Variation Trends and Driving Factors of Green Water in the Loess Hilly and Gully Region: A Postprint

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Abstract

Green water constitutes a vital water source for sustaining terrestrial ecosystem water use on the Loess Plateau and is intimately coupled with vegetation growth. Analyzing the variation characteristics of green water and elucidating the factors governing its changes are essential for addressing water resource scarcity and ecological security issues in arid and semi-arid regions. This study employs the Yanwachuan watershed, a representative catchment in the loess hilly-gully region, as the study area. The Fu Baopu model was utilized to quantify green water resources from 1981 to 2016. Trend analysis and abrupt change detection of green water were performed using the Mann-Kendall statistical test and moving F-test method. Sensitivity analysis of climatic and underlying surface factors influencing green water was conducted via the elasticity coefficient method. Attribution analysis of watershed green water variation was subsequently performed based on the water-heat coupling balance equation. The results demonstrate: (1) The multi-year average green water resource is 503.7 mm, exhibiting a slight increasing trend with an abrupt change detected in 2003, after which green water displays a fluctuating growth pattern; (2) Among climatic factors, green water exhibits the highest sensitivity to precipitation, followed by potential evapotranspiration; (3) Under combined climate change and land use impacts, green water remains most sensitive to precipitation, followed by underlying surface parameters, while showing the lowest sensitivity to potential evapotranspiration; (4) Climate change and land use change contribute 74.42% and 25.58% to green water variation, respectively, indicating that climate change represents the dominant driver, with precipitation and potential evapotranspiration changes contributing 75.63% and -1.21%, respectively.

Full Text

Changing Trend of Green Water and Its Driving Factors in the Gully Region of the Loess Plateau

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Abstract: Green water is a crucial water source for maintaining terrestrial ecosystem water use on the Loess Plateau and is closely related to vegetation growth. Analyzing the variation characteristics of green water and exploring the factors influencing its changes can help address water resource shortages and ecological security issues in arid and semi-arid regions. This study examines the Yanwachuan Basin, a typical watershed in the gully region of the Loess Plateau. The Fu Baopu model was employed to evaluate annual green water resources from 1981 to 2016. Trend analysis and mutation tests of green water volume were conducted using the Mann-Kendall test and sliding F-test, while the elastic coefficient method was applied for sensitivity analysis of climatic factors and underlying surface factors affecting green water. Finally, attribution analysis of watershed green water changes was performed based on the water-heat coupling balance equation. The results show that: (1) The multi-year average green water resource in the basin was 503.7 mm, showing a slight upward trend, with a mutation occurring in 2003, after which green water volume exhibited a fluctuating growth trend; (2) Among the influencing factors, green water is most sensitive to precipitation, followed by potential evapotranspiration; (3) Under the combined influence of climate change and land use, green water is most sensitive to precipitation, followed by underlying surface parameters, and least sensitive to potential evapotranspiration; (4) The contribution rates of climate change and land use change to green water variation were 74.42% and 25.58%, respectively, indicating that climate change is the main factor causing green water changes, with precipitation and potential evapotranspiration contributing 75.63% and -1.21% to green water changes, respectively.

Keywords: green water; climate change; land use change; Fu Baopu model; attribution analysis

1 Study Area Overview

The Yanwachuan Basin, part of the Jinghe River system, is located in Xifeng District and Ning County, Qingyang City, Gansu Province (107°37 -107°55 E, 35°31 -35°44 N), covering a total area of 385.63 km^2. The basin lies in a transitional zone from semi-humid to semi-arid and from warm temperate to mid-temperate zones, characterized by a continental monsoon climate with a multi-year average rainfall of 526.8 mm. The main geomorphic units include table-land surfaces, loess ridge slopes, and valley bottoms. Established in 1981 by the Xifeng Water and Soil Conservation Experiment Station of the Yellow River Conservancy Committee as a typical prototype observation watershed in the loess gully region, the Yanwachuan Basin has accumulated extensive measured data on rainfall, runoff, and other hydrological variables. Since the 1980s, watershed management has undergone three main phases: 1981-1990, 1991-2000, and 2001-2016. Management practices have included reservoir and silt dam construction, afforestation, artificial grass planting, and soil and water conservation ecological projects.

