Postprint: Study on Spatiotemporal Distribution of Vegetation Water Consumption in the Shule River Basin Based on the Improved Penman Formula Method

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Date: 2021-01-25T00:00:00+00:00

Abstract

The Shule River Basin is located in an inland arid region, where water resources are the key factor constraining vegetation growth and development in the basin. Research on vegetation water consumption plays a crucial role in achieving rational water resource allocation in this basin. Based on meteorological data and GIS technology, this study employs the improved Penman formula method to quantitatively analyze the spatiotemporal variation characteristics of water consumption at different growth stages for various vegetation types in the Shule River Basin. The research results indicate that vegetation water consumption in the Shule River Basin showed an upward trend during 2000-2015, with a multi-year average water consumption of 18.24\$$\times 10^8 m^{\{3\}.Vegetationwaterconsumptionexhibitssignificantspatialheterogeneity, withthehighestwaterconsumptionintheQi}$
During 2000-2015, there were substantial differences in water consumption changes among different vegetation growth stages, with water consumption showing a decreasing trend in the initial growth and development stages, and an increasing trend in the mid-growth and late-growth stages. Compared to changes in vegetation distribution, variations in reference evapotranspiration are the primary influencing factor for changes in vegetation water consumption in the Shule River Basin.

Full Text

Spatial and Temporal Distribution of Vegetation Water Consumption in Shule River Basin Based on Improved Penman Formula Method

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Abstract: The Shule River Basin, located in an inland arid region, faces water resource constraints as the key factor limiting vegetation growth and development. Understanding vegetation water consumption is crucial for rational water resource allocation in the basin. Based on meteorological data and GIS technology, this study employs the improved Penman formula method to quantitatively analyze the spatiotemporal variation characteristics of water consumption for different vegetation types across growth stages in the Shule River Basin. Results indicate that vegetation water consumption in the basin increased from 2000 to 2015, with a multi-year average of 18.24×10^8 m^3. Spatial heterogeneity is pronounced, with the highest consumption in the southern Qilian Mountains and the lowest in the northern Mazong Mountains. Desert vegetation exhibits the highest water consumption (11.25×10^8 m^3), while forest land shows the lowest (0.10×10^8 m^3). Water consumption patterns vary significantly across growth stages: consumption decreased during the initial growth and development stages but increased during the mid and late growth stages. Compared with changes in vegetation distribution, variation in reference evapotranspiration represents the primary factor influencing vegetation water consumption changes in the Shule River Basin.

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

Introduction

With socioeconomic development and population growth, irrational water resource exploitation has intensified water scarcity crises in arid inland river basins, leading to vegetation degradation, land desertification, and deteriorating ecological environments. Vegetation constitutes an essential component of watershed ecosystems, providing crucial ecological functions such as water conservation and soil retention that maintain environmental stability. Vegetation growth and development require specific water quantities that vary substantially among vegetation types and growth stages. Comprehensive understanding of spatiotemporal patterns and variation characteristics of vegetation water consumption is therefore vital for optimizing vegetation structure and achieving rational water resource utilization.

Evapotranspiration represents the primary pathway of vegetation water consumption. Recent studies have employed various methods to estimate vegetation water use, including area quota methods, phreatic evaporation methods, remote sensing models, biomass methods, and improved Penman formula approaches. The improved Penman formula method, which calculates vegetation evapotranspiration based on potential evapotranspiration combined with soil moisture and vegetation area factors, has matured into a robust approach with readily accessible data and strong operability, applicable to diverse ecosystems including deserts, grasslands, and forests.

The Shule River Basin, situated in China' s northwest arid region with an area of approximately 1.25×10^5 km^2, represents one of the three major inland river systems in the Hexi Corridor. Characterized by scarce and unevenly distributed precipitation, the basin relies primarily on alpine glacier meltwater and mountain precipitation for water supply. Excessive groundwater exploitation and low water use efficiency have exacerbated water shortages. As a critical ecological barrier in China' s "Two Screens and Three Belts" framework and a key node in the "Belt and Road" initiative, the basin hosts important cultural heritage sites including the Mogao Grottoes. Previous vegetation water consumption studies in the basin have relied on limited station data and single vegetation coefficients, yielding coarse spatial resolution results without intra-annual analysis, insufficient for scientific water resource allocation.

