50 m3/s. The flow based on the 90% assurance method stays below 2.4 m3/s, mainly focused on scheduling and water supply, with a significant reduction in the ecosystem's water demand. The flow calculated using the Q90_Q50 method

Table 2 Ecological water demand of the Yongding River Basin

	January	February	March	April	May	June	July	August	September	October	November	December
Tennant（10%）	1.3	1.3	1.8	2.7	3.1	3.5	3.0	1.9	1.6	1.2	1.2	1.2
Tennant（30%）	4.0	4.0	5.3	8.0	9.4	10.6	8.9	5.7	4.9	3.7	3.7	3.6
Tennant（60%）	8.0	7.9	10.6	16.1	18.8	21.2	17.8	11.4	9.9	7.3	7.4	7.3
Texas	0.45	0.45	0.45	0.45	0.49	0.49	0.45	0.45	0.5	0.49	0.49	0.49
Tessman	8.0	8.0	8.0	10.7	12.5	14.1	11.9	8.0	8.0	8.0	8.0	8.0
Minimum Flow	0.45	0.45	0.45	0.45	0.49	0.49	0.45	0.45	0.5	0.49	0.49	0.49
90% Assurance Level	0.6	0.9	1.1	2.3	2.3	2.1	2.1	1.6	2.4	2.1	1.9	1.1
Q90_Q50	0.6	0.9	1.1	13.7	17.2	18.9	10.9	1.6	2.4	2.1	1.9	1.1

remains low throughout the year, especially in June when the flow at Guanting Reservoir reaches 18.9 m3/s, indicating that the ecosystem's water supply demand is low.

By integrating the advantages of multiple methods, the sustainable needs of the ecosystem are met. The maximum ecological flow uses the Tennant method (60%), based on 60% of the historical flow to meet the higher flow demand throughout the process. The minimum ecological flow uses the Tennant method (10%) to ensure the basic ecological requirements throughout the process. The optimal ecological water demand is provided by the Tessman method, offering the best ecological flow. Overall, the minimum ecological water demand in the Yongding River Basin is 63 million m^3, the maximum ecological water demand is 378 million m^3, and the optimal ecological water demand is 297 million m^3.

3.3. Ecological Replenishment Calculation

The ecological water demand within the river channel was calculated, and the ecological water demand outside the river channel was estimated using the Penman formula. By analyzing the changes in ecological water demand and ecological replenishment volume, the required ecological replenishment volume was further calculated. The plotted curve reflects the fluctuation characteristics of ecological replenishment activities in different years (Fig.3). Positive values on the curve indicate that the ecological replenishment volume is below the baseline level, suggesting that the ecosystem is in a state of water resource deficiency and urgently requires ecological replenishment. The larger the value, the higher the replenishment demand; negative values indicate that the water supply is sufficient and has exceeded the preset replenishment target, meaning no further replenishment is necessary.

The ecological replenishment demand exhibits significant seasonality and interannual fluctuations, like the variations in replenishment volume during periods of weak disturbance. The analysis results show that under the minimum ecological replenishment demand, the Tennant method (10%) was used as the baseline for ecological replenishment. Before 2000, the watershed had sufficient water resources, and there was no need for ecological replenishment. However, since 2007, the demand for ecological replenishment has started to emerge. Although the replenishment volume is small, it still indicates that the watershed's ecosystem is beginning to experience water resource pressure. From 2018 to 2020, the ecological replenishment volume decreased, and it is expected that the replenishment demand will gradually reduce, reflecting the improvement in the water resource status of the watershed's ecosystem.

Under the maximum ecological replenishment demand, the Tennant method (60%) was used as the replenishment standard for analysis. Before 1980, ecological replenishment was nearly unnecessary. However, since 1984, the demand for ecological replenishment has gradually increased and exhibited monthly cyclic variations, particularly in May and June each year, when the demand for replenishment sharply rises. The replenishment demand in 1984 was 3.33 m^3/s, gradually increasing to 10.54 m^3/s in June 1994. From 1995 to 1998, the ecological replenishment demand showed a declining trend, but from 1998 to 2018, the replenishment demand exhibited significant cyclical fluctuations, with the replenishment volume maintaining a stable range from 0 to 14 m^3/s.