2 Data and Methods

2.1 Data Sources

The study period spans 1981-2016, with rainfall and runoff data obtained from actual measurements. Considering data series continuity and the distribution of rain gauge stations, six rain gauge stations with continuous series and uniform distribution within the basin (Fig. 1) were selected, and basin area rainfall was calculated using the Thiessen polygon method. Runoff data were obtained from the Yanwachuan hydrological station at the basin outlet (Fig. 1). Meteorological data, including average temperature, relative humidity, solar radiation, sunshine hours, and wind speed, were sourced from the China Meteorological Data Network (http://data.cma.cn/).

Based on watershed management conditions, land use data for the Yanwachuan Basin from 1985, 1995, 2005, and 2015 were selected as baseline data for analyzing the impact of land use change on green water. Combined with the 1 100,000 watershed boundary, ArcGIS was used for clipping to obtain land use data for the basin.

2.2 Methods

2.2.1 Green Water Resource Calculation Model This study employs the Fu Baopu model to calculate green water resources in the Yanwachuan Basin. The Fu Baopu model, developed by Chinese climatologist Professor Fu Baopu in 1981 through dimensional analysis and mathematical derivation, is an actual evapotranspiration calculation formula. Compared with other evapotranspiration formulas, this model comprehensively considers the influence of underlying surface conditions on green water resources and has demonstrated good application effects in many basins. The specific form of the model is as follows:

$$E = \frac{P \cdot E_{T0}}{(P^{\omega} + E_{T0}^{\omega})^{1/\omega}}$$

where:
P is precipitation (mm);
E is green water resource amount (mm);

E_{T0} is potential evapotranspiration (mm), calculated in this study using the Priestley-Taylor method;
ω is a parameter characterizing underlying surface conditions, with a value range of $(1, \infty)$.

2.2.2 Model Validation (1) Water Balance Method

For a closed watershed, the annual-scale green water cycle process can be expressed as:

$$E = P - R$$

where W is watershed green water resource amount (mm), P is precipitation (mm), and R is runoff (mm).

The entire study period was divided into two stages: 1981–1995 data were used to calibrate parameters in the Fu Baopu model, and 1996–2016 data were used for validation. Using the water balance method calculation results as the standard, the calculation accuracy of the Fu Baopu model was tested.

(2) Evaluation Metrics

The parameter ω in the Fu Baopu model was calibrated through trial-and-error methods. The root mean square error (RMSE) and annual relative error (R_e) between model simulation results and water balance method calculation results were used to test calculation accuracy, with ω adjusted to minimize RMSE. The calculation formulas are as follows:

$$R_e = \frac{E_i - W_i}{W_i} \times 100\%$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(E_i - W_i)^2}$$

where n is the study period, E_i is the green water resource amount simulated by the model in year i, and W_i is the green water resource amount calculated by the water balance method in year i (mm).

2.2.3 Mutation Test The Mann-Kendall (M-K) test is a commonly used non-parametric test method for detecting mutations in various variables in long hydrometeorological series data, which can roughly determine the year when mutation points occur. This paper uses the M-K method to analyze green water resource mutations and verifies them through the sliding F-test, which can both identify and test variation points.

2.2.4 Land Use Characteristics and Attribution Analysis (1) Land Use Change Area Proportion

The land use change area proportion can reflect the overall situation of all types of land use changes in a watershed, characterizing the intensity of land use change. The calculation formula is as follows:

$$D = \frac{A}{S} \times 100\%$$

where D is the land use change area proportion (%), A is the total area of all types of land use changes (km^2), and S is the total watershed area (km^2).

(2) Land Use Change Intensity Index

The land use change intensity index can reflect the degree of increase or loss of a certain land use type. Its calculation formula is:

$$I = \frac{A_b - A_a}{A_a} \times \frac{1}{T} \times 100\%$$

where I is the intensity index (%), A_a and A_b represent the area of the land use type at the beginning and end of the study period (km^2), respectively, and T is the study period. Other parameters have the same meaning as above.