Addressing these limitations, this study employs the improved Penman formula method with meteorological data and MODIS technology to calculate vegetation water consumption at the grid scale, analyzing its spatiotemporal distribution and variation patterns while examining the influence of vegetation type and reference evapotranspiration changes. The objective is to clarify vegetation water resource consumption and provide more accurate scientific references for rational water allocation.

Study Area

The Shule River Basin (93°22 -98°59 E, 38°01 -42°47 N) is located in the hinterland of China' s northwest arid region. The main stream, the Shule River, extends approximately 670 km, with major tributaries including the Danghe, Baiyanghe, Shiyouhe, Yulinhe, and rivers from the northern slopes of the Altun Mountains. Administratively, the basin encompasses Dunhuang City, Yumen City, Subei County, Guazhou County, and Aksai County under Jiuquan City, plus portions of Tianjun County and Delingha City in Qinghai Province.

Precipitation is scarce and highly uneven, decreasing from southeast to northwest, making it one of Gansu Province' s most arid regions. Water resources originate mainly from alpine glacier melt and mountain precipitation. Considering climatic, topographic, and administrative boundaries, the basin is divided into three zones: the southern Qilian Mountains (water source and runoff generation area), the central plain area, and the northern Mazong Mountains (arid with coexisting oasis and desert ecosystems). Representative meteorological stations are Tole (southern mountains), Yumen (central plains), and Mazongshan (northern mountains).

Methodology

Vegetation Water Consumption Calculation Model

Given low vegetation coverage and severe degradation in the Shule River Basin, vegetation does not completely cover the surface, and growth is affected by soil moisture limitations determined by a soil moisture restriction coefficient. Therefore, evapotranspiration calculation for non-fully-covered vegetation requires incorporation of this coefficient based on the FAO-recommended method:

$$ET_p = K_c K_s ET_0$$

where ET_p is vegetation evapotranspiration rate ($\mathrm{mm \cdot d^{-1}}$), K_c is the vegetation coefficient, K_s is the soil moisture restriction coefficient, and ET_0 is reference evapotranspiration ($\mathrm{mm \cdot d^{-1}}$).

Vegetation water consumption accounts for different vegetation types' coverage areas:

$$VWC = \sum_{p=1}^{n} (A_p \times 10^3) \times ET_p$$

where VWC is vegetation water consumption ($\mathrm{m^3}$), A_p is the distribution area of each vegetation type ($\mathrm{km^2}$), ET_p is vegetation evapotranspiration rate ($\mathrm{mm \cdot d^{-1}}$), and n is the number of days in the vegetation growing season.

Reference Evapotranspiration Rate (ET_0) Calculation

Reference evapotranspiration ET_0 is calculated using the Penman-Monteith equation recommended by the FAO:

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

where Δ is the slope of the saturation vapor pressure curve ($\mathrm{KPa \cdot ℃^{-1}}$), R_n is net radiation at the crop surface ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$), G is soil heat flux density ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$), γ is the psychrometric constant ($\mathrm{KPa \cdot ℃^{-1}}$), T is mean air temperature at 2 m height (℃), u_2 is wind speed at 2 m height ($\mathrm{m \cdot s^{-1}}$), e_s is saturation vapor pressure (KPa), and e_a is actual vapor pressure (KPa).

Determination of Vegetation Coefficients

The vegetation coefficient (K_c) represents the ratio between actual vegetation water consumption and maximum potential evaporation. Beyond environmental conditions, K_c varies with vegetation type and growth stage. The annual growth process is divided into four stages: initial, development, mid-season, and late season, with K_c calculated separately for each stage based on representative meteorological station data for each zone.

