Spatial and temporal variability of blue/green water flows in typical meteorological years in an inland river basin in China

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ABSTRACT

Blue/green water closely links the water cycle and ecological processes. On the watershed scale, how blue/green water flows vary among different typical meteorological years (dry years, wet years, and normal years) remains poorly reported. To analyze the spatial and temporal variability of blue/green water in typical years in the Heihe River Basin, typical meteorological years were obtained by using the standardized precipitation index (SPI) and the precipitation anomaly index (H) and simulated blue/green water flows using the Soil and Water Assessment Tool (SWAT). The typical meteorological years are often not consistent from upstream to downstream in the Heihe River Basin, except in 1978 and 1998. Furthermore, the blue/green water quantities in wet years (1998, 27.93 billion m$^3$) are higher than in dry years (1978, 16.80 billion m$^3$). The green water coefficient (GWC) is more than 87.5% in the entire river basin. There was a negative correlation between the GWC and the degree of dry and wet in the typical meteorological years, as the drier the climate, the higher the GWC. This study provided an understanding of green/blue flows in different reference years to inland river green and blue water resource management.

Key words | blue/green water, green water coefficient, Heihe River Basin, SWAT model, typical meteorological years

INTRODUCTION

The influence of climate change on water resource availability has attracted more and more attention around the world (Vörösmarty et al. 2000; Liu et al. 2013a; Evaristo et al. 2015). In recent years, extreme weather events have occurred more frequently due to global warming, resulting in decreases in the water available in many regions in the world and posing serious challenges to the water supply (Vörösmarty et al. 2000, 2010; Alley et al. 2005; Liu et al. 2013b). Particularly in arid and semi-arid regions, competition for available water has been intense due to the relationship between socioeconomic sustainability and ecosystem health; this had led to water crises and ecosystem degradation (Falkenmark & Rockström 2006; Palmer et al. 2015; Sánchez et al. 2015). Therefore, a comprehensive assessment and management of water resources in the context of climate change is a key to understanding the available water endowments and enhancing water management towards sustainable, efficient, and equitable use of scarce fresh water resources. Furthermore, climate change has been a main influencing factor on river basin water resources; there has existed interaction between climate change and water resources (Alley et al. 2005). Water vapor cycling is a major part of the weather system; climate change also influences the spatial and temporal variability of water resources in a watershed (Vörösmarty et al. 2010; Evaristo et al. 2015). The changes of climate factors cause a water shortage or crisis in arid and semi-arid regions (Xiao & Xiao 2004), especially in typical meteorological years.
(dry, normal, and wet). In typical meteorological years, the green water coefficient (GWC), which is defined as the ratio of green water (water stored in unsaturated soils and used as evapotranspiration by plants) to the total water resources, will have significant variability, changing the availability of water and hydrological processes (Zang & Liu 2013). Therefore, assessments of the impacts of climate change on water resources are especially needed to help understand blue and green water variability and sustainable water use in arid and semi-arid regions.

Traditionally, water resource assessment and management by scientists and policymakers has paid more attention to blue water, while ignoring green water (Falkenmark 1995; Cheng & Zhao 2006; Liu & Yang 2010). The concepts of blue and green water were first proposed by Falkenmark (1995), but in the early years, they were not used to distinguish water resources and flows. Falkenmark & Rockström (2006) redefined the concepts of green and blue water in 2006 to explicitly distinguish water resources and flows. Green water plays a critical role in the crop land system and ecosystem (Cheng & Zhao 2006; Falkenmark & Rockström 2006). Liu et al. (2009), Liu & Yang (2010), and Rost et al. (2008) showed that more than 80% of global crop production was supported by green water. Furthermore, water use in grassland and forest ecosystems is predominantly from green water (Rockström 1999; Rost et al. 2008).