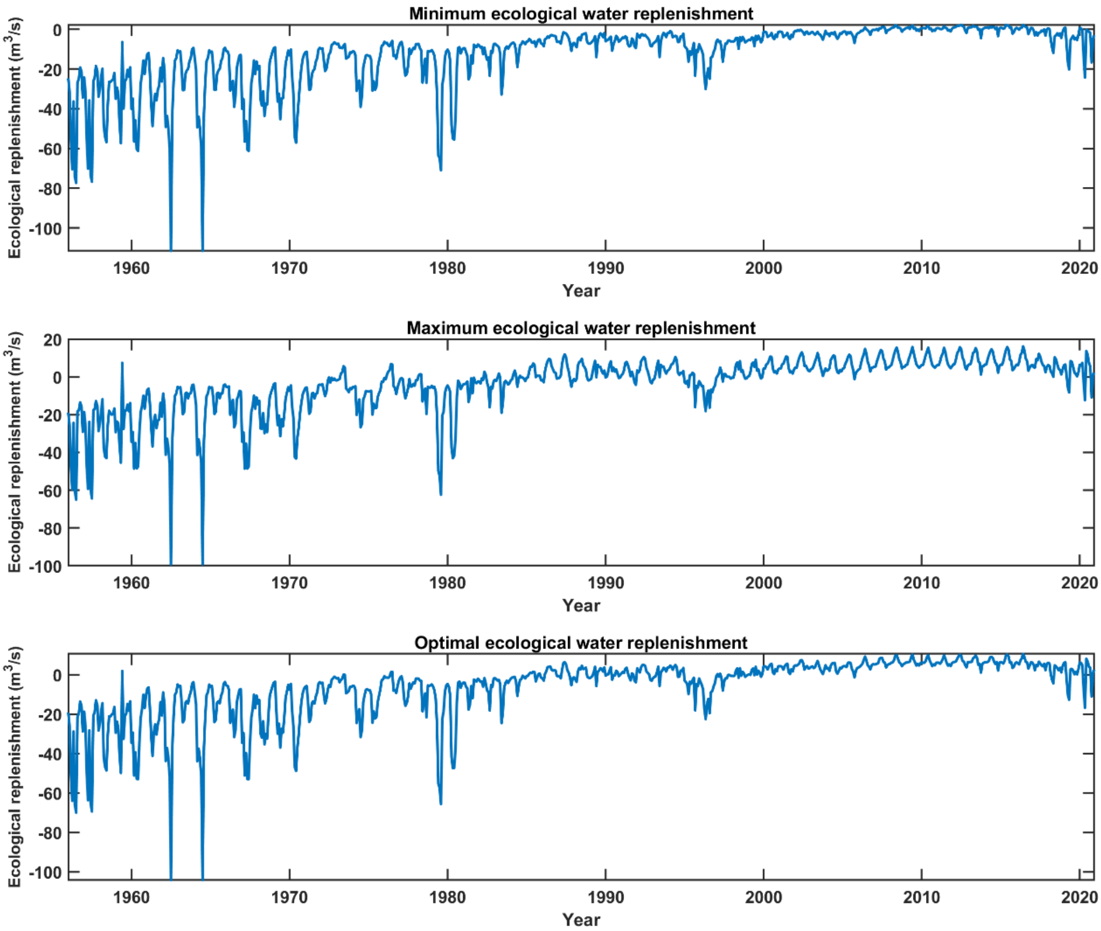

Fig.3 Ecological water supplementation curve of the Yongding River Basin

The optimal ecological replenishment volume is calculated based on the Tessman method as the baseline, which provides the replenishment curve that best meets the ecosystem’s demand. According to the analysis, there was almost no ecological replenishment demand between 1956 and 1984. Although some minor replenishment demands appeared in a few years, such as in June 1956, June 1976, and July 1979, the overall replenishment volume was very limited. Since 1984, the ecological replenishment demand has remained stable, fluctuating between 0 and 8 m^3/s, presenting a relatively stable replenishment pattern. Therefore, to address the changes in ecological replenishment demand in the Yongding River Basin, reasonable water replenishment control measures should be dynamically adjusted based on seasonal fluctuations and interannual variations to ensure the stability and sustainable development of the ecosystem.

4. Conclusions

Through the runoff analysis of the Yongding River Basin from 1962 to 2020, the following main conclusions can be drawn:

(1) This study calculates the minimum, suitable, and maximum ecological flow, and combines multiple methods to ensure that the basic hydrological needs of the Yongding River Basin's ecosystem are met. The minimum ecological water demand for the Yongding River Basin is 63 million m^3, the maximum ecological water demand is 378 million m^3, and the optimal ecological water demand is 297 million m^3. These data reflect the water demand of the basin under different ecological conditions and provide scientific support for water resource management and ecological protection.

(2) The study found that the ecological replenishment demand in the Yongding River Basin exhibits significant seasonality and interannual fluctuations, especially in years of water resource scarcity. Before 2000, the basin had sufficient water resources, and no significant ecological replenishment demand appeared. However, since 2007, the demand for ecological replenishment has gradually emerged, with a downward trend in replenishment demand during the period from 2018 to 2020, indicating an improvement in water resource conditions. Overall, replenishment demand shows significant cyclical fluctuations, especially under extreme climatic conditions, where replenishment demand fluctuates greatly.

(3) By analyzing the changes in ecological water demand and replenishment volume, this study provides important scientific evidence for water resource management and ecological restoration in the Yongding River Basin. The research indicates that reasonable water resource management measures and replenishment strategies can effectively ensure the sustainable development of the basin's ecosystem. In response to the increasingly severe pressures on water resources and the ecological environment, it is recommended to

dynamically adjust replenishment strategies based on seasonal fluctuations and interannual changes to ensure the stability and sustainability of the basin's ecosystem. In the future, strengthening the monitoring and management of the basin's water resources, promoting the implementation of ecological water management measures, and ensuring the achievement of ecological restoration goals are essential.