Based on land use data, vegetation in the Shule River Basin is classified into six types: forest land, shrubland, sparse forest land, high-coverage grassland, medium-coverage grassland, and desert vegetation. Dominant species for each type were identified using Jiuquan Forestry Bureau statistics and NDVI time-series classification results (Table 1). Vegetation coefficients and growth stages were determined based on these dominant species, with stage boundaries defined using phenological information from the Chinese Academy of Sciences' "Annual Report on Phenological Observations" and references to the Heihe River Basin.

The initial growth stage coefficient ($K_{c,ini}$) is primarily determined by soil wetting intervals, wetting degree, and atmospheric evaporation capacity. Mid-season ($K_{c,mid}$) and end-season ($K_{c,end}$) coefficients are determined by effective surface coverage, with development stage coefficients linearly interpolated between $K_{c,ini}$ and $K_{c,mid}$, and late-season coefficients between $K_{c,mid}$ and $K_{c,end}$. This study calculated K_c values using meteorological and MODIS data from 2000–2015.

Determination of Soil Moisture Restriction Coefficient

The soil moisture restriction coefficient (K_s) is determined by soil water content, critical water content, and wilting coefficient. Using MODIS remote sensing data and apparent thermal inertia methods, Liu Jiao (2014) inverted soil moisture content and obtained K_s values for the Tole, Yumen, and Mazongshan station areas. This study adopts those results to represent the three zones.

Analysis Method for Interannual Variation of Vegetation Water Consumption

The least squares method was used to calculate the interannual variation rate of vegetation water consumption at the grid scale:

$$K = \frac{\sum_{i=1}^{n}(VWC_i - \overline{VWC})}{\sum_{i=1}^{n}(i - \bar{i})}$$

where K is the change rate of vegetation water consumption per grid cell [$\mathrm{m}^3 \cdot (5\mathrm{a})^{-1}$], n is the study period length, and VWC_i is vegetation water consumption in year i. Positive K values indicate increasing trends (larger values = stronger increase), while negative values indicate decreasing trends.

Data Sources and Preprocessing

Digital Elevation Model (DEM) data were obtained from the Chinese Geographic Spatial Data Cloud (http://www.gscloud.cn) with 90 m spatial resolution. Meteorological data, including daily maximum/minimum temperature, average temperature, wind speed, sunshine duration, vapor pressure, relative humidity, and precipitation, were provided by the National Meteorological Data Center (http://data.cma.cn). Surface pressure and near-surface wind speed data came from the Chinese Academy of Sciences' Cold and Arid Regions Science Data Center (http://westdc.westgis.ac.cn) —the China Regional High-Temporal-Resolution Surface Meteorological Element Driven Dataset with 10 km spatial resolution and daily temporal resolution.

Land use data (1 km resolution) were obtained from the Chinese Academy of Sciences' Resource and Environmental Science Data Center (http://www.resdc.cn). MODIS 16-day composite vegetation index data (MOD13A2) with 1 km resolution were acquired from NASA (https://ladsweb.modaps.eosdis.nasa.gov). All spatial data were processed using ArcGIS 10.5, unified to the same projection coordinate system and 1 km spatial resolution.

Net radiation was calculated from meteorological station data and interpolated using inverse distance weighting. Maximum/minimum temperature, average temperature, and relative humidity station data were spatially interpolated using the Anusplin method.

Results

Spatiotemporal Variation Analysis of Vegetation Water Consumption

From 2000 to 2015, vegetation water consumption in the Shule River Basin showed an increasing trend (Table 3), with a multi-year average of 18.24 × 10^8 m^3. Spatially, consumption was highest in the southern Qilian Mountains (9.48 × 10^8 m^3), followed by the central plain area (4.64 × 10^8 m^3), and lowest in the northern Mazong Mountains (4.12 × 10^8 m^3), with all zones showing upward trends.

At the county scale (Table 2), Subei County had the highest consumption (9.58 × 10^8 m^3), while Delingha City had the lowest (0.02 × 10^8 m^3). Aksai and Subei counties in the southern mountains decreased by 0.16 × 10^8 m^3 and 0.07 × 10^8 m^3 respectively, while other counties increased, with Tianjun County showing the largest increase (0.38 × 10^8 m^3).