In this study, the Heihe River Basin was selected as the study area (Figure 1). The Heihe River, located in northwestern China, is the second-largest inland river in China. The basin is located in a typical arid region that suffers from a serious shortage of water. In recent years, there have been studies of the temperature, precipitation (Li & Xu 2011), influence of human activity analysis (Zang et al. 2015), potential and actual evapotranspiration trends in this basin (Wang 2011; Zang & Liu 2015), and water footprint analysis (Zeng et al. 2012), but no study has analyzed the flows of green and blue water in typical

![Figure 1](https://iwaponline.com/jwcc/article-pdf/8/1/165/373264/jwc0080165.pdf)

Figure 1 | Location of Heihe River Basin and distribution of hydrology stations within the basin.
meteorological years. Therefore, a detailed and integrated analysis of the water resources in typical meteorological years was urgently needed to support water management for the basin. In our research, hydrological variables in typical years since 1960 were investigated in the context of climate change. To make the article and the results clearer, the influence of human activity was not considered in this paper. Specifically, the objectives of the paper include: (1) to analyze the blue and green water depth on the spatial and temporal scales in typical meteorological years; and (2) to quantify the blue and green water in the up-, mid-, and downstream regions and the entire river basin and the spatial distribution of the GWC in typical meteorological years. Furthermore, the relationship between the GWC and the drought index was discussed.

METHODOLOGY

The study area

The Heihe River originates in the Qilian Mountains and ends in Juyanhai Lake. The total basin area is approximately 0.24 million km², with the majority located in the northwest of China and a minor part in Mongolia (Figure 1). The Heihe River can be divided into three sections: upstream, midstream, and downstream. The upstream section runs from the Qilian Mountain to the Yingluo Canyon (Figure 1), the midstream section from the Yingluo Canyon to Zhengyi Canyon (Figure 1), and the downstream section terminates in Juyanhai Lake (Figure 1). The average annual air temperature is 2–3 °C in the upstream area, 6–8 °C in the midstream area, and 8–10 °C in the downstream area. The average annual precipitation is between 200 and 500 mm in the upstream area, between 120 and 200 mm in the midstream area, and below 50 mm in most of the downstream area (Cheng 2003). The potential evaporation ranges from 1,000 mm/year in the upstream region to 4,000 mm/year in the downstream region (Ma et al. 2011). The precipitation in the Heihe River Basin occurs mainly in the summer and autumn (>70% of the annual precipitation falls between May and August) (Ma et al. 2011), whereas the spring is dry with snow and ice melting (4% of total discharge) (Li & Xu 2011).

Definition of the typical meteorological year

In this study, the typical meteorological year is a typical wet, dry, and normal year. Drought and flood grades were used to define the typical meteorological year.

The standardized precipitation index (SPI) and precipitation anomaly index (H) indicators were used simultaneously to determine the typical dry, wet, and normal year to avoid the error of a single index calculation in this study.

Standardized precipitation index (SPI)

The standardized precipitation index is an index that characterizes the probability of precipitation occurring in a certain period of time. The index was developed by McKee et al. (1995) to assess drought grades of Colorado. The index has multiple time scales for application, with the same drought indexes reflecting different time scales and different water resource conditions, enabling it to be widely used. As the precipitation variation was significant over different times and in different regions, it was difficult to directly compare precipitation over different time and space scales, and the distribution of precipitation was a skewed distribution, not a normal distribution. Therefore, in the analysis of the precipitation, the distribution probability function was used to describe the change in precipitation, and then a normal standard SPI value can be obtained (McKee et al. 1995; Fu & Jin 2012).

\[
f(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \quad (x > 0) \tag{1}
\]

\[
\Gamma(\alpha) = \int_0^{\infty} x^{\alpha-1} e^{-x} dx \tag{2}
\]

In the formula, \( \alpha \) is the shape parameter, \( \beta \) is the scale parameter, \( x \) is the precipitation, and \( \Gamma(\alpha) \) is the gamma function. The best estimates for \( A \) and \( \beta \) can be obtained by using the maximum likelihood estimation method.

\[
\hat{\alpha} = \frac{1 + \sqrt{1 + 4A/3}}{4A} \tag{3}
\]
\[ \hat{\beta} = \frac{\bar{x}}{\alpha} \]  \hspace{1cm} (4)

\[ A = \ln (\bar{x}) - \frac{\sum_{i=1}^{n} (x_i)}{n} \]  \hspace{1cm} (5)

