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Spatial and Temporal Evolution of Vegetation Water Consumption in Arid and Semi-Arid Areas against the Background of Returning Farmland to Forestland

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Abstract: Sustainable development in arid and semi-arid areas is largely constrained by water resources. Expanding ecological space is considered an effective way to conserve water resources. The innovation of this study is the analysis of water consumption in different land-use types from a complete watershed scale, which can evaluate space management against the background of returning farmland to forestland during the past 20 years, and provide suggestions for future space management in semi-arid areas. Based on meteorological data and GIS technology, the current study quantitatively analyzes the spatial and temporal variation characteristics of the water consumption of different vegetation growth stages in the Yanhe River Basin by using the improved Penman formula. The results show that the water consumption of vegetation in the Yanhe River Basin increased from 0.44 km^3 in 2000 to 0.68 km^3 in 2020. The water consumption of vegetation showed obvious spatial heterogeneity, with the highest value in the central Baota area (1.094 km^3) followed by the western Ansai region (0.727 km^3), whereas the consumption in the eastern Yanchang area is relatively low (0.483 km^3). In addition, the annual average water consumption is (0.381 km^3). The cultivated land consumes the most water (0.21 km^3), while the woodland consumes the least (0.072 km^3). The water consumption per unit area of forested land is the highest, reaching 190 m, and the water consumption of low-coverage grassland is the lowest, only reaching 50 m. Vegetation distribution change could be the main influencing factor of vegetation water consumption change in the Yanhe River Basin. Through the establishment of the sustainable development path of ecological space with water as the core, the high-quality development of ecological environments in arid and semi-arid areas will be achieved.

Keywords: Yanhe River Basin; water consumption of vegetation; evapotranspiration; improved Penman formula method

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1. Introduction

Ecological space refers to the functional space with natural attributes that mainly provide ecological services or ecological products [1]. Due to the implementation of the policy of returning farmland to forestland, the ecological space water consumption in the Loess Plateau region of China has increased significantly [2–4]. Evapotranspiration is the main means of water resource consumption in arid areas. There is a close relationship between vegetation and the regional ecosystem and water resources development and evolution. Because different vegetation shows significant differences in albedo, vegetation leaf surface index, etc., there is a relationship between vegetation type and vegetation coverage change, and evapotranspiration change [5]. Therefore, it is necessary to comprehensively understand the vegetation type and distribution law of ecological space in the basin. The spatial and temporal distribution of vegetation water consumption and its changing characteristics are of great significance for the rational utilization of water resources in arid areas.

The increase in vegetation coverage plays an important role in driving the change of evapotranspiration [6]. In recent years, many scholars at home and abroad have explored the relationship between evapotranspiration and vegetation types and vegetation coverage changes. Allen [7] describes three extensions of the evaporation calculation program, which are designed to improve the accuracy of applications when they guarantee additional complexity. Against the background of afforestation in dry areas, Lu [8] has studied the evapotranspiration of vegetation in the dry areas of China based on seven evapotranspiration models, and proved that afforestation in the dry areas of China would aggravate the decline of groundwater. Based on the principle of water balance, long Vicente Serrano [9] has analyzed the analysis of the standardized evapotranspiration index (SPEI) and the worldwide vegetation index, concluding that the vulnerability of arid and semi-arid areas is higher under the influence of vegetation. Based on the Penman–Monteith (PM) formula combined with meteorology, hydrology, vegetation, and land using the calculation method of large-scale vegetation water consumption based on remote sensing data, Jiang Tianliang [10] has discussed the evolution rules of the vegetation water consumption of 9 vegetation types and 17 ecological geographical zones in Northwest China and their response to meteorological drought. The results show that the level of water consumption in Northwest China is generally higher in the southeast and lower in the northwest. From 1990 to 2015, the area and total water consumption of all kinds of vegetation increased, during which time the total water consumption of the region also increased by 87.62 billion m^3. Replacing NDVI with water consumption can better reflect the comprehensive impact of meteorological drought on vegetation. At present, the calculation methods of vegetation water consumption mainly include the area quota method [11–13], the phreatic evaporation method [14–18], the plant evapotranspiration method [19–21], the water balance method [22,23], the biomass method [24,25], and the calculation method based on remote sensing technology [26–29]. Because the research on vegetation water consumption in China is relatively insufficient, a method combining the potential evapotranspiration of vegetation method with the soil moisture and plant area calculation method can be applied to the desert, grassland, forests, and other ecosystems to approximate the ecological water demand of vegetation in the region with relatively comprehensive basic data [2]. Vegetation protection in the basin is of great ecological and political significance. It is a prerequisite for the rational allocation of water resources, as it helps to ensure the normal growth of vegetation by allowing for the mapping of the spatial and temporal distribution of water consumption by vegetation in the basin. This paper uses the improved Penman formula method, with the support of meteorological data and GIS technology, to calculate the vegetation water consumption in 2000, 2005, 2010, 2015, and 2020 in the Yanhe River Basin on a grid scale. Subsequently, it analyzes the spatial and temporal distribution of and change in vegetation water consumption, and discusses the impact of vegetation type and reference evapotranspiration on water consumption. It provides a more accurate and scientific reference for the study of the green and sustainable development of the basin.

2. Study Area

The Yanhe River Basin is located in the middle of the Loess Plateau (Figure 1). It is a first-class tributary of the middle reaches of the Yellow River. The Yanhe River Basin is one of the most serious soil and water loss areas in the Loess Hilly and gully area, and belongs to the warm temperate continental semi-arid climate area [30]. The main tributaries of the Yanhe River are Xichuan, Xingzi River, Nanchuan, and Panlongchuan. The total length of the river is 286.9 km, the altitude is 958–1731 m above sea level, and the total area of the Yanhe River Basin is approximately 7725 km^2. The basin covers six counties and districts including Baota, Ansai, and Yanchang, with a total population of 99×10^4. The average annual water resource of the Yanhe River Basin is 2.74×10^8 m^3. In addition, the sediment concentration [31] value in the river is high. As a result, the utilization of water resources is relatively high, but the utilization rate is low. In addition, after farmland was converted to forest, the irrigation method was relatively backward, and the water consumption of vegetation increased, resulting in an extreme shortage of water resources. Therefore, it is of great significance to study the water consumption of vegetation in the Yanhe River Basin. After the comprehensive consideration of the climatic conditions, topographic and geomorphic characteristics, and administrative divisions of the Yanhe River Basin, the Yanhe River Basin is divided into the Western Ansai district, the central Baota District, and the eastern Yanchang county. The Western Ansai district is a forest belt, which is a water conservation area and a flow production area for the whole basin; the Baota area in the middle is a forest grassland belt, and the Yanchang area in the north is a grassland belt. Its ecological environment is extremely fragile.