(3) Determination of Climate Elasticity and Underlying Surface Elasticity Coefficients

This study uses the elasticity coefficient method based on the Budyko framework to analyze the sensitivity of green water to climate elements and underlying surface changes. This method can evaluate variables with different dimensions. Based on relevant research, this study defines the elasticity coefficients of green water to precipitation, potential evapotranspiration, and underlying surface parameters. The calculation formulas are as follows:

$$\varepsilon_P = \frac{\partial E}{\partial P} \cdot \frac{P}{E} = \frac{1}{1 + \omega x^{\omega}}$$

$$\varepsilon_{ET0} = \frac{\partial E}{\partial E_{T0}} \cdot \frac{E_{T0}}{E} = \frac{\omega x^{\omega}}{1 + \omega x^{\omega}}$$

$$\varepsilon_{\omega} = \frac{\partial E}{\partial \omega} \cdot \frac{\omega}{E} = \frac{\omega \ln x \cdot x^{\omega}}{(1 + \omega x^{\omega})(1 + x^{\omega})}$$

where $x = \frac{E_{T0}}{P}$, ε_P is the elasticity coefficient of green water to precipitation, representing the change in watershed green water amount caused by unit precipitation change; ε_{ET0} is the elasticity coefficient of green water to potential evapotranspiration, representing the change in watershed green water amount caused by unit potential evapotranspiration change; and ε_ω is the elasticity coefficient of green water to underlying surface parameters, representing the change in watershed green water amount caused by unit underlying surface parameter change.

(4) Attribution Analysis

The study period was divided into two stages before and after the mutation point. The change in multi-year average green water amount between the two periods is denoted as Δg, which is caused by climate change (precipitation, potential evapotranspiration) and land use change. Therefore, Δg can be decomposed as:

$$\Delta g = \Delta g_P + \Delta g_{ET0} + \Delta g_\omega$$

where Δg_P is the green water amount change caused by precipitation change, Δg_{ET0} is the green water amount change caused by potential evapotranspiration change, and Δg_ω is the green water amount change caused by underlying surface parameter change.

The calculation formulas are:

$$\Delta g_P = \varepsilon_P \cdot \frac{\Delta P}{P} \cdot g$$

$$\Delta g_{ET0} = \varepsilon_{ET0} \cdot \frac{\Delta E_{T0}}{E_{T0}} \cdot g$$

$$\Delta g_\omega = \varepsilon_\omega \cdot \frac{\Delta \omega}{\omega} \cdot g$$

where ΔP, ΔE_{T0}, and $\Delta\omega$ are the differences in multi-year average precipitation, potential evapotranspiration, and underlying surface parameters before and after the mutation point, respectively.

The contribution rates of precipitation, potential evapotranspiration, and underlying surface parameters to green water change are calculated as:

$$\eta_P = \frac{\Delta g_P}{\Delta g} \times 100\%$$

$$\eta_{ET0} = \frac{\Delta g_{ET0}}{\Delta g} \times 100\%$$

$$\eta_\omega = \frac{\Delta g_\omega}{\Delta g} \times 100\%$$

where η_P, η_{ET0}, and η_ω are the contribution rates of precipitation, potential evapotranspiration, and underlying surface parameters to green water, respectively.

3 Results and Analysis

3.1 Watershed Climate Characteristics Analysis

Table 1 shows the basic hydroclimatic characteristic values of the Yanwachuan Basin. Precipitation showed an increasing trend after 2000. With 1996 as the dividing point, potential evapotranspiration showed a trend of first increasing and then decreasing. Precipitation decreased from 1981 to 1996, while potential evapotranspiration increased to its peak in 1996 and then continued to decrease. Throughout the study period, temperature showed a continuous increasing trend, consistent with the global warming background. The drought index reached its maximum in 1996 with a value of 1.15, and decreased after 1996.

From the perspective of interannual variation trends (Fig. 2), precipitation and potential evapotranspiration in the basin showed a weak increasing trend, while temperature showed a significant increasing trend, with an obvious valley value in 1993 and a peak in 1996. Precipitation was mainly negative anomaly before 1996 and positive anomaly after 1996. Temperature was in a cold period before 1996 and a warm period after 1996, with a clear boundary. The cumulative anomaly of potential evapotranspiration continued to decrease before 1996 and showed an upward trend after 1996, while the cumulative anomaly of precipitation showed a decreasing trend after 1996.

3.2 Land Use Change Characteristics

Statistics on the area and proportion of various land use types in the Yanwachuan Basin in different periods (Fig. 4) show that the land use types in the basin are mainly cultivated land and grassland, with cultivated land accounting for the largest proportion (always above 50.0%), followed by grassland (about 35.0%). Water area is relatively small, accounting for only 0.13%, indicating that the river system in the basin is not well-developed.

