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Assessment of spatial and temporal patterns of green and blue water flows in inland river basins in Northwest China

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Abstract

In arid and semi-arid regions freshwater resources have become scarcer with increasing demands from socio-economic development and population growth. Until recently, water research and management in these has mainly focused on blue water but ignored green water. Here we report on spatial and temporal patterns of both blue and green water flows simulated by the Soil and Water Assessment Tool (SWAT) for the Heihe river basin, the second largest inland river basin in Northwest China. Calibration and validation at two hydrological stations show good performance of the SWAT model in modelling hydrological processes. The total green and blue water flows were 22.09 billion m^3 in the 2000s for the Heihe river basin. Blue water flows are larger in upstream sub-basins than in downstream sub-basins mainly due to high precipitation and large areas of glaciers in upstream. Green water flows are distributed more homogeneously among different sub-basins. The green water coefficient was 88.0 % in the 2000s for the entire river basin, varying from around 80–90 % in up- and mid-stream sub-basins to above 95 % in downstream sub-basins. This is much higher than reported green water coefficient in many other river basins. The spatial patterns of green water coefficient were closely linked to dominant land covers (e.g. glaciers in upstream and desert in downstream) and climate conditions (e.g. high precipitation in upstream and low precipitation in downstream). There are no clear consistent historical trends of change in green and blue water flows and green water coefficient at both the river basin and sub-basin levels. This study provides insights into green and blue water endowments for the entire Heihe river basin at sub-basin level. The results are helpful for formulating reasonable water policies to improve water resources management in the inland river basins of China.

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1 Introduction

Ensuring sufficient water supply is essential for the survival and sustenance of humans and ecosystems (Oki and Kanae, 2006). However, with population growth and socioeconomic development, more and more water is used to solely meet the requirements of humans. This often leads to decreasing water availability for ecosystem use with implications for ecosystem health. In the long term, insufficient water availability for essential ecosystem services and others function of ecosystems can lead to ecosystem degradation with consequent impacts on overall water scarcity and human well-being (Falkenmark, 2003). In particular in arid and semi-arid regions, water use competition is intense between human and ecosystems; hence, a comprehensive assessment of water resources in a spatially and temporarily explicitly way is a key to deepening the understanding of the renewable water endowments as well as to enhancing water management towards sustainable, efficient and equitable use of limited water resources.

Traditionally, water resources assessment and management have put emphasis on blue water, ignoring green water (Falkenmark, 1995a; Cheng and Zhao, 2006) Conceptually, water can be divided into green water and blue water (Falkenmark, 1995a). Blue water is the water in rivers, lakes, wetland and shallow aquifers, while green water is precipitation water stored in unsaturated soil, and later used for evapotranspiration. Although green water is often ignored, it plays an essential role in crop production and other ecosystem services. J. Liu et al. (2009) estimated that green water accounts for more than 80 % of consumptive water use for global crop production. Rost et al. (2008) estimated that green water consumption in global cropland from 85 % in 1971 to 92 % in 2000 of total crop water consumption. Green water dominates water uses in tropical arid regions, where rainfed agriculture accounts for more than 95 % of total cropland area (Rockstrtöm, 1999). Water use in grassland and forest ecosystems is dominantly "green".

Since the concept of green and blue water was introduced (Falkenmark, 1995a, b), green/blue water research has become more and more diversified. The green/blue

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water concept has been extended to be practically applicable for better water management and planning (Falkenmark and Rockström, 2006). Many novel research methods have appeared as well. For instance, Rost et al. (2008) and Gerten et al. (2005) use the LJP model to assess global green water consumption over a time period of nearly 30 yr, while J. Liu et al. (2009) used the GEPIC model to calculate the global green/blue water consumption of cropland. Schuol et al. (2008) and Monireh et al. (2009) used the SWAT model to simulate green/blue water resources of Africa and Iran, respectively. The green/blue water concept has offered a new methodology and fresh ideas for water resources management in many regions, in particular in arid and semi-arid regions where water scarcity is serious due to water-thirsty socioeconomic development and population growth. Novel measures and concepts can aid in underpinning more sustainable and equitable water resources management (Jansson et al., 1999).

The Heihe River is the second largest inland river in China. Located in the northwest of China, the Heihe river basin is a typical arid and semi-arid region suffering from a serious water crisis (Cheng et al., 2006). Water use in mid-stream regions has increased sharply in the Heihe river basin related to socio-economic development (Ma et al., 2011). As a consequence, the Heihe river basin has been confronted with serious ecosystem degradation including the complete dry-up of the downstream West and East Juyanhai lakes (Cheng, 2002). Other related environmental crises in the area include the southward expansion of the Bada in Juran desert and an increased occurrence of sand-storms (Li, 2009). So far, the main measures of water resources management in the Heihe river basin include water transfer, irrigation and hydropower project (Xiao et al., 2011). Most of the water management has paid attention to the liquid blue water, while stored green water has been often ignored. It is not sufficient to only manage blue water in this dry river basin, and a spatially and temporally explicit assessment of green/blue water is the first step to achieve integrated green and blue water management.