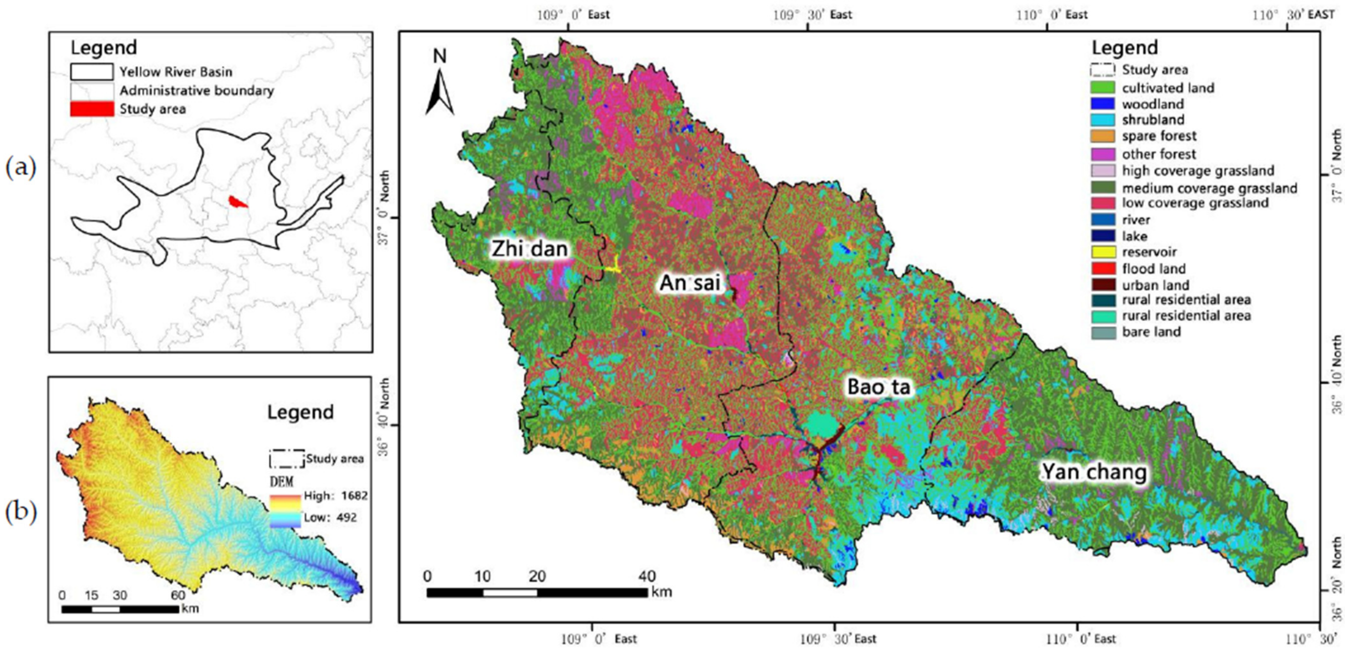

Figure 1. Map of Yanhe River Basin. (**a**). Location of Yellow River Basin (**b**). Location of Yanhe River Basin (**c**). land-use map of Yanhe River Basin in 2020 cited from the resource and environment science data center of the Chinese Academy of Sciences.

3. Methodology and Data

3.1. Data Sources

The meteorological data of meteorological stations in the Yanhe River Basin from 1960 to 2020 were collected from the China Meteorological Science Data Sharing Network "http://data.cma.cn/ (accessed on 25 March 2022)", including the daily observation data of maximum and minimum temperature, average temperature, precipitation, relative humidity, and gale days. The DEM digital elevation images used in this paper were from the international scientific data mirror website of the computer network information center of the Chinese Academy of Sciences "http://www.gscloud.cn/ (accessed on 28 April 2022) ". The land-use data were from the resource and environment science data center of the Chinese Academy of Sciences "http://www.resdc.cn/ (accessed on 21 March 2022)", with a spatial resolution of 30 m. The NDVI data were obtained from NASA landsat8 oli image calculation with a 250-m resolution. The land-use data from five periods, 2000, 2005, 2010, 2015, and 2020, were selected for the study.

3.2. Methodology

The research on vegetation water consumption has been carried out in three aspects, including the determination of evapotranspiration, vegetation coefficient, and soil moisture limit coefficient. The specific steps are shown in the flow chart (Figure 2).

