Blue-Green Water Variation Trends and Predictions in the Jing River Basin under Climate Change: Postprint

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Date: 2024-12-16T00:00:00+00:00

Abstract

Based on observed meteorological station data, hydrological station runoff data, and CMIP6 future climate models for the Jing River basin from 1980–2020, this study processed CMIP6 climate data using the Delta downscaling method and coupled it with the SWAT (Soil and Water Assessment Tool) hydrological model to investigate the variation characteristics of blue and green water under climate change within the basin. The results indicate that: under the SSP1-2.6 pathway, both blue and green water quantities in the study area exhibit non-significant increasing trends; under the SSP3-7.0 pathway, blue water shows a non-significant decreasing trend while green water shows a significant increasing trend; under the SSP5-8.5 pathway, blue water shows a non-significant decreasing trend and green water shows a non-significant increasing trend. The multi-year average blue water under all three pathways decreased compared to the historical period, with mean annual blue water values of 128.8 mm, 117.2 mm, and 126 mm, respectively, whereas the multi-year average green water increased, with values of 372.7 mm, 369.3 mm, and 372.1 mm, respectively, and the green water coefficient was greater than that in the historical period for all pathways. The spatial distribution characteristics of both blue and green water increase from northwest to southeast, and the spatial distribution patterns among the various pathways are essentially identical.

Full Text

Abstract

Based on meteorological station data from 1980-2020, measured hydrological runoff data, and future climate models from CMIP6 in the Jinghe River Basin, this study processed climate data through CMIP6 downscaling methods and coupled them with the Soil and Water Assessment Tool (SWAT) hydrological model to investigate variations in blue-green water resources under climate change. The results indicate that under the SSP1-2.6 pathway, both blue and green water volumes in the study area show non-significant increasing trends. Under the SSP3-7.0 pathway, blue water exhibits a non-significant decreasing trend while green water shows a significant increasing trend. Under the SSP5-8.5 pathway, blue water displays a non-significant decreasing trend and green water shows a non-significant increasing trend. The multi-year average blue water volume under all three pathways decreased compared to the historical period, with values of 128.8 mm, 117.2 mm, and 126 mm, respectively. Conversely, the multi-year average green water volume increased in all cases, reaching 372.7 mm, 369.3 mm, and 372.1 mm, respectively, with green water coefficients exceeding those of the historical period. The spatial distribution of blue-green water increases progressively from northwest to southeast, with essentially identical spatial distribution patterns across all pathways.

Keywords: SWAT model; Delta downscaling; climate change; CMIP6 climate model; blue-green water; Jinghe River Basin

Introduction

With socio-economic development, water resources are becoming a critical strategic resource for nations. Under the dual pressures of natural and economic conditions, water scarcity and uneven spatial distribution are increasingly severe issues. Within China's strictest water resource management system, effective allocation and utilization of water resources have become prominent topics in water resource management. Falkenmark and Rockström pioneered the concepts of blue and green water, incorporating them into water resource management considerations and opening new research frontiers. Both blue and green water constitute important components of water resources. Blue water refers to water stored in lakes, rivers, runoff, and underground aquifers that can be directly utilized by humans, while green water originates from rainfall, is stored in soil, and is consumed through vegetation transpiration. These water types play distinct roles in maintaining ecological environments and socio-economic development, with marked differences in opportunity costs, physical mechanisms, and social effects, each demonstrating unique value.

Using blue-green water concepts for quantitative water resource assessment can improve local and regional water resource management. Over the past decades, scholars have conducted in-depth research on blue-green water resources, primarily focusing on analyzing spatiotemporal distribution characteristics and establishing multiple scenarios to quantitatively assess responses to land use and climate change. However, studies predicting future blue-green water remain limited. Therefore, this research employs the Climate Model Intercomparison Project (CMIP6) to forecast future climate and blue-green water variation characteristics. CMIP6, initiated by the World Climate Research Programme (WCRP), represents the largest international coupled model intercomparison project with the most models and simulation data. Based on latest anthropogenic emission trends and different Shared Socioeconomic Pathways (SSPs), CMIP6 provides new projection data that can predict pre-2055 climate changes. Climate models are crucial tools for studying future climate change, but their low resolution limits regional climate simulation effectiveness. Therefore, low-resolution climate model data must be converted to high-resolution regional climate or station data.