The land use change area proportion and intensity index in different periods show the degree of increase or loss of each land use type (Figs. 5 and 6). The land use change area proportion was largest from 1995 to 2005, indicating that land use change was most intense during this period. Forest land increased the most, while grassland lost the most, which is related to the implementation of the Grain for Green Project and the Yellow River water and soil conservation ecological project during this period. The land use change area proportion was smallest from 2005 to 2015, indicating that land use was relatively stable during this period with relatively small change proportions.

Forest land area accelerated in growth during 1995–2005 and 2005–2015, with change rates of 8.38% and 4.51%, respectively. Grassland and residential land showed a decreasing trend after 1995, with the fastest reduction rates from 1995 to 2005, reaching -8.01% and -4.85%, respectively. Water area continued to decrease throughout the study period (1985-2015) with a change rate of -0.03%. Cultivated land area decreased from 1985 to 1995 and increased from 1995 to 2015, with change rates of -1.32% and -2.06%, respectively.

3.3 Simulation of Watershed Green Water Using the Fu Baopu Model

During the calibration period, the parameter ω in the model was optimized based on the basin’ s multi-year average precipitation, runoff, and potential evapotranspiration data. The relationship between ω values and relative error (R_e) and root mean square error (RMSE) is shown in Fig. 7. When ω deviated from 2.6, both the absolute values of R_e and RMSE increased. Therefore, the optimal ω value for the basin was determined to be 2.6.

The simulation accuracy of the Fu Baopu model for green water resources in the Yanwachuan Basin using the optimal parameter value is shown in Table 2. The absolute value of R_e was smallest during the calibration period. Although simulation accuracy decreased during the validation period, both R_e and RMSE remained within acceptable ranges. Fig. 8 shows the simulation results for the calibration and validation periods. The comparison between green water resources obtained by the water balance method and the Fu Baopu model shows good agreement, indicating that the model can accurately reflect the dynamic changes in watershed green water resources after parameter optimization.

3.4 Green Water Variation Trend and Mutation Point Test in the Watershed

The green water amount variation curve for the Yanwachuan Basin from 1981 to 2016 (Fig. 9) shows that the multi-year average green water amount is 503.7 mm, with an interannual variation range of 288.1-746.1 mm, indicating significant interannual variation. From the trend perspective, annual green water amount increased slightly at a rate of 0.669 $\mathrm{mm} \cdot \mathrm{a}^{-1}$.

According to the cumulative anomaly analysis results of annual green water amount in the Yanwachuan Basin from 1981 to 2016 (Fig. 10), green water amount showed a fluctuating decreasing trend before 2003 and a fluctuating increasing trend after 2003. The M-K test was used to identify mutation points in annual green water resources (Fig. 11). The results show that the UF curve exceeded the critical line, passing the significance test. The two curves had multiple intersection points within the confidence interval, indicating multiple potential mutation points for green water. To further determine the mutation year, the F-test curve was used to verify these possible mutation years (Fig. 12). The results show that the mutation point occurred in 2003, which matches one of the mutation test years identified by the M-K test. These results indicate that the green water amount in the Yanwachuan Basin mutated in 2003, mainly due to intensified soil and water conservation measures in the basin since 2003 under the support of the Yellow River Water and Soil Conservation Ecological Project.

3.5 Climate and Underlying Surface Elasticity Coefficients of Green Water

To further analyze the sensitivity of green water resources in the Yanwachuan Basin to climate change and underlying surface changes, the elasticity coefficient method was used to calculate the sensitivity of each influencing factor. The entire period was divided into two stages: before the mutation point (1981-2003) was defined as the base period, and after the mutation point (2004-2016) was defined as the change period. The elasticity coefficients of green water to climate factors and underlying surface parameters were calculated for these two periods (Table 3).

The elasticity coefficients of green water to climate factors and underlying surface parameters before and after the mutation point show that the elasticity coefficients to precipitation and potential evapotranspiration were 0.93 and 0.07, respectively, while the elasticity coefficient to underlying surface parameters was 0.18. From the perspective of the two periods before and after the mutation point, the elasticity coefficient to precipitation increased from 0.92 before mutation to 0.95 after mutation, indicating that green water change caused by precipitation increased in intensity. The elasticity coefficient to potential evapotranspiration decreased from 0.08 before mutation to 0.05 after mutation, indicating that green water change caused by potential evapotranspiration decreased in intensity. The elasticity coefficient to underlying surface parameters decreased from 0.19 before mutation to 0.16 after mutation, indicating that the impact of underlying surface parameter changes on green water variation weakened. Overall, from 1981 to 2016, green water in the Yanwachuan Basin became more sensitive to precipitation, maintained unchanged sensitivity to potential evapotranspiration, and became less sensitive to underlying surface parameters.