The spatial distribution of annual average vegetation water consumption (Figure 2a) exhibits pronounced heterogeneity, with high values concentrated in mountainous areas of Aksai County and oasis regions of Yumen City, and low values mainly in the Qilian Mountains and desert vegetation areas of the central plain.

The variation rate of vegetation water consumption ranged from -54,056 to 57,440 $m^3 \cdot (5a)^{-1}$, classified into five categories: significant increase, slight increase, basically unchanged, slight decrease, and significant decrease (Table 3). Areas with increased consumption accounted for 52.67% of total vegetation area, with 0.92% showing significant increase (mainly near Huahai irrigation district in the central plain and glacier melt areas in Tianjun County) and 43.96% showing slight increase (mainly in Tianjun County, central plain oasis areas, and Mazongshan region). Decreased consumption areas accounted for 47.33%, with 0.09% showing significant decrease (scattered around oasis edges in Subei and Tianjun counties, likely due to human disturbance) and 37.42% showing slight decrease (mainly in Qilian Mountains, possibly related to decreasing evapotranspiration trends).

Differences in Water Consumption Among Vegetation Types

Average annual water consumption varied significantly among vegetation types (Table 4): desert vegetation (11.26×10^8 m^3) > medium-coverage grassland (3.96×10^8 m^3) > high-coverage grassland (1.64×10^8 m^3) > shrubland (1.07×10^8 m^3) > sparse forest land (0.22×10^8 m^3) > forest land (0.10×10^8 m^3). Due to smaller distribution areas, forest and shrubland accounted for only 0.58% and 6.32% of total consumption respectively, while grassland and desert vegetation accounted for 7.60% and 85.50% respectively.

All vegetation types showed increased water consumption from 2000 to 2015, with forest land increasing by 61.70% (0.04×10^8 m^3), shrubland by 30.70% (0.25×10^8 m^3), and grassland and desert vegetation by 0.84×10^8 m^3, accounting for 34.28% of the total increase. This indicates that increased water consumption by grassland and desert vegetation is the main driver of the overall increase.

Box plots of grid-scale average water consumption (Figure 3) reveal that per-unit-area consumption follows the order: forest land > shrubland > sparse forest land > high-coverage grassland > medium-coverage grassland > desert vegetation (T-test, $P < 0.01$). High-coverage grassland and shrubland show longer boxes, indicating higher heterogeneity, while desert vegetation and medium-coverage grassland show shorter boxes with more concentrated values and lower heterogeneity.

Intra-Annual Water Consumption at Different Growth Stages

Water consumption varies substantially across growth stages (Figure 4). Forest land and sparse forest land concentrate consumption in the mid and late growth stages (>70%). Shrubland, high-coverage grassland, medium-coverage grassland, and desert vegetation show the pattern: mid-season > late season > development stage > initial stage.

Changes in water consumption across growth stages from 2000 to 2015 show that all vegetation types experienced slight decreases during the initial and development stages, with forest land, sparse forest land, and desert vegetation decreasing most during the initial stage, and shrubland and grasslands decreasing most during the development stage. All vegetation types showed substantial increases during the mid and late growth stages, with forest land and shrubland increasing most during mid-season, and sparse forest land, grasslands, and desert vegetation increasing most during late season.

Impacts of Vegetation Distribution and Reference Evapotranspiration Changes on Water Consumption

Since vegetation distribution area and reference evapotranspiration are the only time-varying variables in the estimation method, their combined effects drive the increase in vegetation water consumption. To clarify their relative impacts, we applied a controlled variable approach, assuming reference evapotranspiration remained at 2000 levels while only vegetation distribution changed. Results show that from 2000 to 2015, forest land area increased by 10.57 km^2, sparse forest land decreased by 3.52 km^2, shrubland decreased by 6.51 km^2, and high-coverage and medium-coverage grasslands and desert vegetation increased by 19.29 km^2 and 4.23 km^2 respectively. These vegetation distribution changes increased water consumption by 0.38×10^8 m^3, accounting for 4.53% of the total increase.