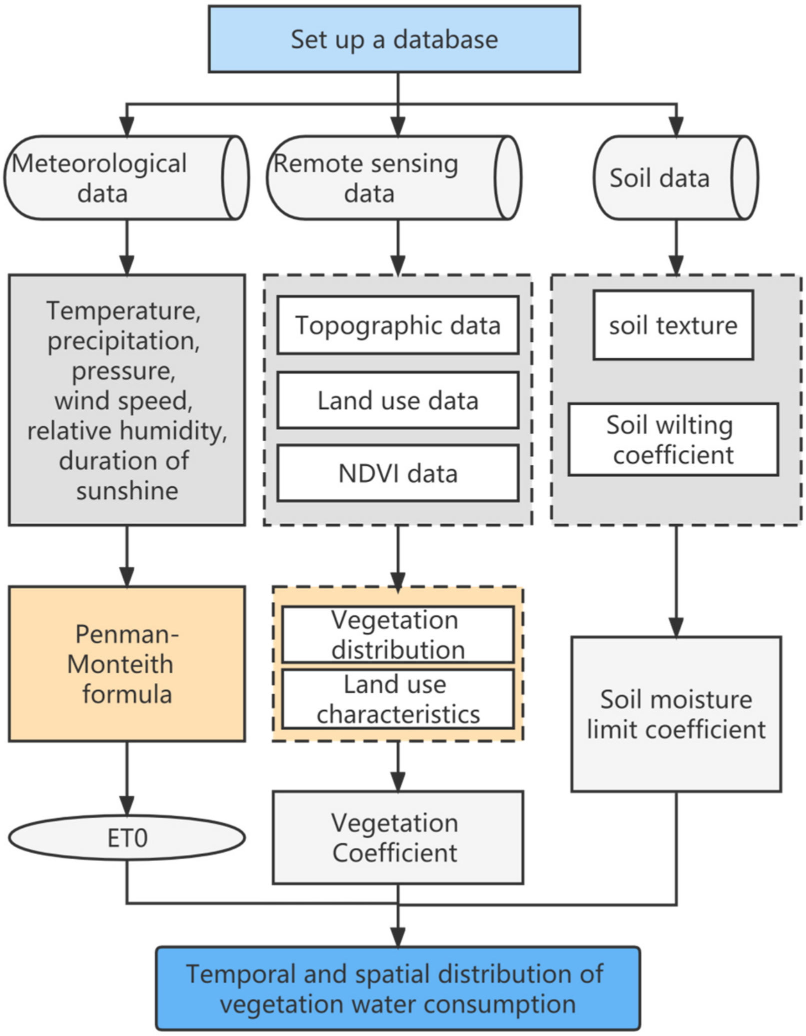

Figure 2. The methodology flow chart.

3.2.1. Calculation Method of Vegetation Water Consumption

The calculation method of vegetation water consumption recommended by FAO was adopted, and the formula is as follows:

$$\mathrm{ET_{p,i}} = \mathrm{K_{c,i}} \times \mathrm{K_{s,i}} \times \mathrm{ET_{0,i}} \tag{1}$$

where $\mathrm{ET_{p,i}}$ is the evapotranspiration rate of a certain vegetation type (mm/d); $K_{c,i}$ is the crop coefficient of a certain vegetation type; $K_{s,i}$ is the soil water limiting conditions of a certain vegetation type's distribution area; and $ET_{0,i}$ is the potential evapotranspiration rate of a vegetation type's distribution area (mm/d).

The vegetation water consumption took into account the coverage area of different types of vegetation, and the calculation formula is as follows:

$$VWC_i = \sum_{n=1}^{N} ET_{p,i,n} \times A_i \times 10^{-3} \tag{2}$$

where VWC_i is the vegetation water consumption of a certain vegetation type (m^3); A_i is the distribution area of a certain vegetation type (m^2); $ET_{p,i,n}$ is the evapotranspiration rate (mm/d) of a certain vegetation type on the nth day (mm/d); and N is the growth period days of a certain vegetation type.

3.2.2. Determination of Potential Evaporation ET_0

Based on the semi-empirical formula combining the water vapor diffusion theory and heat balance theory, the Penman–Monteith method recommended by FAO in 1998 was used to calculate the reference crop evapotranspiration [32]. The formula is:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3}$$

where ET_0 is the reference crop evapotranspiration (mm/d); R_n is the net radiation on the crop surface (MJ/m^2 d); G is the soil heat flux (MJ/m^2 d); Δ is the slope of the relationship curve between saturated water vapor pressure and temperature; T is the average air temperature at 2 m height (k Pa/°C) (°C); e_s is the saturated water vapor pressure of air (k Pa); e_a is the saturated water vapor pressure of air (k Pa); γ is the hygrometer constant (k Pa/°C); and u_2 is the wind speed at 2 m above the ground (m/s). The determination methods of the relevant parameters are as follows:

$$\Delta = \frac{4098\left[0.6108exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T + 237.3)^2} \tag{4}$$

$$R_n = R_{ns} - R_{nl} \tag{5}$$

where R_{ns} is net short-wave radiation (MJ/m^2 d), determined by solar radiation and sunshine hours and R_{nl} is net long-wave radiation (MJ/m^2 d), which is jointly determined by sunshine hours, daily maximum temperature, daily minimum temperature, altitude, and actual water vapor pressure e_a (see FAO-56 for the specific calculation method).

The value of soil heat flux G was small on the daily scale, which was ignored as 0. The calculation formula under the monthly scale is as follows:

$$\text{G} = 0.07(T_i - T_{i-1}) \tag{6}$$

where T_i is the average temperature of the i month (°C) and T_{i-1} is the average temperature of the $i - 1$ month (°C).

$$\gamma = 0.00163\frac{p_a}{\lambda} \tag{7}$$

$$e_s = \frac{e^0(T_{max}) + e^0(T_{min})}{2} \tag{8}$$

$$e^0(T_{max}) = 0.6108 * \exp\left(\frac{17.27T_{max}}{T_{max} + 237.3}\right) \tag{9}$$

$$e_a = e_s\frac{RH_{mean}}{100} \tag{10}$$

$$u_2 = u_s\frac{4.87}{\ln(67.8 * s - 5.42)} \tag{11}$$

where p_a is atmospheric pressure (kPa); λ is the latent heat of vaporization (MJ/kg); T_{max} is the monthly average maximum temperature (°C); T_{min} is the monthly average minimum temperature (°C); RH_{mean} is the monthly average relative humidity (%) and u_s is the wind speed at the height of Sm (m/s).

3.2.3. Determination of Crop Coefficient KC

The crop coefficient KC represents the ratio between the maximum water demand of vegetation and the maximum possible evapotranspiration. Due to the sparse vegetation in arid areas, KC is directly related to the plant area index and coverage. According to the recommendation of FAO-56, the plant growth cycle was divided into four stages: the initial growth stage, development stage, middle-growth stage, and late-growth stage, and the crop coefficient KC [33] for each is calculated individually. The change law of the crop coefficient KC in the four stages of the plant growth cycle is shown in Figure 3.