References

Ding, X.W., Liu, Z., 2011. Hydrological cycle and spatiotemporal distribution patterns in the Yongding River Basin, Hebei Province. South-to-North Water Diversion and Water Conservancy Science and Technology. (5).

Döll, P., Schmied, H.M., 2012. How is the impact of climate change on river flow regimes related to the impact on mean annual runoff? A global-scale analysis. Environmental Research Letters. 7(1), 014037.

Feng, Q., Long, A.H., Wang, N.L., et al., 2019. Integrated technology and application for water resource security in the northwest inland region. People's Yellow River. 41(10), 103–108.

Ji, G.X., Gao, H.S., Gao, H.K., et al., 2024. Vegetation changes and their impact on runoff in the Hanjiang River Basin. South-to-North Water Diversion and Water Conservancy Science and Technology (Chinese and English Edition). 22(3), 512–520.

Jury, W.A., Vaux Jr, H., 2005. The role of science in solving the world's emerging water problems. Proceedings of the National Academy of Sciences. 102(44), 15715–15720.

Piao, S., Friedlingstein, P., Ciais, P., et al., 2007. Changes in climate and land use have a larger direct impact than rising CO2 on global river runoff trends. Proceedings of the National Academy of Sciences. 104(39), 15242–15247.

Portela, M.M., Santos, J., de Carvalho Studart, T.M., 2019. Effect of the evapotranspiration of Thornthwaite and of Penman-Monteith in the estimation of monthly streamflows based on a monthly water balance model. In: Current Practice in Fluvial Geomorphology-Dynamics and Diversity. IntechOpen.

Shrestha, N.K., Du, X., Wang, J., 2017. Assessing climate change impacts on freshwater resources of the Athabasca River Basin, Canada. Science of the Total Environment. 601, 425–440.

Sun, J.C., Wang, G.Q., Sun, Q.C., 2009. Crack spacing of unsaturated soils in the critical state. Chinese Science Bulletin. 54(12), 2008–2012.

Rampisela, D.A., Suzuki, M., Fukushima, Y., 1990. Application of the Penman-Monteith model to the estimation of the evapotranspiration rate of a forested watershed. Journal of the Japanese Forestry Society. 72(1), 1–10.

Tegos, A., Efstratiadis, A., 2013. Evapotranspiration estimation based on a simplified formulation of the Penman-Monteith equation. Evapotranspiration: An Overview. 143.

Wang, W.Y., Ma, G.Y., Wang, Z., et al., 2020. Study on ecological water requirements in the rural section of the Yitong River. Journal of Northeast Normal University (Natural Science Edition). 52(2), 137–142.

Wu, L., Chen, Y., Chen, X., et al., 2019. Future runoff changes in the Shanmei Reservoir Basin under climate change. Journal of Subtropical Resources and Environment. 14(4), 18–22, 35.

Xu, Z.X., Ban, C.G., Zhang, R., 2022. Runoff evolution and attribution analysis in the Yarlung Tsangpo River Basin. Advances in Water Science. 33(4), 519–530.

Yang, K., Liu, Z.Q., Lei, K., et al., 2023. Spatiotemporal evolution of precipitation in the Yongding River Basin from 1957 to 2018. China Rural Water Resources and Hydropower. (4), 134–144.

Ye, S.L., Ye, H.L., Zhao, J.Y., et al., 2023. Changes in different runoff components and their causes in the source area of the Yangtze and Yellow Rivers. China Rural Water Resources and Hydropower. (6), 79–85, 94.

Zeng, S.D., Zhang, L.P., Xia, J., et al., 2013. Water cycle characteristics in the Yongding River Basin and its response to climate change. Journal of Applied Basic and Engineering Sciences. (3), 501–511.

Zhang, C., Sun, J., 2023. Analysis of temporal evolution characteristics of precipitation in Beijing. International Journal of Ground Sediment & Water. 18, 1141–1157.

Zhang, J.Y., Wang, G.Q., Jin, J.L., et al., 2020. Evolution and variation characteristics of river runoff in China from 1956 to 2018. Advances in Water Science. 31(2), 153–161.

Zhang, L., Hong, T., Wang, Y.F., 2012. Multiple measures are needed to alleviate urban water scarcity. China Development Observation. (6), 21–23.

Zhang, W.K., Lü, D.S., Wang, Z.H., et al., 2024. Ecological water requirements in and around the riverbed of the Baiyang River Basin, Xinjiang. Journal of Shihezi University (Natural Science Edition). 42(2), 192–197.

Zheng, X.K., Hou, H.Y., Fu, Y.F., 2015. Analysis of ecological and environmental water requirements in the Huangshui River Basin based on the improved Tennant method. South-to-North Water Diversion and Water Conservancy Science and Technology. 13(4), 681–685, 690.

Zhang, Z., Sun, J., 2024. Regional landslide susceptibility assessment and model adaptability research. Remote Sensing. 16(13), 2305.

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This paper DOI: 10.5281/zenodo.15033706

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