# Assessment of Spatial and Temporal Patterns of Green and Blue Water Flows Under Natural Conditions 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 has mainly focused on blue water but ignored green water. Furthermore, in data poor regions hydrological flows under natural conditions are poorly characterised but are a prerequisite to inform future water resources management. Here we report on spatial and temporal patterns of both blue and green water flows that can be expected under natural conditions as 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 22.05 – 25.51 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 a large amount of snow and melting water in upstream. Green water flows are distributed more homogeneously among different sub-basins. The green water coefficient was 87% - 89% 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 coefficients in many other river basins. The spatial patterns of green water coefficients were closely linked to dominant land covers (e.g. snow cover upstream and desert downstream) and climate conditions (e.g. high precipitation upstream and low precipitation 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 under natural conditions for the entire Heihe river basin at sub-basin level. The results are helpful to benchmark the natural flows of water in the basin as part of improved water resources management in the inland river basins of China.

## 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 human requirements. 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 functions and services 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. Liu et al. (2009a) 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, 1995 a, b), green/blue water research has become more and more diversified, especially after Falkenmark and Rockström (2006) conceptualized a wider green-blue flows approach for water-resource planning and management. Many novel research methods have appeared as well. For instance, Rost et al. (2008) and Gerten et al. (2005) use the LPJmL model to assess global green water consumption over a time period of nearly 30 years, while Liu et al. (2009a) 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).

Importantly, and especially for data poor regions, hydrological flows under conditions unaffected by human activities are often poorly characterized. Many studies tend to pay attention to the influence of human activities, but generally fail to characterize the state of the ecosystem under natural conditions. Modelling tools can aid in representing natural conditions and can be used as reference for follow-up studies and inform researchers and policy makers about the original state of a river basin as an input into decision-making.

The Heihe river is the second largest inland river in China, located in the northwest of China it originates in the Qilian Mountains, and discharges into the Juyanhai Lake. 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 ignored.

Furthermore, to formulate water management to be in line with environmental capacity a good understanding of the spatio-temporal patterns of the natural hydrological flows in the basin is needed. Unfortunately, this type of information and subsequent interpretation and analysis are currently lacking for the Heihe river basin. Therefore, the aim of our current research was to establish a benchmark for the natural flows of water in the basin and to quantify the spatial and temporal dynamics of green and blue water in the entire Heihe river basin under natural conditions. This information can provide a reference for subsequent studies and it can also be used to inform policy makers about the original state of water resources in the basin. Importantly, we focus on the complete river basin opposed to other studies that have looked at certain segments of the basin which is not sufficient to achieve integrated green and blue water management.

Specific objectives were (1) to calibrate and validate the SWAT model at two hydrological stations accounting for 85% of the total discharge in the Heihe river basin but that are not much affected by human intervention; (2) to quantify the spatial and temporal dynamics of green and blue water under natural conditions in the entire Heihe river basin and discuss implications for further research.

## 2. Methodology

### 2.1 The Study Area

The Heihe River basin lies between longitudes 97°05′-102°00′ E and latitudes 7°45′-42°40′ N. With a total basin area of 0.234 million km$^2$, this river basin is mainly located in the northwest of China, but it also has a part in Mongolia (Figure 1). There are two often-used river basin boundaries. The old one has an area of 0.116 million km$^2$. Such a boundary was created based on administrative boundaries (mainly the boundaries of different counties), but it lacked a practical hydrological sense. Realizing this, the Heihe Data Research Group has worked on a more accurate and complete new river basin boundary by integrating hydrological simulation with measured river system data (http://www.westgis.ac.cn/datacenter.asp). The output is the new river basin boundary with an area of 0.234 million km$^2$. Such a boundary not only reflects a more accurate division with an explicit hydrological meaning, but also reflects a watershed boundary under natural conditions. 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 run 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 Bada in Juran desert. The annual temperature is 2-3 ℃ upstream, 6-8 ℃ midstream, and 8-10 ℃ downstream. 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 year$^{-1}$ upstream to 4000 mm year$^{-1}$ downstream (Liu et al., 2008). The precipitation in the Heihe river basin occurs mainly in summer, spring and autumn are dry and some melting water is generated in spring, there is much snow in winter. The climate of the Heihe river basin is very dry, especially downstream where the drought index defined by the ratio of potential evapotranspiration and precipitation equals 47.5 (Li, 2009). There are 24 tributary channels with a total annual runoff larger than 10 million m$^3$, with more than 0.375 billion m$^3$ coming from the Qilian Mountains. The multi-year annual average precipitation is 122.6 mm, and most of this falls between May and August, accounting for over 70% of the total annual precipitation (Li, 2009). The melting water of Heihe river basin amounts to 0.1 billion m$^3$, or 4% of the total discharge (Li, 2009). Since the 1980s, agriculture water use has increased sharply midstream. From the 1980s to the 1990s, the annual discharge through the Zhengyi Canyon decreased from 0.942 billion m$^3$ to 0.691 billion m$^3$ (Xiao et al., 2011). River runoff provides about 65% of the irrigation water in midstream region while groundwater provides over 90% of the irrigation water in the downstream region (Xiao et al., 2011). 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 has been diminishing year by year. For example, Zhangye, the biggest city of the Heihe river basin located mid-stream, has witnessed a population increase of 14000 persons per year, with the population amounting to 1.27 million in 2000.