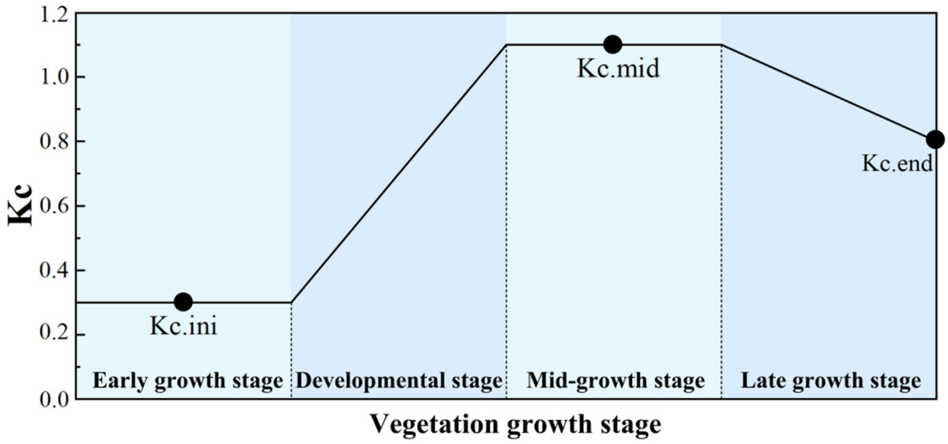

Figure 3. Crop coefficient KC in four stages of vegetation growth cycle.

3.2.4. Determination of Soil Water Limiting Conditions KS

KS is a function reflecting the influence of soil moisture conditions on vegetation evapotranspiration [34], and its expression is as follows:

$$K_s = \begin{Bmatrix} 1, \theta > \theta_c \\ \frac{\theta - \theta_z}{\theta_c - \theta_z}, \quad \theta_z \le \theta \le \theta_c \\ 0, \theta < \theta_z \end{Bmatrix} \tag{12}$$

where θ is soil water content (m^3/m^3); θ_c is the critical water content of soil (m^3/m^3), which is generally 70–80% of the field water capacity, and 70% is recommended in this study. Moreover, θ_z is the soil wilting coefficient (m^3/m^3).

3.2.5. Mann–Kendall Statistical Test

The Mann–Kendall statistical test was used to analyze the changing trend of potential evapotranspiration [35]. In this study, the Mann–Kendal (M–K) trend test was applied to perform the trend analysis and mutation test of the regional drought risk index. The M–K trend test is a non-parametric statistical test that has been recommended by WMO for long-term meteorological trend and mutation analysis [18,36]. For the time series x with n as the sample size, the sequence S_k is constructed as follows:

$$S_k = \sum_{i=1}^{k} r_i \; k = 1, 2, \cdots, n \tag{13}$$

where

$$r_i = \begin{cases} 1, x_i > x_j \\ 0, x_i < x_j \end{cases} j = 1, 2, \cdots, i; \; i = 1, 2, \cdots, n \tag{14}$$

In Equation (14), the cumulative number of samples when $x_i > x_j$ is the value of the ranking sequence S_k. Assuming that the time series x is random and independent, the mean and variance of the S_k are calculated as follows:

$$E_{S_k} = \frac{k(k-1)}{4}, \; k = 1, 2, \cdots, n \tag{15}$$

$$\mathrm{var}(S_k) = k(k-1)(2k+5)/72, 2 \le k \le n \tag{16}$$

Then the following statistic $\mathrm{UF_k}$ is defined as:

$$\mathrm{UF_k} = \frac{\mathrm{S_k} - \mathrm{E_{S_k}}}{\sqrt{\mathrm{var}(\mathrm{S_k})}}\alpha \tag{17}$$

where $\mathrm{UF_k}$ is the standard normal distribution. Given a defined significance level α, the value of $\mathrm{UF}_{\alpha/2}$ could be found in the standard normal distribution table. If $|\mathrm{UF_k}| > \mathrm{UF}_{\alpha/2}$, there is a significant upward or downward trend in the time series.

The temporal order was reversed, and the above process is repeated while making $\mathrm{UB_k} = -\mathrm{UF_{k'}}\left(\mathrm{k'} = \mathrm{n} + 1 - \mathrm{k}; \mathrm{UB_1} = 0\right)$ to plot and analyze the $\mathrm{UF_{k'}}$ curve and $\mathrm{UB_k}$ curve. When the $\mathrm{UF_{k'}}$ curve exceeds the critical line of a certain confidence interval, it indicates a significant changing trend in the time series. When the two curves intersect and the intersection is between the two critical lines, the corresponding time of intersection is the start of the mutation.

3.2.6. Land-Use Transfer Matrix

The land-use transfer matrix can not only quantitatively indicate the transformation between different land-use types, but also reveal the transfer rate between different land-use types. The calculation was performed [37] according to the following formula:

$$S_{xy} = \begin{Bmatrix} S_{11} & S_{11} & S_{11} \\ S_{21} & S_{22} & S_{2n} \\ \ldots & \ldots & \ldots \\ S_{n1} & S_{n2} & S_{n3} \end{Bmatrix} \tag{18}$$

where S is the area of the land-use type (km^2); n is the type of land-use, which is the area and S_{xy} is the area of the land in the study area from the initial x stage of the study period to the y stage at the end of the study period.

4. Results and Analysis

4.1. Potential Evapotranspiration ET0

4.1.1. Temporal Characteristics of Potential Evapotranspiration in the Yanhe River Basin

The potential evapotranspiration change characteristics of the Yanhe River Basin from 2000 to 2020 are shown in Figure 4. The average annual potential evapotranspiration of the Yanhe River Basin is 947.55 mm, with a fluctuation range of 922.57–1047.79 mm. The maximum value appeared in 2005 and the minimum value in 2019. Since 2000, the potential evapotranspiration in the Yanhe River Basin has shown a decreasing trend year by year, with a decreasing rate of 1.13 mm/a. Based on the M–K trend analysis, the rising trend of potential evapotranspiration passed the significance test of 95%. The UF and UB curves crossed in 2001, 2004, and 2006, indicating that the average potential evapotranspiration of the three years was abrupt. On the whole, both UF statistics and UB statistics are basically less than 0, indicating a downward trend. Figure 5 shows the monthly variation characteristics of the potential evapotranspiration in the river basin along the river. The monthly potential evapotranspiration in the river basin is unimodal, with a high value from May to August. Figure 6 shows the seasonal variation characteristics of potential evapotranspiration in the river basin along the river. The seasonal potential evapotranspiration is shown as follows: summer > spring > autumn > winter.