3.6 Attribution Analysis of Green Water Changes

Table 4 presents the attribution analysis results of green water changes. From the base period to the change period, the average annual green water amount increased by 52.07 mm. Climate change increased green water amount by 38.75 mm, with a contribution rate of 74.42% to green water change. Among climate elements, precipitation contributed 75.63% to green water increase (increasing green water by 39.38 mm), while potential evapotranspiration contributed -1.21% (decreasing green water by 0.63 mm). Compared with climate elements, land use change increased green water amount by 13.32 mm, with a contribution rate of 25.58% to green water change.

In the driving factors of green water change, climate change is the main influencing factor. Green water is more sensitive to precipitation than to potential evapotranspiration because green water mainly originates from rainfall. The greater the rainfall, the more sufficient the evapotranspiration water in the watershed, and the larger the green water amount. At the same time, land use change also causes green water resources to change. In this study, due to the implementation of the Grain for Green Project, forest land area increased while cultivated land area decreased. The increase in cultivated land area would increase agricultural irrigation water use, increase soil water content and crop evapotranspiration, and convert more blue water into green water, leading to increased green water.

4 Discussion

Climate change and land use change are two key factors affecting watershed hydrological processes. Quantifying their relative contributions to green water resources can provide a scientific basis for the application and management of watershed green water resources under future climate and land use changes. Against the background of global warming and land use change, this study provides new ideas for solving water shortage problems in the gully region of the Loess Plateau. It analyzes the variation characteristics of green water resources and quantitatively examines the impact of climate factors and land use factors on green water resources and their contribution to green water changes. The research results can provide scientific guidance for grain production and vegetation restoration in the gully region of the Loess Plateau, and offer new solutions for water resource shortage problems in the Loess Plateau region.

From 1981 to 2016, green water resources in the Yanwachuan Basin showed a weak upward trend. Climate change increased green water amount by 38.75 mm from the base period to the change period, with a contribution rate of 74.42%. Precipitation increased green water by 39.38 mm, with a contribution rate of 75.63%, while potential evapotranspiration decreased green water by 0.63 mm, with a contribution rate of -1.21%. These results are consistent with findings from Feng et al. in the Lianshui River Basin using the SWAT model. This outcome is mainly caused by climate change factors such as increased precipitation. Since green water mainly originates from rainfall, greater rainfall leads to more sufficient watershed evapotranspiration and larger green water amounts.

In this study, land use change increased green water amount by 13.32 mm, with a contribution rate of 25.58%. This conclusion is consistent with research results from Zhao et al. in the Weihe River Basin and Lian et al. in the upper Yiluo River Basin. However, Rong et al. found that land use change caused a decreasing trend in green water resource changes in the Xixi watershed of the Jinjiang Basin. The main reason for this difference is the reduction of forest land, cultivated land, and grassland area in that study area. The Grain for Green Project changed the proportions of cultivated land, forest land, and grassland in the total area, converting cultivated land to grassland and forest land, reducing slope runoff, and increasing soil water content, thereby increasing green water amount.

5 Conclusions

This study takes the Yanwachuan Basin as the research area and conducts attribution analysis of green water changes in the watershed from 1981 to 2016 based on the water-heat coupling balance equation. The following conclusions are drawn:

1) From 1981 to 2016, precipitation, temperature, and potential evapotranspiration in the Yanwachuan Basin showed increasing trends, with abrupt changes occurring around 1996. Land use change was most significant in 1995–2005, with forest land increasing the most and grassland losing the most.

2) Over the past 36 years, the multi-year average green water amount in the Yanwachuan Basin was 503.7 mm, showing an upward trend with a mutation occurring in 2003.

3) Among climate elements, the elasticity coefficients of green water to precipitation and potential evapotranspiration were 0.93 and 0.07, respectively. The elasticity coefficient to underlying surface parameters was 0.18. Green water is most sensitive to precipitation, followed by underlying surface parameters, and least sensitive to potential evapotranspiration.

4) Under the combined effects of climate change and land use change, green water resources increased by 52.07 mm. Climate change increased green water amount by 38.75 mm, with a contribution rate of 74.42%. Land use change increased green water amount by 13.32 mm, with a contribution rate of 25.58%. Climate change is the dominant factor in green water change.

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