In the formula, \( n \) is used for calculating the length of the sequence. The cumulative probability of a given time scale can therefore be obtained as follows:

\[ g(x) = \int_{0}^{x} f(x)dx = \frac{1}{\hat{\beta}^\alpha \Gamma(\alpha)} \int_{0}^{x} x^{\alpha-1} e^{-x/\hat{\beta}}dx \]  \hspace{1cm} (6)

If \( t = x/\hat{\beta} \), the type for the incomplete gamma equation can be obtained from Equation (6):

\[ g(x) = \frac{1}{\Gamma(\alpha)} \int_{0}^{t} t^{\alpha-1} e^{-t}dt \]  \hspace{1cm} (7)

Because the gamma equation does not exist when \( x \) is 0, but the precipitation in reality can be 0, the cumulative probability can be expressed as follows:

\[ H(x) = q + (1-q)g(x) \]  \hspace{1cm} (8)

In the formula, \( q \) is the probability when the precipitation equals 0. If \( m \) is the number of rainfall time series with a precipitation of 0, then \( q = m/n \). The cumulative probability of \( H(x) \) can be determined through the type conversion as a standard normal distribution function.

When \( 0 < H(x) \leq 0.5 \), the formula is as follows:

\[ SPI = -\left( t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right) \]  \hspace{1cm} (9)

\[ t = \sqrt{\ln \frac{1}{H^2(x)}} \]  \hspace{1cm} (10)

when \( 0.5 < H(x) < 1 \), the formula is as follows:

\[ SPI = \left( t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right) \]  \hspace{1cm} (11)

The parameter values are as follows: \( c_0 = 2.515517; c_1 = 0.802853; c_2 = 0.010328; d_1 = 1.432788; d_2 = 0.189269; d_3 = 0.001308 \). The SPI can be obtained according to the above formula, and the drought and flood level values are shown in Table 1 (McKee et al. 1995).

### Precipitation anomaly index

The precipitation anomaly percentage reflects the average state of the deviation degree over a certain period of time (Ju & Yang 1998), as different areas in different periods have different average rainfalls. Therefore, it is a relative indicator of the comparative variation over time and space. In meteorology, people often use the precipitation anomaly percentage as a classified index of drought and flood on a daily basis. It was calculated as follows:

\[ H = \frac{p - \bar{p}}{\bar{p}} \times 100\% \]  \hspace{1cm} (13)

\( H \) is the precipitation anomaly percentage, \( p \) is the precipitation over a certain period of time, and \( \bar{p} \) is the average rainfall over many years and here is 51 years. The drought and flood levels calculated by the precipitation anomaly values are shown in Table 1 (Ju & Yang 1998).

<table>
<thead>
<tr>
<th>Percentage of precipitation anomalies (H)</th>
<th>Standard precipitation index (SPI)</th>
<th>Drought and flood grades</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; - 75%</td>
<td>&lt; - 1.96</td>
<td>Extremely dry</td>
</tr>
<tr>
<td>-75% to -50%</td>
<td>-1.96 to -1.48</td>
<td>Very dry</td>
</tr>
<tr>
<td>-50% to -25%</td>
<td>-1.48 to -1.0</td>
<td>Dry</td>
</tr>
<tr>
<td>-25% to 25%</td>
<td>-1.0 to 1.0</td>
<td>Normal</td>
</tr>
<tr>
<td>25% to 50%</td>
<td>1.0 to 1.48</td>
<td>Wet</td>
</tr>
<tr>
<td>50% to 75%</td>
<td>1.48 to 1.96</td>
<td>Very wet</td>
</tr>
<tr>
<td>&gt;75%</td>
<td>&gt;1.96</td>
<td>Extremely wet</td>
</tr>
</tbody>
</table>

### Table 1 | Grades of flood/drought for the standard precipitation index and anomalous percentages of precipitation
The SWAT model

In this study, the Soil and Water Assessment Tool (SWAT) was used to simulate green and blue water flows in the whole Heihe River Basin. The SWAT model is a semi-distributed basin-scale model that has been used around the world under different conditions (Neitsch et al. 2004; Schuol et al. 2008; Faramarzi et al. 2009), and it has been successfully applied to simulate hydrological processes in the Heihe River Basin, including blue and green water flows (Huang & Zhang 2004; Zang et al. 2012).