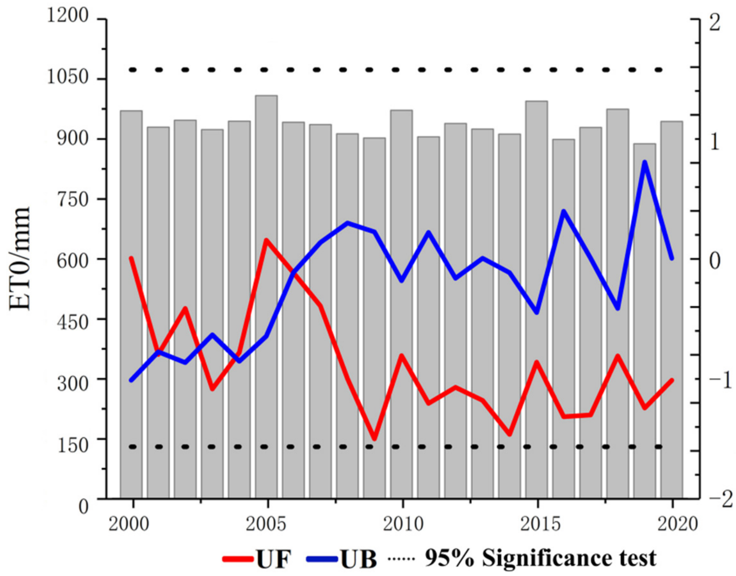

Figure 4. Variation Characteristics of potential evapotranspiration and m-k mutation detection in Yanhe River Basin.

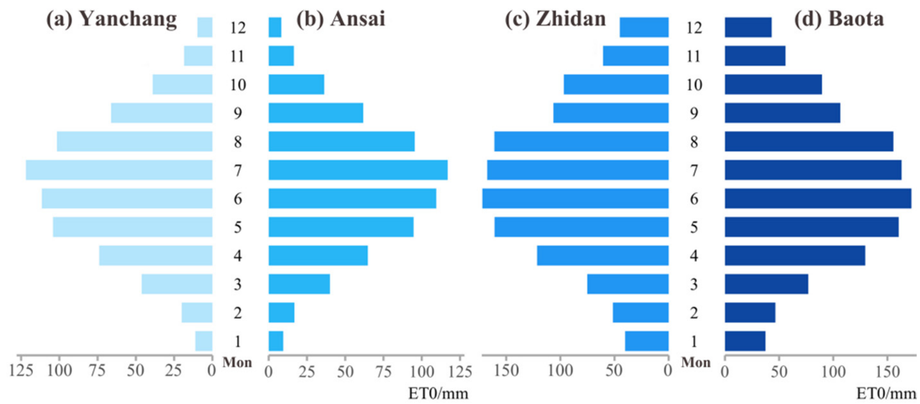

Figure 5. Monthly variation characteristics of potential evapotranspiration in Yanhe River Basin.

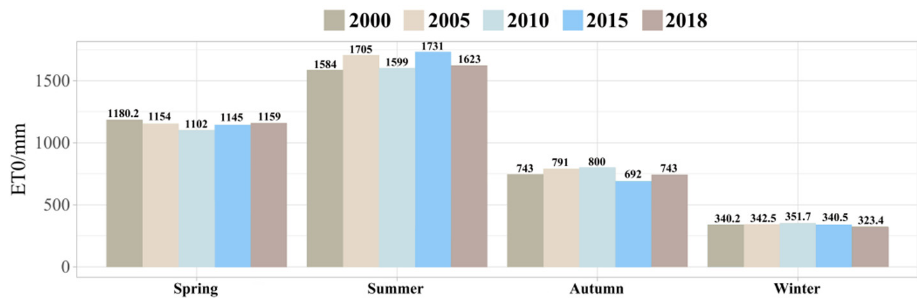

Figure 6. Seasonal variation characteristics of potential evapotranspiration in Yanhe River Basin.

4.1.2. Spatial Characteristics of Potential Evapotranspiration

The temporal and spatial changes of potential evapotranspiration in 2000, 2005, 2010, 2015, and 2020 in the Yanhe River Basin are shown in Figure 7. The potential evapotranspiration of the basin shows a trend of increasing from south to north and then decreasing to the southeast. The maximum evapotranspiration (1283.41 mm) is in the Baota District, and the minimum evapotranspiration (620.566 mm) is in the Ansai district. Among them, the rising trends of the Yanchang station, the Zhidan station, the Ansai station, and the Baota station all pass the 95% significance test. The Baota station has the highest change rate of potential evapotranspiration, and the Ansai station has the lowest change rate.

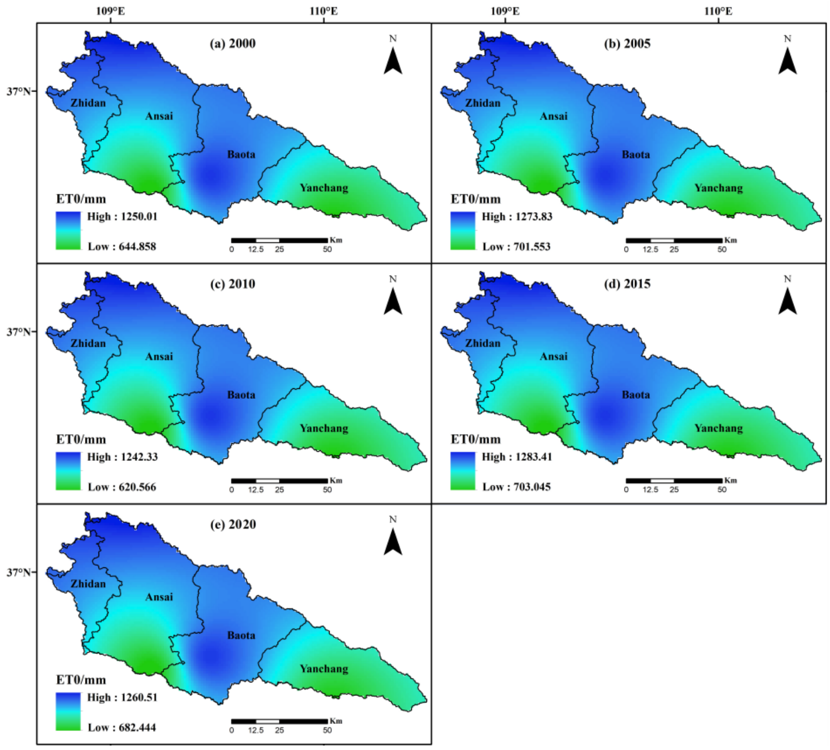

Figure 7. Temporal and spatial variation of potential evapotranspiration in Yanhe River Basin in 2000, 2005, 2010, 2015, and 2020.