The most significant vegetation transitions contributing to increased consumption were other land types converting to desert vegetation (545.85 km^2, increasing consumption by 1.32×10^8 m^3, 31.35% contribution), and conversions to high-coverage grassland and shrubland (increasing consumption by 0.23×10^8 m^3 and 0.34×10^8 m^3 respectively). Conversely, desert vegetation converting to other land types (485.22 km^2) reduced consumption by 1.18×10^8 m^3 (contribution: -29.20%). Medium-coverage grassland and shrubland converting to other land types also substantially reduced consumption.

After accounting for vegetation distribution effects, the remaining 95.47% of the increase was attributed to reference evapotranspiration changes. From 2000 to 2015, reference evapotranspiration in vegetation areas ranged from -149.11 to 302.19 mm, with 56.37% of areas showing increases (mainly in central plain oasis areas, Tianjun County, and Mazongshan region) and 43.62% showing decreases (mainly in Qilian Mountains and northwest Guazhou). All vegetation types experienced increased reference evapotranspiration, with sparse forest land showing the largest increase (104.18 mm), followed by forest land, shrubland, and grasslands (24.76–76.43 mm), and desert vegetation showing the smallest increase (64.66 mm).

Discussion

In arid inland river basins facing population growth and water scarcity, the allocation of water resources between ecological and production needs is a critical concern. Vegetation water consumption, as a major component of ecological water demand, is key to maintaining stable growth of natural and artificial oasis protection systems. Supported by meteorological data and MODIS technology, this study calculated vegetation water consumption at the grid scale using the improved Penman formula method, examined its spatiotemporal distribution and variation patterns, and analyzed the impacts of vegetation distribution and reference evapotranspiration changes to provide references for more rational water resource allocation.

We validated our results against vegetation water consumption quotas from the Shule River Basin and similar arid basins (Heihe and Aksu). Within the same basin, our estimates are slightly higher than Zeng Jianjun' s, likely due to differences in evapotranspiration estimation methods. However, our forest land quotas are similar to Liu Jiao' s results from the adjacent Heihe River Basin, and our Populus euphratica forest quotas align with Zhang Ruiwen et al.' s Aksu River Basin study, confirming the credibility of our grid-scale calculations. While our 1 km resolution improves upon previous county-scale studies, scale effects in landscape ecology research suggest that multi-scale studies with higher spatial resolution would provide clearer local insights.

Vegetation water consumption in the Shule River Basin increased from 2000 to 2015, with increases concentrated in Tianjun County, central plain oasis areas, and Mazongshan region. The increase in Tianjun County is mainly attributed to enhanced glacier melt from global warming, providing adequate moisture for natural vegetation growth. Increases in the central plain oasis and Mazongshan regions primarily result from active ecological restoration measures (afforestation and grass planting) that have improved vegetation conditions. However, the spatial heterogeneity of consumption (Figure 2) and differences in intra-annual consumption patterns across growth stages (Figure 4) suggest that water resource allocation should account for regional vegetation types and consumption distribution characteristics. Particularly during the mid-growth stage when consumption peaks, monitoring precipitation and vegetation conditions in non-zonal vegetation areas (natural oases and artificial protection systems) is essential to detect water stress-induced degradation promptly.

Vegetation distribution and reference evapotranspiration are critical parameters for estimating vegetation water consumption. Their distinct impacts on consumption changes are important for vegetation health in arid inland basins. Although vegetation distribution conversion was limited (Table 5), increased reference evapotranspiration across all vegetation types (Figure 5) was the main driver of consumption increase. Vegetation distribution changes are primarily human-induced, and their impact on water consumption will likely decrease under stricter land use policies, while reference evapotranspiration effects will amplify. Climate change is a key factor affecting reference evapotranspiration, and under continued climate change, vegetation water consumption in the Shule River Basin may further increase, intensifying water scarcity crises. Therefore, scientific water resource allocation is urgent.