Irrigated agricultural area has increased by 2.87 thousands ha year$^{-1}$, 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.

## 2.2 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 aquifers. 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 below (Liu et al., 2009a).

$$GWC = {}^{\mathrm{g}}\!\big/_{(\mathrm{b}+\mathrm{g})} \qquad (1)$$

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.

$$RCR = {}^{(V_i - V_0)}\!\big/_{V_0} \times 100\% \qquad (2)$$

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

## 2.3 The SWAT model

We use the Soil and Water Assessment Tool (SWAT) to simulate green and blue water flows. The SWAT model is a semi-physically based, semi-distributed, basin-scale model (Neitsch et al., 2004), which has been used widely in many countries around the world (Schuol et al., 2008; Gerten et al., 2005; Faramazi. et al., 2009). There are two main reasons for selecting the SWAT model. Firstly, it has already been successfully applied for water quantities (Faramazi et al., 2009; Schuol et al., 2008) and quality (Gassman et al., 2007) assessments for a wide range of scales and environmental conditions, including green/blue water assessments, secondly, the SWAT model has been used to simulate the hydrological processes in a small upstream segment of the Heihe river basin successfully (Huang and Zhang, 2004; Li et al., 2009). There are more than nine types of hydrological models that have been used in the Heihe river basin for water resources research (Li, 2009). Nevertheless, 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. An important reason is that past research on hydrological cycles is often focused on human water use, particularly blue water use, thus overlooking water use by ecosystems. The up- and middle segments are regions where blue water is generated and used, but the downstream segments and surrounding areas are dominated by natural ecosystems and a low population density. Hence, most of the studies have focused on simulating upstream segments and not the entire basin or downstream watersheds. However, we argue that studying the hydrological processes for the entire basin is essential since water is not only required by human beings but also needed by natural ecosystems. In addition, a study covering the entire basin makes more sense from a hydrological point of view. An additional reason for the emphasis on upper river segments may also be the lack of available data for the downstream river segments.

In our research, we use SWAT2005, which was running on Arcview 3.3 with a daily time step. In SWAT the modelled area is divided into multiple sub-basins and hydrological response units (HRUs) by overlaying elevation, land cover, soil, and slope classes. The HRUs are 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, 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 Neitsch et al. (2004). The pre-processing of the SWAT model input was performed within ESRI Arc-GIS 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.

## 2.4 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 obtained from the Heihe Data Research Group (http://www.westgis.ac.cn/datacenter.asp). The collection of the data was followed by an accuracy assessment and analysis of the quality and integrity of the data. The basic input maps included DEM at a resolution of 30 meters (USGS/EROS, 2009) and land cover at a resolution of 1 km from the Heihe Data Research Group. There are 26 classes of land use in the Heihe river basin including cropland, forest, grassland, lakes, wetland, among others. We have built the land use database using Chinese land cover type characters (http://westdc.geodata.cn). 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). 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 (Figure 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.

## 2.5 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 natural conditions. 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 Figure 1) and have also been used for calibration and validation by Li (2009). Our reasons are twofold; (1) more than 85% of the annual discharge in the Heihe river flows through these two hydrological stations so the optimized parameters of the upstream area will be very important in representing the entire watershed; (2) the stations are not much affected by human interference which is in line with our aim of analysing the green and blue water distribution under natural conditions. Furthermore, 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: a calibration (1979-1987) and a validation period (1990-2004).