4.2. Analysis of Land-Use Change Results

4.2.1. Baota Distract

From 2000 to 2020, 252.66 hectares, 763.50 hectares, and 1987.31 hectares of cultivated land in the Baota District were converted to urban land, rural residential land, and other types of construction land, respectively. In addition, 7410.87 hectares and 18,374.92 hectares were converted to forest land and grassland, respectively. The expansion of construction land and the conversion of farmland to forestland and grassland coexisted, resulting in the increase or decrease in regional ecological functions depending on the balance between the increase or decrease in ecological space and the occupation of urban construction.

4.2.2. Ansai Distract

From 2000 to 2020, on the whole, the ecological space of Ansai has been greatly reduced, with 506.8, 29.9, and 96.9 hectares of cultivated land, forest land, and grassland, respectively, occupied by construction. Although the water area and other lands have not changed significantly, the ecological space of this distract has changed dramatically.

4.2.3. Yanchang Distract

From 2000 to 2020, the area of Yanchang's rural residential land, infrastructure, and other construction land increased significantly. However, the increase was relatively small compared with other areas. The implementation of the policy of returning farmland to forestland and grassland was the core of the change of the ecological space and the regional ecological protection function. The area of forest land and grassland has increased significantly, which has continuously enhanced the regional ecological conservation function and played a vital role in regulating the regional microclimate and water and soil conservation. The most intuitive manifestation of this was the continuous and significant increase in the vegetation coverage index.

4.3. Result of Analysis of Vegetation Water Consumption

4.3.1. Spatial and Temporal Variation Analysis of Vegetation Water Consumption

From 2000 to 2020, the water consumption of vegetation in the Yanhe River Basin showed an upward trend (Figure 8), which increased from 0.44 km^3 to 0.68 km^3 in 2020, and the annual average water consumption was 0.537 km^3. The water consumption of vegetation in the central Baota District was the highest, rising from 0.18 km^3 to 0.32 km^3, which may be due to the conversion of 7410.87 hectares and 18,374.92 hectares of arable land to forest land and grassland, respectively, over the 18-year period. The Ansai district in the west took second place and showed a fluctuating upward trend. The minimum water consumption appeared in 2000 at 0.082 km^3 and the maximum value of 0.214 km^3 was reached in 2005. The main reason may be that the land-use type of Ansai County changed significantly due to the drive to return farmland to forestland from 2000 to 2005, and the transfer of cultivated land to ecological land was particularly obvious, with 9834.3 hectares converted to forest land and 2494.3 hectares converted to grassland. After that, the water consumption of plants in the Ansai area (0.145 km^3) fluctuated up and down, which may be due to the impact of urbanization in the Ansai area, and 506.8, 29.9, and 96.9 hectares of arable land, forest land, and grassland were occupied by construction, respectively. The northern Yanchang area was stable at 0.1 km^3 and the minimum value appeared in 2010. During the period of 2000–2020, the increase in rural residential land, infrastructure, and other construction land was significant. However, the increase was relatively small compared with other areas, and the vegetation coverage index of ecological space continued to increase significantly. Water consumption in the Zhidan area, which is located in the most upstream of the Yanhe River Basin, fluctuated greatly, and the minimum and maximum values appeared in 2005 (0.057 km^3) and 2015 (0.129 km^2), respectively. Due to the small area of the central urban area of Zhidan County in the Yanhe River Basin, the vegetation coverage index of the ecological space continued to increase significantly, and the water consumption showed a fluctuating upward trend. The spatial distribution of vegetation water consumption in the main areas of the Yanhe River Basin in 2000, 2005, 2010, 2015, and 2020 is shown in Figure 8 with an obvious spatial heterogeneity. The high-value area is mainly concentrated in the shrub forest in the upper reaches of the basin and the shrub forest in the Baota area, and the low-value area is mainly distributed in the grassland plant area of the Ansai district, and the Yanchang district, which has more grassland.

4.3.2. Analysis of Water Consumption Differences between Different Vegetation Types

Figure 9 reflects the water consumption proportion space of different vegetation types in the main areas. The water consumption of vegetation per unit area in Zhidan is relatively high, showing a trend of woodland (0.276 m) > shrubland (0.216 m) > spare forest land (0.172 m) > medium-coverage grassland (0.124 m) > cultivated land (0.114 m) > low-coverage grassland (0.064 m). The water consumption of vegetation per unit area in Yanchang is lowest compared with the other three areas, with woodland (0.148 m) > shrubland (0.114 m) > spare forest land (0.092 m) > medium-coverage grassland (0.074 m) > cultivated land (0.07 m) > low-coverage grassland (0.04 m). This means that it is beneficial to increase plant coverage in the Yanchang area in the lower reaches of the Yanhe River basin, and grassland should be given priority in the restoration of ecological space in the upper reaches.