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2 The study area

The Heihe River basin lies between longitudes 97°05′–102°00′ E and latitudes 37°45′–42°40′ N. With a total basin area of 0.24 million km^2, this river basin is mainly located in the northwest of China, but it also has a part in Mongolia (Fig. 1). The average altitude of the basin is over 1200 m. With a total length of 821 km, the Heihe river is divided into three sections: upstream, mid-stream and downstream. The upstream runs from the Qilian mountain to the Yingluo Canyon with a length of 303 km, the mid-stream runs from the Yingluo Canyon to Zhengyi Canyon, while the downstream goes from the Zhengyi Canyon and terminates into the Juyanhai Lake. The average annual precipitation is between 200 to 500 mm in the upstream, less than 200 mm in the mid-stream, and less than 50 mm in the downstream area. Potential evaporation ranges from 1000 mm yr^{-1} in upstream to 4000 mm yr^{-1} in downstream (Liu et al., 2008). The main land cover types are desert, mountains and oasis, which cover 57.15 %, 33.16 % and 8.19 % of the total basin area, respectively (Cheng et al., 2006).

The Heihe river basin has complex ecosystems ranging from mountains in the South, oases in the middle and deserts in the North (Cheng et al., 2006). These ecosystems are linked from upstream to downstream by the water cycle. In recent years, with socio-economic and population development, the water flow through the Heihe river basin have diminished year by year. For example, Zhangye, the biggest city of the Heihe river basin located mid-stream, has witnessed a population increase of 14 000 persons per year, with the population amounting to 1.27 million in 2000. Irrigated agricultural area has increased by 2.87 thousands ha yr^{-1}, with the total irrigated area reaching 216 thousands hectares in 2007 (Liu et al., 2008). Therefore, a detailed and integrated simulation study of the water resources of the complete river basin is critical and urgent for better water management.

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3 Methodology

3.1 Green and blue water flows

Green/blue water can refer to both volume and flow. Here the flow concept is taken. Green water flow refers to actual evapotranspiration, while blue water flow is the sum of surface runoff, lateral flow, and return flow from shallow aquifer. The green water coefficient (GWC) is defined as the ratio of green water flow to the total green and blue water flows, and it is calculated by the equation as below (J. Liu et al., 2009).

$$\mathrm{GWC} = \frac{g}{(b+g)} \tag{1}$$

Where b and g are blue and green water flows, respectively, in mm yr^{-1}.

The relative change rate (RCR) is used to indicate the change of green/blue water flows in different periods.

$$\mathrm{RCR} = \frac{(V_i - V_0)}{V_0} \times 100\,\% \tag{2}$$

where V refers to the variables such as green water flow or blue water flow, i indicates the latter period and 0 indicates the initial period.

3.2 The SWAT model

We use the Soil and Water Assessment Tool (SWAT) (Arnold and Fohrer, 2005) to simulate green and blue water flows. There are two main reasons for selecting the SWAT model. Firstly, it has already been successfully applied for water quantity and quality assessments for a wide range of scales and environmental conditions (Monireh et al., 2009); secondly, the SWAT model has been used to successfully simulate the hydrological process of a small upstream segment of the Heihe river basin (Huang and Zhang, 2004; Li et al., 2009; Li, 2009). There are more than nine types of hydrological

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models that have been used in the Heihe river basin for water resources research (Li, 2009). But all of these model simulations have focused on upstream river segments in the Qilian Mountains, which form only 14.7 % of the total river basin area. The hydrological processes have never been studied for the entire river basin.

The SWAT model is a semi-physically based, semi-distributed, basin-scale model (Arnold and Fohrer, 2005), which has been used widely in many countries around the world (Schuol et al., 2008; Gerten et al., 2005; Monireh et al., 2009). In our research, we use the version SWAT2005, which was running on Arcview 3.3. SWAT operates on a monthly time step and only the hydrologic component of the model was used in this study. In SWAT the modelled area was divided into multiple sub-basins and hydrological response units (HRUs) by overlaying elevation, land cover, soil, and slope classes. In the SWAT model, the HRU were characterized by combinations of dominant land-use, soil, and slope classes. This choice was essential for keeping the size of the model at a practical limit. For each of the sub-basins, water balance was simulated for four storage volumes: snow and glacier, soil profile, shallow aquifer, and deep aquifer. Potential evapotranspiration was computed using the Hargreaves method (Hargreaves et al., 1985). The calculation of evaporation requires the input of daily precipitation, and minimum and maximum temperature. Surface runoff was simulated using a modified SCS Curve Number (CN) method and snow and melting water calculated by the energy balance equation. Further technical model details are given by (Arnold and Fohrer, 2005). The pre-processing of the SWAT model input was performed within ESRI ArcGIS 9.3.

The Av-SWAT interface was used for the setup and parameterization of the model. The entire river basin was divided into 303 HRUs and 34 sub-basins on the basis of the digital elevation model (DEM). The geomorphology, stream parameterization, and overlay of soil and land cover were automatically done within the interface. We only present results for the River Basin within the Chinese boundary due to the lack of data for Mongolia.

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3.3 Data

The SWAT model mainly requires five types of data: DEM, land use data, soil data, climate data, and other management data. A large part of the data for the Heihe river basin was delivered from the Heihe Data Research Group (http://www.westgis.ac.cn/datacenter.asp). The collection of the data was followed by an accurate assessment and analysis of the quality and integrity of the data. The basic input maps included DEM at a resolution of 30 m (USGS/EROS, 2009) and land cover at a resolution of 1 km from the Heihe Data Research Group. There are 26 types of land use data in the Heihe river basin which include cropland, forest, grassland, glacier, lakes, wetland, among others (http://westdc.geodata.cn/Portal/metadata/viewMetadata.jsp?id=730000-10121). We have built the land use database as the China's land cover type characters. The soil data was obtained from the Harmonized World Soil Database produced by the Food and Agriculture Organization of the United Nations (FAO), the International Institute for Applied Systems Analysis (IIASA), and the Institute of Soil Science-Chinese Academy of Sciences (ISSCAS) (http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/index.html?sb=1). This dataset has a spatial resolution of 30 arc-second (about 1 km), and it includes 63 soil types for the Heihe river basin with two soil layers (0–30 cm and 30–100 cm depth) for each type. The climate data for 19 weather stations were used for model simulation (Fig. 1). The daily climate input data (precipitation, minimum and maximum temperature) for the period of 1977–2004 were obtained from the Heihe Data Research Group and China Meteorological Data Sharing Services System (http://cdc.cma.gov.cn/index.jsp). River discharges for a time period from 1977–1987 and 1990–2004 were also provided by the Heihe Data Research Group. As a first step, we aim to simulate green and blue water flows without human intervention; hence, management data such as irrigation were not collected.