In SWAT, the Heihe River Basin was divided into 32 sub-basins and 309 hydrological response units by overlaying elevation, land cover, soil attributes, management, and slope class. The details of the SWAT model settings, database and definition information have been published by Zang et al. (2012). The Nash–Sutcliffe coefficient ($E_{ns}$) and the coefficient of determination ($R^2$) were selected to evaluate the goodness of the calibration and validation (Nash & Sutcliffe 1970). The SUFI-2 method in the SWAT-CUP interface (Abbaspour 2007) was chosen for parameter optimization.

This study was an expansion of our previous research. SWAT was calibrated and validated to simulate the flows of green and blue water at the whole-basin level by using climate data from 1980 to 2004 and land use data for 2000, as in Zang et al. (2012). The calibration and validation results indicated the high values of $E_{ns}$ (>0.87) and $R^2$ (>0.9). In the present study, the calibration parameters derived in the previous study were used, and the research period was expanded to include 1960 to 2010. The typical meteorological years were then defined based on the precipitation, and analyzed the spatial and temporal distributions of the blue and green water flows and the GWC. Further information on the model simulation, parameters, calibration, and validation can be found in Zang et al. (2012). In previous research, several issues have been discussed including the precipitation, temperature, and green/blue water variability in the Heihe River Basin over a recent 50 year period (Zang & Liu 2015), but the spatial and temporal distributions of green/blue water and the GWC variability in a typical meteorological year were not determined. Therefore, this study combined the previous research (Zang et al. 2012, 2015; Zang & Liu 2013) and expanded its content to a typical meteorological year to explore the variability of green/blue water flows and the GWC in typical years.

Green and blue water flows and GWC definition

The green water flow refers to the actual evapotranspiration, whereas the flow of blue water is the sum of surface runoff, lateral flows, and groundwater recharge (Schuol et al. 2008). To account for the relative importance of the two flows, the GWC is defined as the ratio of the green water flow to the total flows of green and blue water (Liu & Yang 2010).

RESULTS

The determination of typical dry, wet, and normal years in Heihe River Basin

Through the calculation of the standard precipitation index (SPI) and precipitation anomaly percentage ($H$) of the up-, mid-, and downstream areas of the Heihe River Basin, it was found that the typical meteorological years in the three reaches are disparate (Table 2). For example, the mid-stream region suffered from extreme drought in 1965, but this was a normal year in the up and downstream regions. The whole river basin was moderately moist in 1983, but there was drought downstream. Similar situations occurred in 1970 and 2009 (Table 2). According to the detailed analysis, the Heihe River Basin was typical arid only in 1978 and typical wet only in 1998, within the period from 1960 to 2010 (Table 2). The year of 1984 was selected for a comparative analysis, as the two indicators are normal in this year, and the 1980s was between two typical meteorological years. Table A1 (available with the online version of this paper) shows that in a drought year (1978), the precipitation was low, not only significantly below that of a wet year (in 1998) but also significantly lower than that in a normal year (1984) and the average of the 51 years (Table A1), which indicated that the SPI and $H$ values calculated were reliable. Therefore, the selected typical dry, wet, and normal years were 1978, 1998, and 1984, respectively (Table 2, shown in bold font).
The spatial differences of blue/green water depth in typical meteorological year

As observed in Figure 2(a), the blue water depth (blue water in per unit area) in the Heihe River Basin presented a decreasing trend from the upstream to downstream. The blue water depth (the average of 1978, 1984, and 1998) ranged from 14.8 mm to 98.3 mm from the upstream to the middle reaches and decreased to 6.62 mm in the downstream region (calculated by Figure 2(a)). The blue water depth in the drought years (1978) and wet years (1998) increased significantly (Figure 2(a)). The blue water in the up-, mid-, and downstream had clearly different distributions in 1978 and 1998, especially in the mid- and upstream, the blue water increased significantly in the wet year (Figure 2(a)). The blue water depth in the drought years (1978) and wet years (1998) increased significantly in the upstream and downstream region (calculated by Figure 2(a)). The blue water depth in the up-, mid-, and downstream regions also had clearly different distributions in 1978 and 1998, especially in the mid- and upstream, the blue water increased significantly in the wet year (Figure 2(a)). In the upstream, blue water depth was 75.2 mm in 1978 and 139.3 mm in 1998 (calculated by Figure 2(a)); in the midstream, the blue water depth was 12.1 mm in 1978 and 19.4 mm in 1998 (calculated by Figure 2(a)) in the downstream.