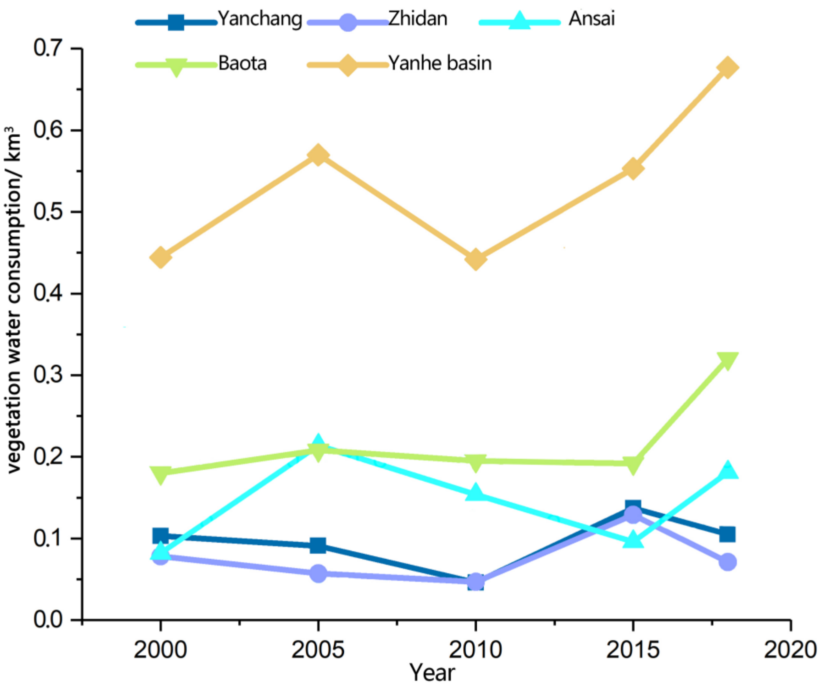

Figure 8. Variation Characteristics of vegetation water consumption in main areas of Yanhe River Basin in 2000, 2005, 2010, 2015, and 2020.

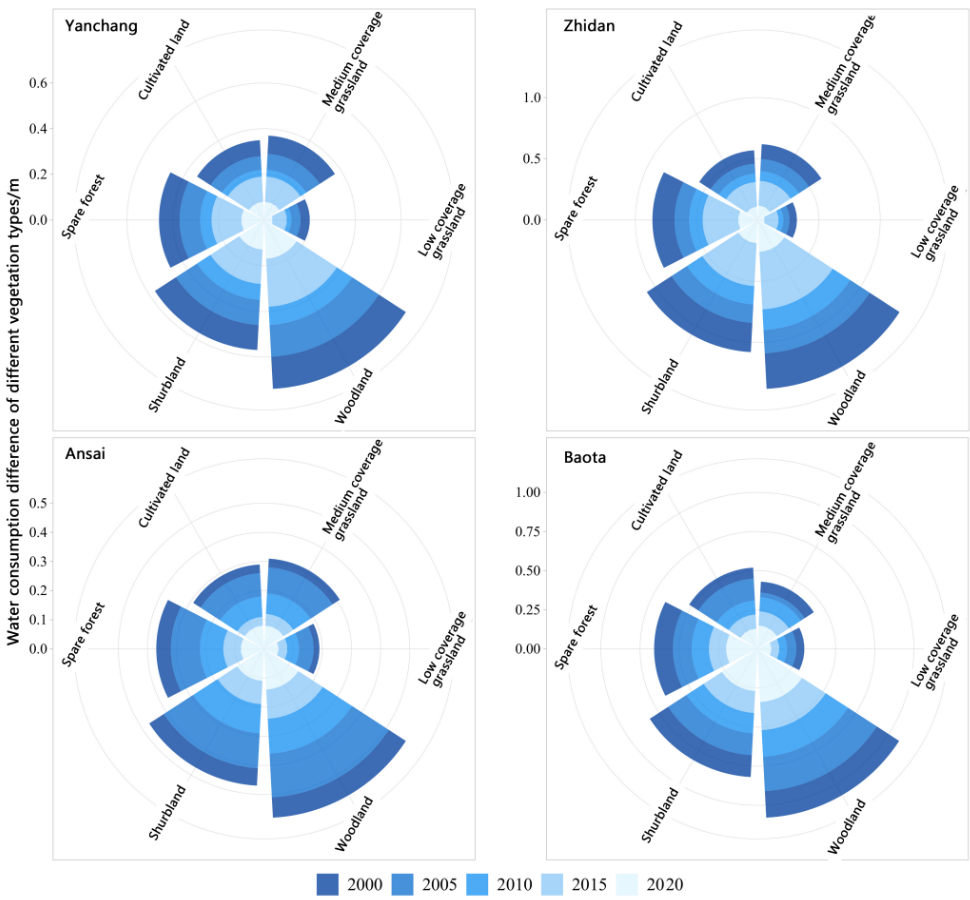

Figure 9. Analysis of the proportion of vegetation water consumption in main areas of Yanhe River Basin in 2000, 2005, 2010, 2015, and 2020.

4.3.3. Analysis of Water Consumption in Different Growth Stages of Different Vegetation Years

The water consumption in different growth stages of the vegetation in the year is quite different (Figure 10). Forestland, shrubland, high-coverage grassland, medium-coverage grassland, and desert vegetation all show a decreasing trend of middle-growth period > development period > late-growth period > early-growth period. The water consumption of woodland in the middle-growth period accounts for more than 89% of the total amount. The change of water consumption in each growth stage of vegetation shows that the water consumption of all vegetation in the development stage, initial stage, and late stage of growth decreases, with the highest decrease in woodland, open woodland, and shrub, and the smallest decrease in low- and medium-coverage grassland. In addition, the water consumption of arable land in the development stage is relatively large.