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3.4 Model calibration and validation

Model calibration and validation is a challenging and to a certain degree subjective step in a complex hydrological model. We aim for the model simulation to reflect the natural condition. Therefore, the SWAT model of the Heihe river basin was calibrated and validated using monthly river discharges for two upstream stations where human activities are not intensive. These stations are the Zhamushike station and Yingluo canyon (see the locations in Fig. 1). We selected these stations because, in addition to little human intervention, they have the most complete discharge data for 1977–1987 and 1990–2004.

The simulation period was from 1977 to 2004. The first two years were used as warm-up period to mitigate the effect of unknown initial conditions, which were subsequently excluded from the analysis. Hence, we divide the discharge data into two periods: calibration period (1979–1987) and validation period (1990–2004).

Based on the built-in sensitivity analysis tool (Arnold and Fohrer, 2005) in SWAT, we have identified the 11 most sensitive parameters. In addition, based on previous studies, three other parameters (SMFMX, SMFMN and TIMP in Table 1) are also important for SWAT simulation in the Heihe river basin (Li, 2009). These 14 parameters are listed in Table 1. Two indexes, the Nash-Sutcliffe coefficient (Eq. 3) and the Coefficient of Determination (Eq. 4), are used to evaluate the goodness of the calibration and validation.

$$E_{\text{ns}} = 1 - \frac{\sum_{i=1}^{n} (Q_{\text{o},i} - Q_{m,i})^2}{\sum_{i=1}^{n} (Q_{\text{o},i} - \overline{Q}_{\text{o}})^2} \quad (3)$$

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$$R^2 = \frac{\left[\sum_{i=1}^{n}(Q_{\mathrm{o},i} - \overline{Q}_{\mathrm{o}})(Q_{m,i} - \overline{Q}_m)\right]^2}{\sum_{i=1}^{n}(Q_{\mathrm{o},i} - \overline{Q}_{\mathrm{o}})^2 \sum_{i=1}^{n}(Q_{m,i} - \overline{Q}_m)^2} \quad (4)$$

E_{ns} is the Nash-Sutcliffe coefficient, $Q_{o,i}$ the observed data of runoff in i years, $Q_{m,i}$ the simulation data of runoff in i years, and n is the length of the time series. The closer E_{ns} and R^2 are to 1, the more accurate the model prediction, an $E_{ns} > 0.0$ indicates that the model is a better predictor than the mean of the observed data. More information about the Nash-Sutcliffe coefficient and SWAT-CUP can be found in respectively (Nash and Sutcliffe, 1970) and (Abbaspour, 2007)

The SUFI-2 method in the SWAT-CUP interface (Abbaspour et al., 2007) was used for parameter optimization. In this method all uncertainties (parameter, conceptual model, input, etc.) are mapped onto the parameter ranges, which are calibrated to bracket most of the measured data in the 95 % prediction uncertainty (Abbaspour et al., 2007). The overall uncertainty analysis in the output is calculated by the 95 % prediction uncertainty (95PPU) with two indices: the *P*-factor, which is the percentage of data bracketed by the 95PPU band and the *R*-factor, which is the average width of the band divided by the standard deviation of the corresponding measured variable (Abbaspour, 2007; Monireh et al., 2009). The maximum value for the *P*-factor is 100 %, and ideally we would like to bracket all measured data, except the outliers, in the 95PPU band. The *R*-factors calculated as the ratio between the average thickness of the 95PPU band and the standard deviation of the measured data. It represents the width of the uncertainty interval and should be as small as possible. The *R*-factor indicates the strength of the calibration and should be close to or smaller than a practical value of 1 (Abbaspour, 2007).

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4 Results and discussion

4.1 Calibration and validation

The calibration and validation performed with SWAT at the two hydrological stations was satisfactory, as indicated by high values of E_{ns} and R^2 (Fig. 2). The E_{ns} values at both Zhamushike and Yingluo canyon are above 0.87, and the R^2 values are greater than 0.90. Interestingly, the agreement between simulation results and observations was even better for the validation period than the calibration period. Our calibration and validation results seem better than those from Huang and Zhang (2004) and Li (2009). Meanwhile, the simulated and observed discharges have very similar variation trends (Fig. 2), especially in the validation period of Yingluo Canyon. The good agreement between the simulation results and observations indicates that the SWAT model set-up is suitable for the Heihe river basin. The most sensitive parameters with their best parameter intervals and best parameter values eventually used in this study are shown in Table 1.

4.2 Total water flow (sum of green and blue water flows)

The spatial and temporal distribution of total water flow (sum of green and blue flows) in the Heihe river basin is showed in Fig. 3. There is a general decreasing trend in per unit area water flow (in $\text{mm}\,\text{yr}^{-1}$) from upstream to downstream sub-basins (Fig. 3). This is easy to understand because annual precipitation decreases from upstream to downstream and a large area of glaciers are located upstream (Wang and Zhou, 2010; Shi, 2005).