1. Study Area and Data Sources

1.1 Study Area Overview

The Jinghe River, a second-order tributary of the Yellow River, originates from the Liupan Mountains in Ningxia and flows through 45 counties and cities in Ningxia, Gansu, and Shaanxi provinces before joining the Wei River in Gaoling County, Shaanxi. The river stretches 450 km with a drainage area of 45,421 km^2. The basin features sparse vegetation, frequent human activity, and severe soil erosion, representing one of the most serious soil loss regions on the Loess Plateau and a primary source of Yellow River sediment. As the largest tributary of the Wei River, the Jinghe's runoff serves as a precious water source for vast areas along its course in this arid and semi-arid region of northwest China. Studying blue-green water in the Jinghe River Basin enhances understanding of runoff evolution patterns and regional hydro-ecological functional succession trends, which is essential for maintaining ecological balance, socio-economic development, and water resource allocation.

The Zhangjiashan Hydrological Station, located at Yuejiapo Village, Wangqiao Town, Jingyang County, Shaanxi, is a first-class precision hydrological station monitoring water level, discharge, sediment concentration, water temperature, precipitation, evaporation, and water quality. This study utilized the station's measured daily runoff data from 1980-2020 for model calibration and validation.

1.2 Data Sources

Elevation data (DEM) was obtained from the Geographic Spatial Data Cloud with 90m resolution. Land use data came from the Chinese Academy of Sciences Resource and Environment Data Center, primarily covering 2020 with 30m resolution. Soil data originated from the World Soil Database (Harmonized World Soil Database) with 1km resolution. Meteorological data comprised daily data from 1980-2020 for 11 meteorological stations within and around the basin, sourced from the China Meteorological Data Network. Hydrological data consisted of daily measured runoff data from 1980-2020 at the Zhangjiashan Hydrological Station, obtained from the Yellow River Conservancy Commission. Future climate data were selected from CMIP6 daily data, with the NorESM2-MM model chosen for its applicability, using 1980-2014 as the historical baseline period and 2025-2055 as the future period. Data sources are summarized in .

2. Methods

2.1 Blue-Green Water Calculation Method

The Soil and Water Assessment Tool (SWAT), developed by the United States Department of Agriculture (USDA), is a distributed watershed hydrological model widely applied in runoff simulation, non-point source pollution control, and analysis of climate and underlying surface change impacts. Based on blue-green water concepts and SWAT model results, this study calculated blue water as the sum of water yield (WYLD) and deep aquifer recharge (DA_{RCHG}) in each sub-basin, while green water was represented by the sum of actual evapotranspiration (ET) and soil water content (SW). The Green Water Coefficient (GWC) represents the proportion of green water resources to total water resources in a given basin. The calculation formulas are as follows:

$$B = WYLD + DA\_RCHG$$
$$G = ET + SW$$
$$GWC = \frac{G}{B+G} \times 100\%$$

where G is green water resources (mm), including green water flow and storage; B is blue water resources (mm); and GWC is the green water coefficient.

2.2 Delta Downscaling Method

The Delta downscaling method, recommended by the U.S. National Assessment Center (http://www.nacc.usgcrp.gov/), is a statistical downscaling approach for generating future climate scenarios. For precipitation, the method calculates the ratio between historical station-measured monthly precipitation and CMIP6-simulated historical precipitation, then multiplies this ratio by CMIP6-predicted future precipitation:

$$P_{fu} = \frac{P_{obs}}{PG_{obs}} \times PG_{fu}$$

where P_{fu} is the downscaled future precipitation (mm), P_{obs} is historical observed precipitation (mm), PG_{obs} is CMIP6-simulated historical precipitation (mm), and PG_{fu} is CMIP6-predicted future precipitation (mm).

For temperature, the method calculates the difference between observed and CMIP6-simulated historical monthly mean maximum/minimum temperatures, then adds this difference to CMIP6-predicted future temperatures:

$$T_{fu} = T_{obs} - TG_{obs} + TG_{fu}$$

where T_{fu} is the downscaled future temperature (°C), T_{obs} is historical observed temperature (°C), TG_{obs} is CMIP6-simulated historical temperature (°C), and TG_{fu} is CMIP6-predicted future temperature (°C).

3. Results

3.1 Model Applicability Analysis

To evaluate the CMIP6 model's simulation capability for precipitation and temperature in the Jinghe River Basin, this study compared station-measured monthly mean precipitation, maximum temperature, and minimum temperature with CMIP6 historical data from 1980-2014. The evaluation used correlation coefficient (R^2) and root mean square error (RMSE) to assess model applicability. shows that temperature simulation performed better than precipitation simulation, with temperature R^2 values of 0.98 and precipitation R^2 of 0.85. Precipitation RMSE was 3.3 mm, while temperature RMSE values were 2.92°C and 1.78°C, respectively, meeting basic requirements. These results indicate good model applicability for predicting future precipitation and temperature changes in the basin.