Water resource management should balance economic development and ecological protection. On one hand, water allocation should prioritize ecological protection areas, adjusting water distribution flexibly based on monitoring of vegetation degradation. On the other hand, excessive vegetation construction consumes substantial water resources, requiring clear understanding of regional groundwater and precipitation conditions to determine vegetation carrying capacity and rationally control afforestation and grass planting. Policies should coordinate water resource supply-demand relationships for both economic development and ecological protection. Additionally, "source" and "conservation" approaches can increase water availability: "source" through inter-basin water transfer, and "conservation" through controlling cultivated land, adjusting agricultural structure, and developing water-saving agriculture to allocate more water for ecological restoration.

This study has limitations requiring further improvement. First, using single representative stations for K_c and K_s values for entire zones neglects within-zone vegetation and soil heterogeneity; incorporating more meteorological stations and remote sensing data for finer-scale K_c and K_s would improve accuracy. Second, the impact of climate change on vegetation water consumption warrants deeper investigation to complete the study.

Conclusions

1) The Shule River Basin' s average annual vegetation water consumption is 18.24×10^8 m^3, highest in the southern Qilian Mountains (9.48×10^8 m^3), followed by the central plain area (4.64×10^8 m^3), and lowest in the northern Mazong Mountains (4.12×10^8 m^3).

2) Vegetation water consumption shows an increasing trend, with increases mainly in Tianjun County, central plain oasis areas, and Mazongshan region, and decreases mainly in the Qilian Mountains.

3) Water consumption differs significantly among vegetation types: desert vegetation > medium-coverage grassland > high-coverage grassland > shrubland > sparse forest land > forest land.

4) Forest land and sparse forest land concentrate consumption in mid and late growth stages, while other vegetation types follow the pattern: mid-season > late season > development stage > initial stage. All vegetation types showed substantial increases in mid and late stage consumption and slight decreases in initial and late stage consumption.

5) Vegetation distribution changes increased water consumption by 0.38×10^8 m^3 (4.53% of total increase), with the remaining increase driven by reference evapotranspiration changes.

References

[1] Cai Y P, Huang G H, Yang Z F, et al. Identification of optimal strategies for energy management systems planning under multiple uncertainties[J]. Applied Energy, 2009, 86(4): 480-495.

[2] Hu Q, Huang G, Cai Y, Sun W. Planning of electric power generation systems under multiple uncertainties and constraint-violation levels [J]. Journal of

Environmental Informatics, 2014, 23(1): 55-64.

[3] Tan Q, Huang G H, Cai Y P. Radial interval chance-constrained programming for agricultural non-point source water pollution control under uncertainty[J]. Agricultural Water Management, 2011, 98(10): 1595-1606.

[4] Hu Guanglu, Zhao Wenzhi. Reviews on calculating methods of vegetation ecological water requirement in arid and semiarid regions[J]. Acta Ecologica Sinica, 2008, 28(12): 501-510.

[5] Wang Hongchang. Climate in Western China, Ecological Succession: History and Prospects[M]. Beijing: Economic Management Press, 2001.

[6] Zheng Hongxing, Liu Changming, Feng Huali. On concepts of ecological water demand[J]. Advances in Water Science, 2004, 15(5): 626-633.

[7] Lu C, Zhao T, Shi X, et al. Ecological restoration by afforestation may increase groundwater depth and create potentially large ecological and water opportunity costs in arid and semiarid China[J]. Journal of Cleaner Production, 2018, 176: 1213-1222.

[8] Gao G, Shen Q, Zhang Y, et al. Determining spatio-temporal variations of ecological water consumption by natural oases for sustainable water resources allocation in a hyper-arid endorheic basin[J]. Journal of Cleaner Production, 2018, 185: 1-13.

[9] Kang Dan, Tian Meirong, Gao Jixi, et al. Characteristics of actual evapotranspiration and water consumption of forest and grassland ecosystems under vegetation restoration projects based on the SEBAL model in Chifeng, China[J/OL]. Research of Environmental Sciences. https://10.13198/j.issn.1001-6929.2020-03-36.