The total water flow was 22.09 billion m^3 in the 2000s for the entire river basin. There are several regions in blue color stand out with relative high total water flow in volume: those in the upstream generally have high precipitation and often with a large area of glaciers (Li, 2009), while those in downstream are often a result of large sub-basin area. SWAT generates sub-basins based on DEM, land use and soil types. Because

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downstream regions have more homogeneous distribution of elevation, land use and soil types, the sub-basin areas in downstream could be ten times larger than those in upstream. From the 1980s to the 1990s, the total water flow has a general decreasing trend in upstream and midstream sub-basins, but has a general increasing trend in downstream sub-basins. However, from the 1990s to 2000s, there are very different change patterns, with increasing trends in upstream and middle stream sub-basins but decreasing trends in downstream sub-basins (Fig. 3). In upstream and mid-stream sub-basins, precipitation and temperature had decreasing trends from the 1980s to 1990s, but increasing trends from 1990s to 2000s (Wang and Zhou, 2010), leading to different change patterns in total amount of precipitation water and glaciers melting water (Shi, 2005). In downstream sub-basins, sunshine durations increased from the 1980s to 1990s but decreased from the 1990s to 2000s (Y. Liu et al., 2009), which caused increasing and decreasing temperature in the two periods, respectively. The temperature variation caused evapotranspiration changes downstream (Cheng et al., 2007). Therefore, climate variability is a main reason for the variation of total water flow in the Heihe river basin. From 1980 to 2004, the total water flow of Heihe river basin did not change much with a very slight increase by about 0.98 % (Fig. 4).

4.3 Spatial and temporal distribution of green/blue water flows per unit area

Both the green and blue water flows per unit area in the Heihe River basin decrease from up stream to downstream (Fig. 5). Generally, where blue water flows per unit area are high, green water flows also tend to be high (Fig. 5), in line with findings of previous research (Schuol et al., 2008). The spatial patterns of the green/blue water flows per unit area are mainly influenced by the spatial patterns of precipitation, which generally decreases from upstream to downstream. Land cover also plays a role here. Sub-basins with a large amount of glaciers and frozen soils often have higher blue water flows per unit area. This is because glaciers and frozen soils can generate much runoff through melting.

4.4 Spatial and temporal distribution of blue water flows

The blue water flows in the Heihe river basin were generally high in upstream sub-basins and low in downstream sub-basins (Fig. 6). Two factors contribute to this spatial pattern: precipitation and land cover type. In upstream sub-basins, precipitation is generally high where glaciers and frozen soils often exist. Both the conditions result in a relatively large amount of runoff and blue water flows. In downstream sub-basins, precipitation is very low while desert is the dominant land cover. Runoff is small and hence blue water flows are low.

It seems that, from the 1980s to 1990s, blue water flows decreased upstream and middle-stream and increased downstream. However, from the 1990s to 2000s, different trends occur with blue water flows increasing upstream but decreasing downstream. When comparing blue water flows in the 1980s with those in the 2000s, there are no clear trends of changes among regions. We can not identify a clear trend related to climate change. Climate variations in the Heihe river basin influences precipitation and temperature, which caused the variation in blue water flow.

4.5 Spatial and temporal distribution of green water flows

Green water flows are distributed more homogeneously than blue water flows among regions. Flows lower than 400 million m^3 can be found in both upstream and downstream sub-basins, while flows higher than 1000 million m^3 can also be found in different sub-basins upstream and downstream (Fig. 7). In upstream sub-basins, precipitation is high, but due to the low temperature, evapotranspiration may be relatively small. In downstream sub-basins, precipitation is low, but in the desert areas, there is little runoff, or in the other words, precipitation is almost directly evaporated into the atmosphere. Besides the climatic factors and land cover, the area of sub-basins is often larger in downstream than in upstream. This also contributes to the more even distribution of green water flows.

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There is no clear evidence that shows significant impacts of climate change on green water flows. In many middle and downstream sub-basins, green water flows increased from the 1980s to the 1990s but decreased since the 1990s, while in several upstream sub-basins, green water flows decreased from the 1980s to the 1990s but increased since the 1990s. There are no clear signals of increase or decrease of green water flows with time.

4.6 Spatial and temporal distribution of green water coefficient

Within the Heihe river Basin, the green water coefficient is relatively lower upstream and higher downstream. The green water coefficient is generally 80–90 % in upstream sub-basins, while it is generally above 95 % in downstream sub-basins (Fig. 8). The spatial distribution of green water coefficient is closely linked to land cover and geographical patterns. In upstream regions, precipitation is high at high altitude with low temperatures and evapotranspiration rates; consequently discharge is high (Wang and Zhou, 2010; Guo et al., 2011). In particular, there are many glaciers upstream, which generate a large amount of runoff through melting. This is obvious particularly for one sub-basin (in dark blue) in the 1980s where green water coefficient is even lower than 65 %. This sub-basin links the upstream and mid-stream. Most of the discharge from upstream flows through the Yingluo Canyon in this sub-basin to mid- and downstreams (Li, 2009). As a flow accumulation region, this sub-basin has the lowest green water coefficient among all sub-basins. Downstream, precipitation is low and desert is often the dominant land cover. Runoff seldom occurs as precipitation dominantly evaporates. Hence, the green water coefficient is extremely high. From the 1980s to the 2000s, the green water coefficient does not change much for most of the sub-basins (Fig. 8).