Spatial analysis of meteorological factors using inverse distance weighting revealed relatively non-significant spatial differences. [Figure 3: see original paper] shows that historical annual average precipitation, maximum temperature, and minimum temperature in the Jinghe River Basin generally increased from north to south. High precipitation values appeared in the western basin, with low values in the north. High maximum temperatures occurred in the southeast, while low values appeared in the west. Minimum temperature patterns were similar, with high values in the southwest and low values in the west.

3.2 Historical Climate Change Characteristics

Climate change significantly influences blue-green water variations in the basin. Analyzing precipitation and annual mean maximum/minimum temperatures from 1980-2020 helps understand these trends. Using Thiessen polygons to calculate area-weighted regional meteorological elements, [Figure 2: see original paper] shows that basin annual precipitation remained stable with an overall fluctuating upward trend, reaching a historical maximum of 719.9 mm in 2019. Annual maximum temperatures ranged 13-18°C, averaging 15.5°C, while annual minimum temperatures ranged 3.3-17.2°C, averaging 4.5°C. Both temperature metrics showed steady upward trends.

Mann-Kendall trend tests revealed that precipitation exhibited a significant upward trend (passing the 0.05 significance test), while annual maximum and minimum temperatures showed non-significant upward trends.

3.3 SWAT Model and Historical Blue-Green Water Simulation

3.3.1 Watershed Parameter Sensitivity Analysis This study selected 25 parameters sensitive to blue-green water research in the Jinghe River Basin. Sensitivity analysis identified the most critical parameters: V_ESCO (soil evaporation compensation coefficient), V_CN2 (runoff curve number), V_CH_K2 (effective hydraulic conductivity of main channel bed), V_ALPHA_BNK (baseflow alpha factor for bank storage), and V_GW_DELAY (groundwater delay coefficient). The SUFI-2 program calibrated the model with 500 simulations and 5 iterations. Optimal parameter values are listed in .

3.3.2 Model Calibration and Validation Using measured monthly runoff data from Zhangjiashan Hydrological Station, the SWAT model was calibrated (1990-2000) and validated (2001-2010) at a daily time step with a 3-year warm-up period. Calibration results showed correlation coefficient $R^2 = 0.85$, Nash-Sutcliffe efficiency $NSE = 0.84$, and relative error $RE = 0.65\%$. Validation yielded $R^2 = 0.82$, $NSE = 0.81$, and $RE = 1.2\%$. These results meet established criteria, confirming good model applicability for blue-green water research in the basin.

3.3.3 Historical Blue-Green Water Change Analysis SWAT model simulations revealed that annual blue water in the Jinghe River Basin ranged 86.1-234.9 mm, averaging 152.5 mm, while green water ranged 331.2-390.7 mm, averaging 364.8 mm. Both showed significant increasing trends (passing the 0.05 significance test). Green water was approximately 2.4 times more abundant than blue water. Maximum annual blue water (234.9 mm) occurred in 2019, and maximum green water (390.7 mm) occurred in 2003.

Blue water formation correlated directly with precipitation (Pearson correlation coefficient = 0.85), while correlations with temperature were weaker. Green water showed positive correlations with both precipitation (r = 0.72) and temperature, indicating that increased temperature or precipitation enhances evapotranspiration.

Spatial distribution of multi-year average blue-green water showed significant differences, with both increasing from northwest to southeast [Figure 6: see original paper]. High blue water values appeared in central and southern regions, while high green water values occurred in eastern and southern areas. Low values for both were concentrated in northwestern and central regions, correlating with precipitation and temperature distribution patterns.

3.4 Future Climate Change Characteristics

Under future climate scenarios [Figure 7: see original paper], multi-year average precipitation in the SSP1-2.6 pathway increased compared to the historical period, while SSP3-7.0 and SSP5-8.5 pathways showed slight decreases. Multi-year average maximum temperature decreased under SSP1-2.6 but increased under SSP3-7.0 and SSP5-8.5, rising with pathway concentration. Multi-year average minimum temperatures increased across all pathways (by 11.1%, 16.3%, and 21.2%, respectively), with SSP5-8.5 showing the highest values. Overall, mean temperatures increased with emission concentration, except for SSP1-2.6.