[10] Chi D, Wang H, Li X, et al. Estimation of the ecological water requirement for natural vegetation in the Ergune river basin in northeastern China from 2001 to 2014[J]. Ecological Indicators, 2018, 92: 141-150.

[11] Guo Qiaoling, Feng Qi, Yang Yunsong, et al. Estimation of ecological water consumption in the region from Dadunmen to Langxin Mountain in the Heihe river basin[J]. Arid Zone Research, 2007, 24(5): 584-589.

[12] Wang Jucui, Ding Hua, Hu Anyan. Preliminary estimation of water consumption for the ecology in the Guanzhong region, Shaanxi province, China[J]. Arid Zone Research, 2008, 25(1): 22-27.

[13] Liu Xinhua, Xu Hailiang, Ling Hongbo, et al. Study on ecological water requirements along the mainstream channel of the Tarim river[J]. Journal of Desert Research, 2013, 33(4): 1198-1205.

[14] Peng Fei, He Xinlin, Liu Bing, et al. A study on estimation method for ecological water requirement of desert vegetation in arid area[J]. Water Saving Irrigation, 2017(12): 90-93.

[15] Li Qiangkun, Li Huaien, Zhang Huimin, et al. Study on the schemes for restoring the Erjina oasis based on the redistribution of ecological water consumption[J]. Arid Zone Research, 2008, 25(4): 457-463.

[16] Mansur Shabiti, Yusup Maimaiti, Hu Jiangling. Study on ecological water consumption in the Ogan-Kuqa river delta oasis in Xinjiang[J]. Arid Region Research, 2008, 25(3): 325-330.

[17] Zhang L. Ecological water requirement based on ecological protection and restoration targets in the lower reaches of the Heihe river, northern China[J]. Frontiers of Forestry in China, 2009, 4(3): 263-270.

[18] Ye Hongmei, Chen Shaohui, Sheng Feng. Dynamic estimation for vegetation ecological water demand in Shule River irrigation district during 2000-2014[J]. Journal of Glaciology and Geocryology, 2016, 38(1): 231-240.

[19] Qi Jinghui. The Research on Oasis Ecological Evolution of Shule River Basin[D]. Lanzhou: Lanzhou University, 2017.

[20] Sun Dongyuan, Hu Xiangquan, Jin Yanzhao, et al. Prediction and evaluation of ecological water requirement of natural vegetation in the middle reaches oasis of Shulehe river basin[J]. Arid Land Geography, 2016, 39(1): 154-161.

[21] Zeng Jianjun. Change of Ecological Carrying Capacity and Ecological Water Demand along with Landscape Pattern Evolution in Shule River Basin[D]. Lanzhou: Lanzhou University, 2018.

[22] Zhou Yanyan, Guo Xiaojuan, Guo Jianjun, et al. Spatiotemporal dynamics of evapotranspiration in Shule River basin based on SEBAL model[J]. Research of Soil and Water Conservation, 2019, 26(1): 174-183.

[23] Gao Qianzhao. The features of water cycle in inland river basins in Hexi region[J]. Journal of Arid Meteorology, 2003, 21(3): 23-30.

[24] Yue Dongxia, Chen Guanguang, Zhu Minxiang, et al. Biocapacity and ecological water demand in Shule River basin over the past 20 Years[J]. Acta Ecologica Sinica, 2019, 39(14): 5178-5187.

[25] Li Man, Ding Yongjian, Yang Jianping, et al. The impact of runoff on the oasis area, agro-output value and ecological benefits in the Shulehe River[J]. Journal of Desert Research, 2015, 35(2): 514-520.

[26] Liu Jiao. Study on Vegetation Ecological Water Requirement of the Heihe River Basin Based on 3S Technology[D]. Yangling: Northwest A & F University, 2014.

[27] Wang L, Zhang J, Liu Z, et al. Ecological water requirement of plant-soil systems along the Silk Road Economic Belt: A case study of the Guanzhong-Tianshui region, China[J]. Geological Journal, 2018, 53(Suppl.): 293-300.