For the entire basin, the green water coefficient remained relatively stable and first decreased from 87.5 % in the 1980s to 89.2 % in the 1990s then decreased to 88.0 % in the 2000s (Fig. 4). The green water coefficient is very high compared to previous studies on other locations, e.g. 58 % in congoriver basin and 61 % in west of Iran (Schuol et al., 2008; Monireh et al., 2009). The high green water coefficient in the Heihe river

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basin is mainly a result of the arid- and semi-arid climate conditions, which leads to low runoff and groundwater discharge but high evapotranspiration. We do not find significant trend of change on the green water coefficient. The change is likely due to the climate variations, which results in variation of the green water coefficient. The fluctuation of the green water coefficient also occurs upstream and mid-stream (Fig. 4). Downstream, the green water coefficient increased from the 1980s to 1990s, but has been decreasing since the 1990s.

5 Summary and conclusion

In this study the semi-distributed SWAT model was successfully applied to quantify the green and blue water flows for the entire Heihe river basin. Calibration and validation at two hydrological stations in the upstream showed good performance of the SWAT model in modelling hydrological processes without human intervention. The spatial and temporal distributions of blue and green water flows were presented for the entire river basin.

Generally, green and blue water flows per unit of area decrease from upstream to downstream. The total water flow in the Heihe river basin has changed little during 1980–2004. Since we do not consider human intervention in the simulation, the changes are completely related to climatic factors, i.e. precipitation and temperature. Our results show variation without any clear temporal trend on total water flow in the Heihe river basin. Instead, natural climate variability is likely the main reason for the temporal changes of water flows.

The present research on green and blue water flows considers only natural conditions without human intervention e.g. land use change. However, water resources are altered not only by climate factors, but also by intensified human activities. For example in the middle of the Heihe river basin, human water use is the most important factor influencing the hydrological cycle (Cheng et al., 2006), especially agricultural water use which accounts for more than 70 % of the total water consumption (Li, 2009). The

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huge quantity of human water use has changed the surface and groundwater transfer frequency (Guo et al., 2011). It will impact the green/blue water flow variation and transformation. Therefore, including human activities for the simulation of green/blue water flows in Heihe river basin is necessary, and will be the next step of our research.

This study is limited by several shortcomings. First, the limited number and uneven distribution of weather and hydrological stations (Fig. 1) influences the accuracy of results. Only 19 weather stations and two hydrological stations were used in this study and shortage of data will influence simulation accuracy. Second, for now we neglect the effects of irrigation water use, land use change and reservoirs operation. Human activities, especially the expansion of irrigated area, can influence water cycling significantly. Third, the lack of soil moisture data to gives difficulties validate the green water flow simulations.

This study provided insights into green and blue water flows for the entire Heihe river basin at sub-basin level. This information is very useful for developing an overview of the actual water resources status and will help to improve the water resources management of the inland river basins of China.

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Table 1. The most sensitive parameters and their best parameter intervals and values.

Aggregate parameter*	Description	Best parameter interval	Best parameter value
r__CN2	Initial SCS CN II value	0.47–0.59	0.51
v__ALPHA_BF	Base-flow alpha factor [days]	0.92–0.99	0.94
v__GW_DELAY	Groundwater delay [days]	462–473	467
v__GWQMN	Threshold water depth in the shallow aquifer for flow [mm]	0.72–0.85	0.77
v__GW_REVAP	Groundwater "revap" coefficient	0.094–0.11	0.098
v__ESCO	Soil evaporation compensation factor	0.78–0.80	0.79
v__CH_K2	Channel effective hydraulic conductivity [mm hr^{-1}]	23–29	27
R__SOL_AWC(1)	Available water capacity [mm H_2O mm $soil^{-1}$]	0.11–0.18	0.14
r__SOL_K(1)	Maximum canopy storage [mm]	0.22–0.23	0.23
v__SFTMP	Snowfall temperature [°C]	−1.87–1.41	0.79
v__SURLAG	Surface runoff lag time [days]	4.18–5.19	4.68
v__SMFMX	Melt factor for snow on 21 June [mm H_2O °C day^{-1}]	5.85–6.27	6.02
v__SMFMN	Melt factor for snow on 21 December [mm H_2O °C day^{-1}]	3.05–3.51	3.25
v__TIMP	Snow pack temperature lag factor	0.38–0.622	0.49

* The aggregate parameters are constructed according to Yang's work (Yang et al., 2007, 2008). "v_", "r_" means an absolute increase, a replacement and a relative change to the initial parameter value respectively. The range of the aggregate parameter best distribution for is mainly based on SWAT-CUP calibration results.