Mann-Kendall tests indicated that under SSP3-7.0, precipitation showed a non-significant decreasing trend while other climate factors showed non-significant increasing trends, suggesting relatively stable future climate conditions with limited fluctuations. Spatial distribution patterns remained similar to historical conditions, with all factors increasing from north to south.

3.5 Future Blue-Green Water Change Characteristics

Linear regression and Mann-Kendall test results show that under SSP1-2.6, both blue and green water exhibit non-significant upward trends. Under SSP3-7.0, blue water shows a non-significant downward trend while green water shows a significant upward trend. Under SSP5-8.5, both blue and green water display non-significant upward trends. Overall blue-green water resources decreased compared to the historical period, indicating intensified water scarcity and declining river runoff.

Multi-year average blue water decreased under all three pathways (128.8 mm, 117.2 mm, and 126 mm), representing reductions of 23.7 mm, 35.3 mm, and 26.5 mm, respectively. Multi-year average green water increased (372.7 mm, 369.3 mm, and 372.1 mm), representing increases of 7.9 mm, 4.5 mm, and 7.3 mm, respectively. Consequently, the green water coefficient will increase, indicating green water's growing importance in the basin.

Spatial distribution characteristics under future climate models [Figure 8: see original paper] remained largely unchanged from historical patterns, increasing from northwest to southeast with distributions similar to precipitation. Blue water extremes appeared in central and southern regions, while green water highs occurred in southern and east-central areas. Southeastern green water decreased relative to historical conditions, with low-value zones shifting from northwestern margins toward the center and high-value areas shrinking. Northwestern blue water low-value ranges expanded.

4. Discussion

This study reveals that blue-green water changes in the Jinghe River Basin closely correlate with future precipitation and temperature trends. Blue water is primarily precipitation-driven, following similar trends, while green water, dominated by plant evapotranspiration, is mainly temperature-driven. Rising temperatures across all pathways increase green water, suggesting future warming may intensify drought conditions, reduce runoff, and convert more precipitation to green water through evapotranspiration.

These findings align with previous research, though some differences exist, likely because blue-green water is influenced not only by climate but also by human activities and land surface condition changes. This study did not fully account for factors such as returning farmland to forest, agricultural irrigation, or national land policies. Future research should incorporate these land use changes. Additionally, results may be affected by SWAT model limitations in the Jinghe Basin and Delta downscaling effectiveness. This study used only one CMIP6 model and one downscaling method; future work should employ multiple models and methods for comprehensive analysis.

Green water resources are crucial for agricultural irrigation, and the green water coefficient indicates green water's proportion of total water resources. Results show that under future climate models, the Jinghe Basin will have limited blue water but abundant green water, with green water volumes consistently exceeding blue water and the green water coefficient rising. This underscores green water's increasing importance. However, green water's development potential remains underutilized. Water resource management in the Jinghe Basin should shift perspectives to rationally develop both blue and green water resources and achieve supply-demand balance.

5. Conclusions

Based on the established SWAT distributed hydrological model and CMIP6 dataset, this study analyzed blue-green water variation characteristics in the Jinghe River Basin under SSP1-2.6, SSP3-7.0, and SSP5-8.5 pathways, yielding the following conclusions:

1. **Historical Climate (1980-2020):** Basin precipitation ranged 338-719 mm, showing a significant upward trend. Annual minimum temperatures ranged 3.3-17.2°C and maximum temperatures 13-18°C, both showing non-significant upward trends. Spatially, precipitation and temperatures increased from north to south.

2. **Historical Blue-Green Water (1980-2020):** Blue water ranged 86.1-234.9 mm (average 152.5 mm) and green water 331.2-390.7 mm (average 364.8 mm), both showing significant increasing trends. Blue water correlated strongly with precipitation ($r = 0.85$), while green water correlated positively with both precipitation and temperature. Spatially, both increased from northwest to southeast.

3. **Future Climate (2025-2055):** Climate factors remained relatively stable. Under SSP3-7.0, precipitation showed a non-significant decreasing trend while other factors showed non-significant increasing trends. Spatial distribution patterns remained similar to historical conditions, increasing from north to south.

4. **Future Blue-Green Water (2025-2055):** Under SSP1-2.6, both blue and green water showed non-significant upward trends. Under SSP3-7.0, blue water decreased non-significantly while green water increased sig-

nificantly. Under SSP5-8.5, both showed non-significant upward trends. Multi-year average blue water decreased across all pathways while green water increased, with spatial distribution patterns remaining essentially unchanged from historical conditions.

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