The blue water depth was 1.3 mm in 1978 and 9.1 mm in 1998 (calculated by Figure 2(a)). The blue water depth was higher in the upstream than in the mid- and downstream regions in the Heihe River Basin due to the greater rainfall from upstream to downstream; the precipitation was higher in wet years than in dry years (Figure A1, available with the online version of this paper). The green water depth (green water in per unit area) of the Heihe River Basin in wet years (1998) was significantly higher than that in drought years (1978) in the upstream and middle reaches, although the downstream was less (Figure 2(b)). The green water depth of the entire river basin was 120.6 mm in 1978 and 175.4 mm in 1998 (calculated by Figure 2(b)). However, the overall green water depth exhibited a trend of increasing from a dry year (1978) to a wet year (1998). Over the space of the whole river basin, the green water depth still presented a decreasing trend from the upstream to downstream (Figure 2(b)).

The total blue/green water depth (total blue/green water in per unit area) in the Heihe River Basin from the space pattern decreased from the upstream to downstream. The total blue/green water depth was 380.5 mm (the average of 1978, 1984, and 1978) in the upstream, descending to 122.3 mm in the midstream; on average, the downstream was 56.3 mm (calculated by Figure 3(a)). The total blue/green water depth from drought years (1978) to wet years (1998) significantly increased, from 150.1 mm in drought years to a wet year of 231.3 mm (calculated by Figure 3(a)). Furthermore, the total blue/green water depth significantly changed between typical meteorological years, mainly focused on the south-east of the upstream and middle.
reaches but not changed significantly in the downstream (Figure 3(a)).

**GWC and total blue/green water volume differences in typical meteorological year of Heihe River Basin**

The GWCs in Heihe River Basin showed an increasing trend from the upstream to the downstream (Figure 3(b)). The GWC (the average of 1978, 1984, and 1998) increased from the upstream (77%) to the downstream (94%) (calculated by Figure 3(b)). At the same time, the GWC showed clear differences in different typical years; that of typical drought years was 90%, while that of typical wet years was 83%. This showed that the evapotranspiration was higher in drought years than in wet years, up-, mid-, and downstream, while the blue water was higher in wet than in drought years (Figure 4). The GWC between wet years in the up-, mid-, and downstream was lower than in drought years. The GWC in a normal year (1984) was 87%. This showed that most of the available water resources in the Heihe River Basin participate in the regional hydrologic cycle in the form of green water. According to Figure 4, the total blue/green water flows of the Heihe River Basin in wet years (in 1998, 27.93 billion m³) were significantly greater than in dry years (1978, 16.8 billion m³); the blue water also changed from 1978 (1.7 billion m³) to 1998 (4.6 billion m³). This was mainly because the precipitation in drought years was less than in wet years (Figure A1).

**The relationship of GWC and drought climate weather condition**

To explore the relationship between the GWC and the drought environment, the GWCs were ordered according to the degree of drought according to the SPI raised to the
order of the corresponding arrangement from dry to wet, without considering the order of years. The GWC showed a regressive trend from dry to wet over the entire river basin (Figure 5). The variation in the amplitude of the GWC decreased from the upstream to downstream (Figure 5); it decreased more significantly in the upstream than in the mid- and downstream, which had only a slight variation. This was consistent with the dry and wet degrees from the up- to downstream in the Heihe River Basin. This showed that there was a negative correlation between GWC and the degrees of dry and wet in a typical meteorological year. The variation in the GWC amplitude was more sensitive to the wet weather environment; the wetter the climate, the greater the change, and the drier the climate, the smaller the change (Figure 5). However, the drier the climate, the higher the GWC, and the wetter the climate, the smaller the GWC (Figure 5).