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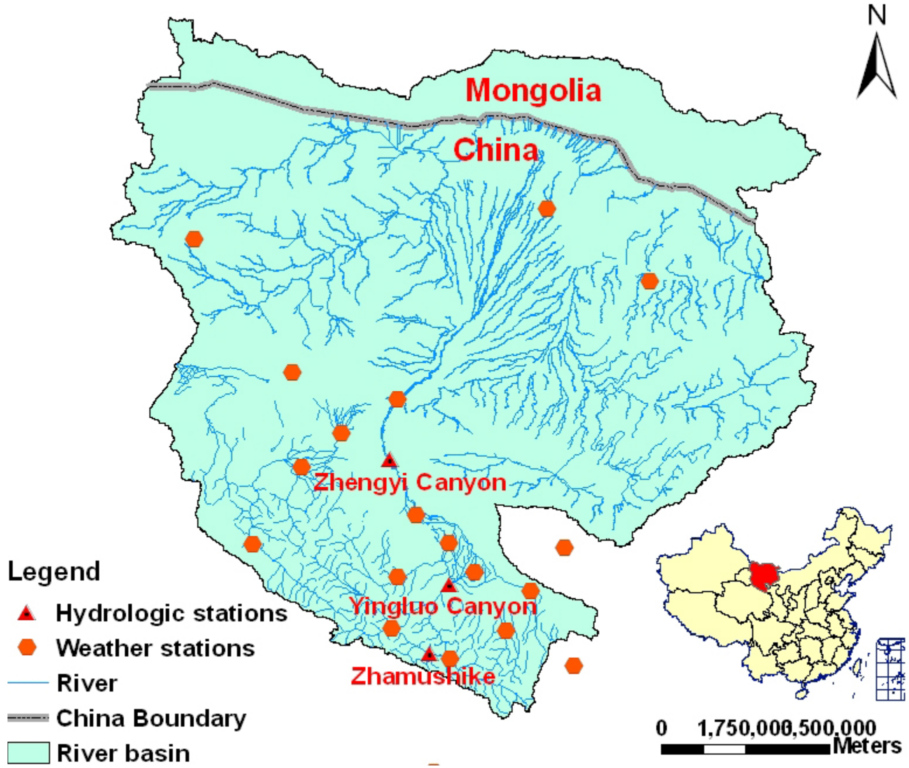

Fig. 1. The Heihe river basin with rivers, hydrological and weather stations indicated. The location of the Heihe river basin in China is shown in the inset.

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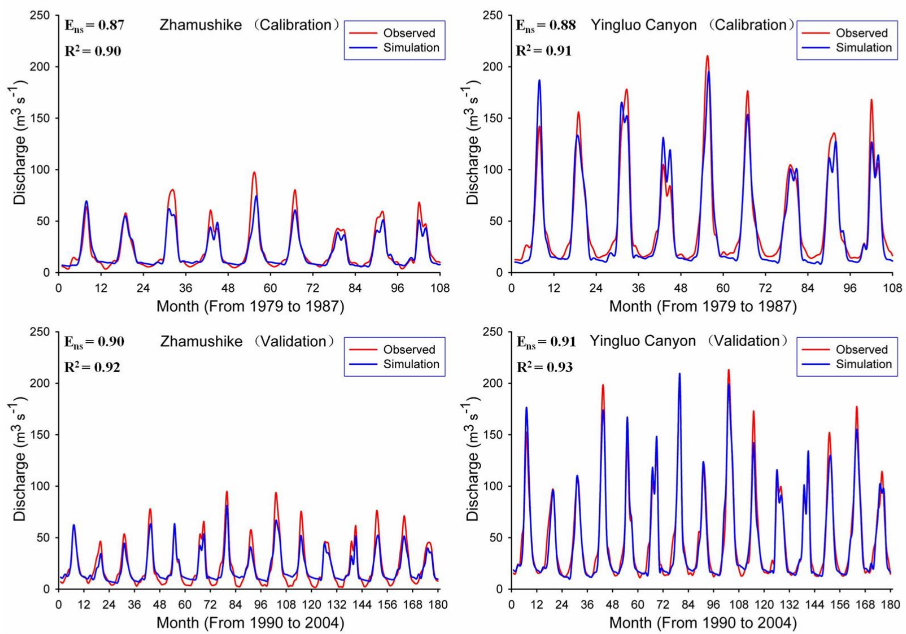

Fig. 2. Comparisons between the observed and simulated discharge for the Zhamushike and Yingluo canyon hydrological stations in Heihe River Basin.

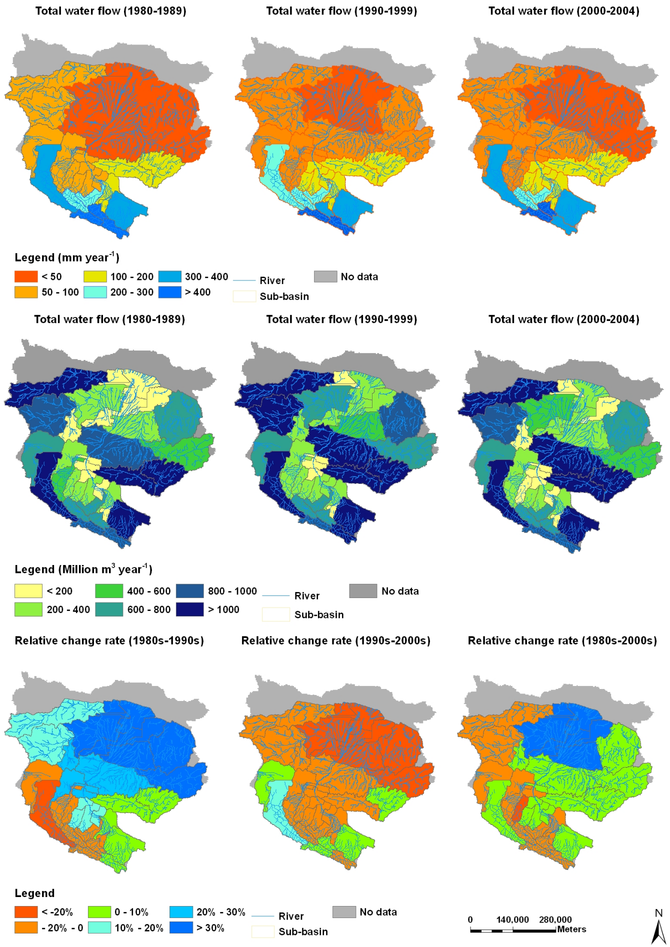

Fig. 3. The total amount of water flow and its relative change rate in the Heihe river basin.