[28] Xie Lei, Long Aihua, Deng Mingjiang, et al. Study on ecological water consumption in delta of the lower reaches of Ili river[J]. Journal of Glaciology

and Geocryology, 2011, 33(6): 1330-1340.

[29] Bai Yuan, Xu Hailiang, Zhang Qingqing, et al. Evaluation on ecological water requirement in the lower reaches of Tarim river based on groundwater[J]. Acta Ecologica Sinica, 2015, 35(3): 630-640.

[30] Fan Yayun, Guo Yuchuan, Lu Gang, et al. Vegetation ecological water requirement of Ebinur lake watershed[J]. Journal of Desert Research, 2018, 38(4): 865-871.

[31] Zhao Wenzhi, Chang Xueli, He Zhibin, et al. Study on ecological water requirement of vegetation in Erjina desert oasis[J]. Scientia Sinica (Terrae), 2006, 36(6): 559-566.

[32] Wang Gailing, Wang Qingchu, Shi Shengxin. Vegetation’ s ecological water requirement in Yongding river watershed in Shanxi province[J]. Journal of Natural Resources, 2013, 28(10): 95-105.

[33] Allen R G, Pereira L S, Raes D, et al. Crop evapotranspiration guidelines for computing crop requirements. FAO Irrig. Drain. Report 56, Rome, Italy, 1998.

[34] Liu Huifeng. Vegetation Classification of the Basin of Shule River Based on NDVI Time Series[D]. Lanzhou: Lanzhou University, 2014.

[35] Feng Xianghua. Study on Vegetation Ecological Water Requirement of Grassland Ecosystem in Typical Pastoral Areas of Western China[D]. Xi’ an: Xi’ an University of Technology, 2019.

[36] Institute of Geography, Chinese Academy of Sciences. Annual Report on Phenological Observations of Chinese Flora and Fauna: NO. 8 (1981-1982)[M]. Beijing: Science Press, 1988.

[37] Lin P, He Z, Du J, et al. Impacts of climate change on reference evapotranspiration in the Qilian mountains of China: Historical trends and projected changes[J]. International Journal of Climatology, 2018, 38(7): 1-14.

[38] Deng Xingyao, Liu Yang, Liu Zhihui, et al. Temporal-spatial dynamic change characteristics of evapotranspiration in arid region of Northwest China[J]. Acta Ecologica Sinica, 2017, 37(9): 2994-3008.

[39] Zhang Ruiwen, Zhao Chengyi, Wang Dandan, et al. Ecological water consumption characteristics of Populus euphratica forest under different water conditions in extremely arid area[J]. Journal of Soil and Water Conservation, 2019, 33(4): 270-278.

[40] Guo Jianjun, Li Kai, Jiang Baohua, et al. Effects of the spatial scale on regional biocapacity: A case study of Shiyang river basin[J]. Journal of Lanzhou University (Natural Sciences), 2014, 50(3): 383-389.

[41] Jiang Tianliang, Ma Wenzhen, Tao Li. Vegetation design area calculation

of Weihe source large-scale forest farm based on water resources carrying capacity[J]. Water Resources and Power, 2019, 37(9): 24-27.

[42] General Office of the People' s Government of Gansu Province. General Office of the People' s Government of Gansu Province on the Issuance of the General Plan for Land Use of Gansu Province (2006-2020) Adjustment and Improvement of the Program Notice[EB/OL]. http://www.gansu.gov.cn/art/2017/11/1/art_{4786}_{325467}.html. 2017-11-02.

[43] Liu Y, Song W, Deng X. Spatiotemporal patterns of crop irrigation water requirements in the Heihe river basin, China[J]. Water, 2017, 9(8): 616-637.

[44] Chao Qingchen, Yan Zhongwei, Sun Ying, et al. A recent scientific understanding of climate change in China[J]. China Population, Resources and Environment, 2020, 30(3): 1-9.

Note: Figure translations are in progress. See original paper for figures.

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