**DISCUSSION**

In the past 51 years, the blue and green water depth and GWC exhibited spatial and temporal differences from the upstream to the downstream in Heihe River Basin, especially in typical meteorological years. As the cross section was larger (more than 800 km) from the upstream to the downstream of the Heihe River Basin and the terrain varies, the sources of precipitation and regional climates showed significant differences. The regional climates were most strongly affected by different forms of atmospheric circulation (Wu et al. 2010), namely, precipitation in the upstream, oceanic evaporation in the midstream basins, and terrestrial evapotranspiration in the downstream basin (Lan et al. 2004; Jia et al. 2008). This difference led to the dry and wet year inconsistency from the upstream to the downstream. The blue/green water depths of...
Heihe River Basin presented a decreasing trend and spatial difference from the typical dry year to wet year, mainly due to the spatial distribution characteristics of precipitation in typical meteorological years (Zang & Liu 2013; Figure A1). The water amount of some sub-basins in the up- and mid-stream was larger, especially in the southeast basin, mainly due to the distribution of some ice, snow melt water and lake groups in typical wet years (Zang et al. 2015).

The GWC of a drought year in the downstream of the Heihe River Basin was higher; in the wet year, it was relatively low in the up- and midstream regions (Figures 4 and 5). This showed that there was a negative correlation between the GWC and the degree of dry and wet in a typical meteorological year. The precipitation and the GWC were inversely related; the variation amplitude decreases according to the annual precipitation (Figure 5). However, the GWC variation increases with the precipitation (Figures 5 and A1). This showed that the GWC variability was more sensitive in wet than in dry climate environments.

The average GWC was 88% for the entire Heihe River Basin (Zang et al. 2012); in this study, the GWC in the past decade was 87%, 90% in the drought year, and 83% in the wet year. Based on the GWC in a normal year, it was inferred that approximately 87.5% of the available water resources in the Heihe River Basin participated in the hydrologic cycle in the form of green water. This result can help develop a scientific understanding of the evolution of the blue and green water resources under the climate change background in continental inland river basins in arid and semi-arid regions and enable reasonable management of the available water resources, especially green water resources.

Although the spatial distribution of blue/green water was studied in different typical years, the green and blue water transformation mechanism and the laws of the Heihe River Basin are still not clear, especially the human activity influence, so further research is still needed (Zhao et al. 2016). Further typical meteorological year blue/green water research will help to prevent and control drought and flooding in a typical year in some regions and more efficiently manage water...
resources, especially in continental inner river basins in arid and semi-arid areas. Strengthening green water research in northwestern China and other arid regions will help to alleviate water shortage crises and the eco-system pressure in these areas. In our research, human activities were not included, although they are very important to water resources. Therefore, further exploring the spatial and temporal distribution patterns and the transformation law of green and blue water in the arid and semi-arid inland river basins in China will be helpful to solve the problems of water cycle and ecological system science and developing protocols for sustainable water resource utilization and management. This has important theoretical and realistic significance for socioeconomic sustainable development in the Heihe River Basin.

CONCLUSION

In our research, the spatial and temporal variations of the blue/green water depth and GWC variability were analyzed in typical years in the up-, mid-, and downstream and the entire river basin over the past 51 years. The main conclusions are as follows:

1. The total blue/green water depth of the Heihe River Basin showed a gradually decreasing tendency from the upstream to downstream, and the blue and green water depths also showed the same decreasing trend from the upstream to the downstream due to the geographical environment differences in the Heihe River Basin.
2. The green and blue water depths of the Heihe River Basin were significantly lower in a typical drought year than in a typical wet year; the total blue/green water depth changed from 150.1 mm in drought years to 231.3 mm in wet years due to the differences in precipitation.
3. The GWC in the Heihe River Basin presented an increasing trend from the upstream to downstream, changing from 77% in the upstream to 94% in the downstream. Furthermore, the GWC in the typical drought
years was higher than in the typical wet years. Therefore, evapotranspiration (green water) accounted for a proportion of water consumption in typical dry years that was significantly higher than that in normal and wet years, while runoff (blue water) accounts for a proportion of water in wet years that was significantly higher than in dry years.

(4) The GWC had a regressive relationship with the drought index; wetter weather caused more significant variability in the GWC.

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