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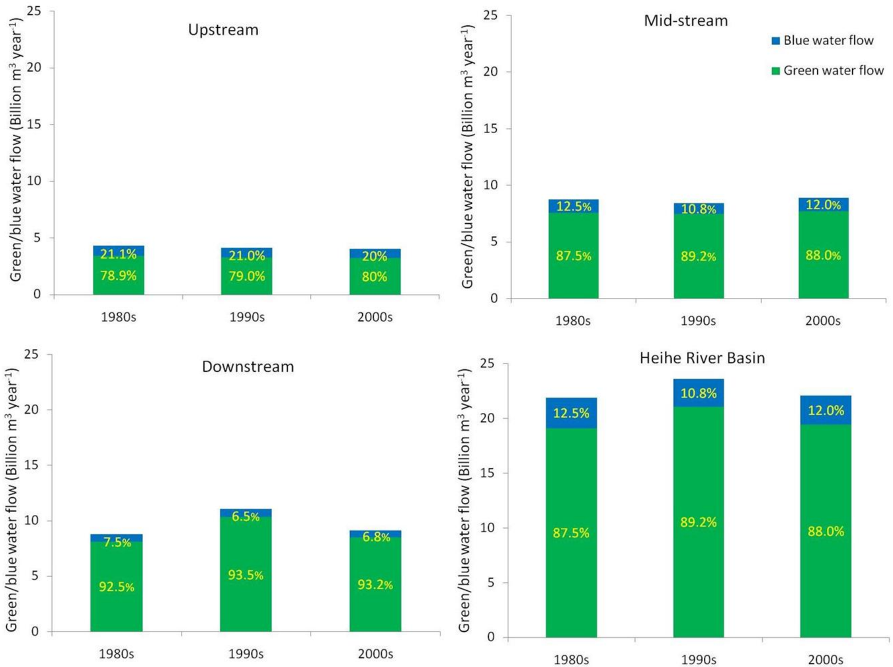

Fig. 4. The total water flow and green/blue water coefficients from the 1980s to the 2000s in the Heihe river basin.

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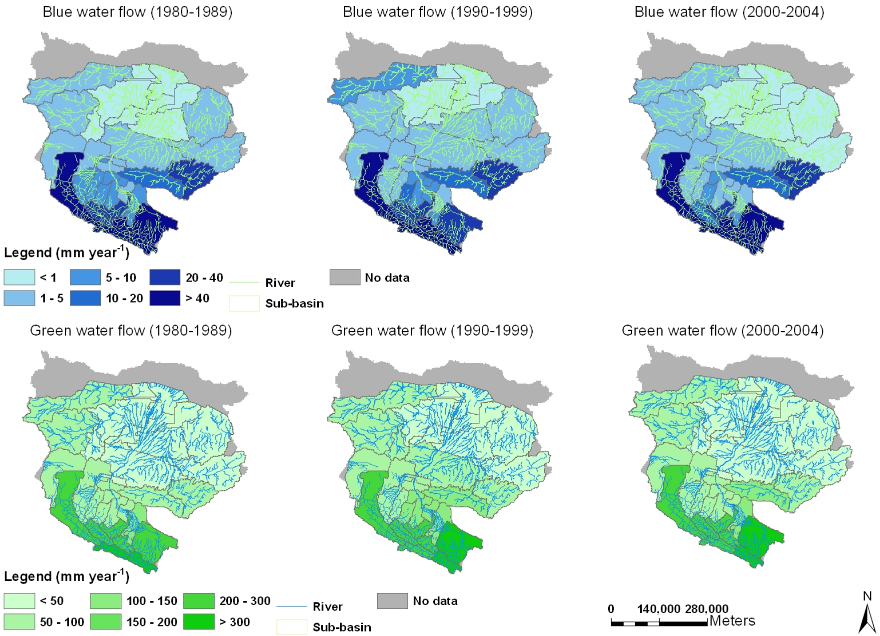

Fig. 5. The green/blue water flows per unit area (mm yr^{-1}) from the 1980s to the 2000s in the Heihe river basin.

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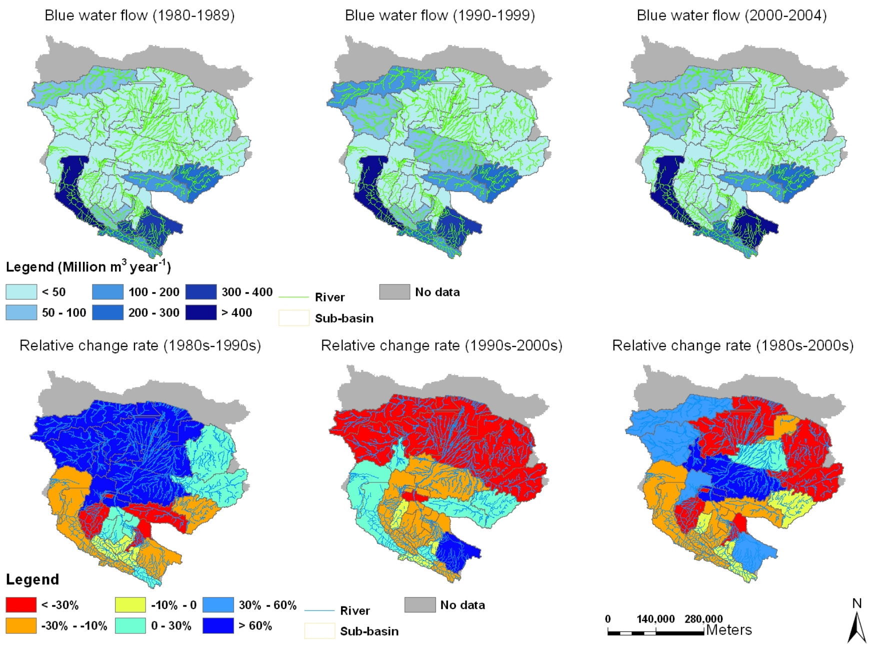

Fig. 6. The blue water flows (million $m^3\,yr^{-1}$) from the 1980s to the 2000s in the Heihe river basin.