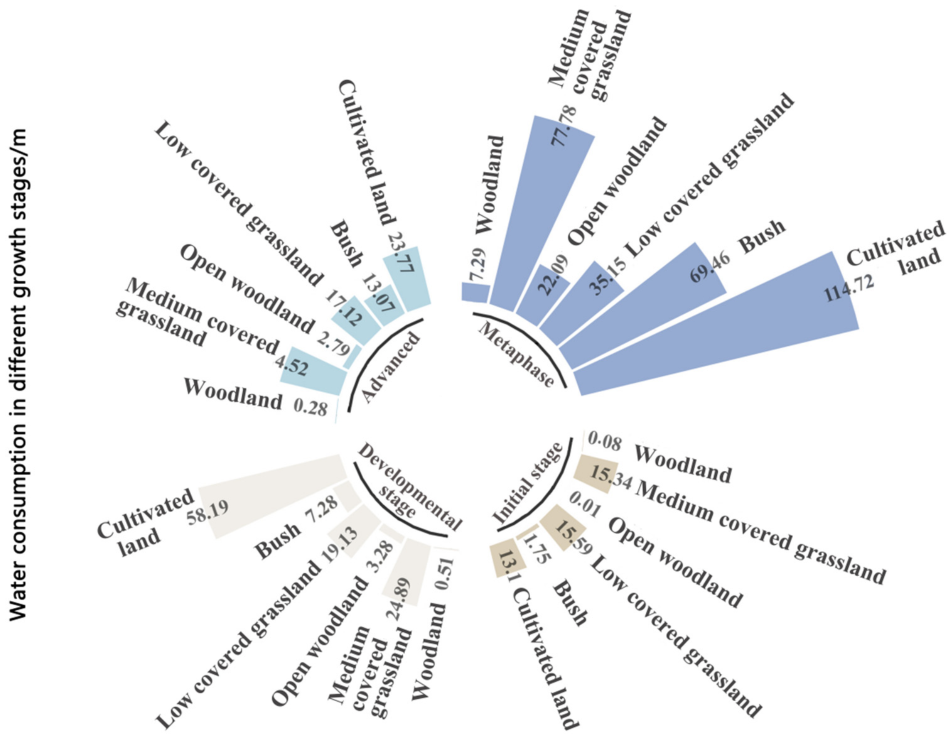

Figure 10. Water consumption of different vegetation types in different plant growth stages.

5. Discussion

Previous studies used the phreatic evaporation formula to estimate the ecological water demand of vegetation in the Yanhe River Basin [38]. However, these works also used limited site data and single vegetation coefficients as the basic data without analyzing the annual vegetation water demand. The current study has conducted an in-depth investigation of the local dominant plant community species, vegetation growth period, and vegetation distribution through field research. Thus, the results are authentic and credible, and can be used as a reference for the scientific allocation of water resources. The results of this study are consistent with the findings of many scholars in the arid and semi-arid regions of China, finding that: the water consumption of vegetation exceeded the regional precipitation, aggravating the decline of the groundwater level [8,19,39]; and the water consumption of forest land has increased significantly, causing serious water deficit, especially in the initial and developmental stages [19,40].

The study found that the annual average water consumption of vegetation in the ecological space of the Yanhe River Basin is 0.537 km^3, with the highest consumption occurring in the central Baota area (1.094 km^3), followed by the Ansai region in the west (0.727 km^3), and the lowest in the eastern extension area (0.483 km^3). In addition, the annual average water consumption is 0.381 km^3. The water consumption of vegetation in the Yanhe River Basin shows an upward trend, and the areas of increased consumption are mainly located in the Baota District and the Ansai district. The water consumption of different vegetation types is obviously different and decreases in the trend of forest land > irrigated forest land > sparse forest land > medium-coverage grassland > cultivated land > low-coverage grassland. Forestland, shrubland, high-coverage grassland, medium-coverage grassland, and desert vegetation all show the trend of middle-growth period > development period > late-growth period > early-growth period. The water consumption of all vegetation in the development period, initial stage and late stage of growth decreased, with woodland, open woodland, and shrub decreasing the most, and grassland with medium and low coverage decreasing the least. In addition, the water consumption of arable land in the development period is relatively high.

Therefore, the significance of this study is stated as follows. It is necessary to think deeply about the sustainable development of ecological space and guide the regional ecological space development in a healthier, more harmonious, more stable, and more sustainable way. Based on the actual demand raised from water shortage in arid and semi-arid areas, this study quantifies the increase in water consumption caused by ecological space changes and pays attention to the ecological space change and its impact on water resources under the guidance of policies. In addition, the calculation of the water demand for ecological space reduces the impact of human subjective evaluation and improves the scientific and objective identification results of ecological space management to a certain extent. In the development process of arid and semi-arid areas, most of them face the problem that the construction of ecological space is not coordinated with the distribution of water resources. The temporal and spatial distribution of vegetation water consumption will directly determine the combination efficiency and construction mode of water resources and ecological space elements during the development. The section on ecological space management under the constraints of regional water resources can serve as a reference for the construction of ecological space in other arid and semi-arid regions.

Despite its significance, this study still has the following limitations. Although the spatial expression of vegetation water consumption in the Yanhe River basin has been realized on a spatial raster scale of 30 m, more accurate vegetation water consumption research needs to be carried out at more scales considering the scale effect on the landscape ecology research. Investigations about vegetation water consumption with higher spatial resolution can make up for the loss of local information in large-scale research, leading to a clearer understanding of vegetation water consumption. In addition, although the existing research and the experiences of experts have been considered, there are still some shortcomings when determining the vegetation coefficient. Under the condition of the given data collection, future research could use more accurate data and scenario analysis to select the most appropriate one from different ecological spatial distribution scenarios.

6. Conclusions

This study demonstrated that in arid and semi-arid areas, the sustainable development of ecological space requires understanding the relationship between the available water resources and water consumption in the regional ecological space. Based on the analysis of the water consumption of vegetation in the Yanhe River basin in the Shaanxi Province, it was found that the annual water consumption of vegetation in the Yanhe River basin is on the rise from 2000 to 2020, indicating that the water resources in the study area have continued to decline in recent years, and ecological construction should be reexamined in the future. Affected by the policy of returning farmland to forestland, the forest land along the upper reaches of the river has increased excessively. The increasing trend of vegetation water consumption upstream is more obvious than that in the downstream areas. If conditions permit, the optimization and control of ecological space should be carried out. It is necessary to pay attention to spatial fine governance and regional differential development in the construction of regional ecological space. In the Ansai and Baota areas, priority should be given to vegetation types with low water consumption after returning farmland to improve grassland coverage. This shows that policies in the upstream areas in the future should focus on farmland protection rather than expanding forest land. Grassland should be the first choice for restoring ecological space. In the future, it is very necessary to reduce water use in semi-arid areas. Although the water consumption of vegetation in the Yanchang area fluctuates slightly, the proportion of forest land should be controlled. To sum up, the increase in vegetation water consumption indicates that the spatial distribution of vegetation types in the watershed ecological space is unreasonable. The policy of returning farmland to forestland and the development of the region has led to a huge change in vegetation water consumption, and the increase in forest land is the main reason for the changing trend of water consumption. Nowadays, the focus of regional ecological space planning has changed from increasing vegetation coverage to coordinating between water resource carrying capacity and spatial planning, digging out the key elements of urban green space. This study has a certain reference value for other similar regions regarding planning and management, and ecological land delimitation, and can be widely used in the planning and management of ecological space in arid and semi-arid regions.

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