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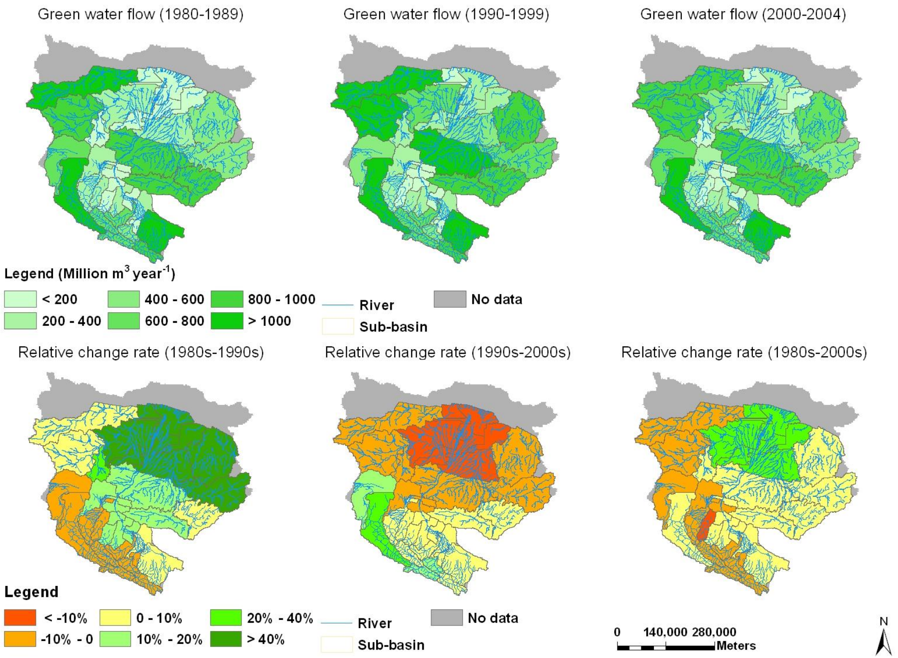

Fig. 7. The green water flows (million $m^3\,yr^{-1}$) from the 1980s to the 2000s in the Heihe river basin.

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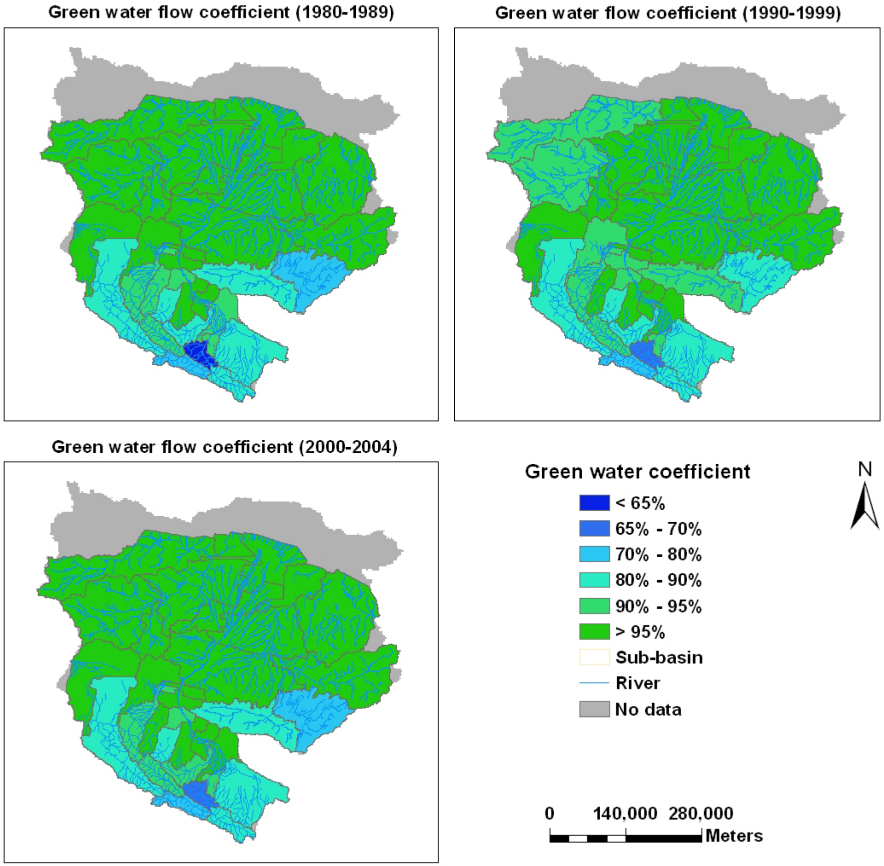

Fig. 8. The green water coefficient from the 1980s to the 2000s in the Heihe River basin.

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