Based on the built-in sensitivity analysis tool in SWAT (Neitsch et al., 2004), we have identified the 11 most sensitive parameters. In addition, based on previous studies, three other parameters (SMFMX, SMFMN and TIMP in Table 1) were identified as also being important for SWAT simulation in the Heihe river basin (Li, 2009). These 14 parameters are listed in Table 1. Two indices, the Nash-Sutcliffe coefficient (Eq. 3) and the Coefficient of Determination (Eq. 4), are used to evaluate the goodness of the calibration and validation.

$$E_{ns} = 1 - \frac{\sum_{i=1}^{n}(Q_{oi} - Q_{mi})^2}{\sum_{i=1}^{n}(Q_{oi} - \overline{Q}_o)^2} \qquad (3)$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}(Q_{oi} - \overline{Q}_o)(Q_{mi} - \overline{Q}_o)\right]^2}{\sum_{i=1}^{n}(Q_{oi} - \overline{Q}_o)^2 (Q_{mi} - \overline{Q}_o)^2} \qquad (4)$$

$E_{ns}$ 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 Nash and Sutcliffe, (1970) and Abbaspour, (2007) respectively.

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) and we chose two different indices to compare measurement to simulation: the P-factor and the R-factor. The P-factor is the percentage of data bracketed by the 95PPU band. 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-factor is the average width of the band divided by the standard deviation of the corresponding measured variable (Abbaspour, 2007; Faramarzi et al., 2009). The R-factors were 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. R-factor indicates the strength of the calibration and should be close to or smaller than a practical value of 1 (Abbaspour, 2007).

## 3. Results and Discussion

### 3.1 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 $R^2$ (Figure 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. 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 (Figure 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. Nevertheless, several challenges remain while optimizing the parameters, for instance, model calibration using river discharge alone does not provide confidence on the partitioning of water between soil storage, actual evapotranspiration and aquifer recharge. When additional data (e.g. measured evapotranspiration) are available, a multi variable calibration is required to calculate water resources availability based on water yield and green water components.

## 3.2 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 Figure 3. From the relative change rate, we found that there is a general decreasing trend in per unit area water flow (in mm year$^{-1}$) from upstream to downstream sub-basins (Figure 3). This is easy to understand because annual precipitation decreases from upstream to downstream with snow and melting water upstream (Wang and Zhou, 2010).

The total water flow was 22.05 - 25.51 billion m$^3$ in the 2000s for the entire river basin. There are several blue colored regions that stand out with relative high total water flow in volume: those upstream generally have high precipitation and often a large volume of snow and melting water (Li, 2009), while those downstream are often resulting from large sub-basin areas. SWAT generates sub-basins based on DEM, land use and soil types. Because downstream regions have more homogeneous distribution of elevation, land use and soil types, the downstream sub-basin areas can be ten times larger than those upstream. From the 1980s to the 1990s, the total water flow has a general decreasing trend in upstream and midstream sub-basins, but the relative change rate has a general increasing trend in downstream sub-basins.

However, for the relative change rate 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 (Figure 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 snow and melting water. In downstream sub-basins, sunshine durations increased from the 1980s to the 1990s but decreased from the 1990s to the 2000s (Liu et al., 2009b), 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 under natural conditions in the Heihe river basin. From 1980s to 2000s, the total water flow of Heihe river basin did not change much with a very slight increase by about 1.1% - 1.4 % (Figure 4).

### 3.3 Spatial and temporal distribution of green/blue water flows per sub-basin

Both the green and blue water flows per unit area in the Heihe River basin decreased from up stream to downstream (Figure 5). Generally, where blue water flows per unit area are high, green water flows also tend to be high (Figure 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 snow and melting water often have higher blue water flows per unit area.

The blue water flows in the Heihe river basin were generally high in upstream sub-basins and low in downstream sub-basins (Figure 6). Two factors contribute to this spatial pattern: precipitation and land cover type. In upstream sub-basins, precipitation is generally high where snow and melting water 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 relative change rate decreased upstream and middle-stream and increased downstream (Figure 6). However, from the 1990s to 2000s, relative change rate has 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't 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.

Green water flows are distributed more homogeneously than blue water flows among regions. 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 downstream than upstream. This also contributes to the more even distribution of green water flows. Furthermore, the green water flow quantity is similar to previous research. Jin and Liang (2009) studied the actual evapotranspiration of Zhangye in the Heihe river basin, which is located at midstream and close to Zhengyi canyon. They showed that annual evapotranspiration ranged from 238 million $m^3$ in the 1980s to 355 million $m^3$ in the 2000s. Our results show annual evapotranspiration of about 200 to 400 million $m^3$ in the above two periods (Figure 7). Similar results were also estimated by Cheng et al. (2007).

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 flow relative change rate 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 (Figure 7). There are no clear signals of increased or decreased green water flows with time.

### 3.4 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 (Figure 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 is much snow and melting water upstream, which generate a large amount of runoff through melting. This is particularly obvious for one sub-basin (in dark blue) in the 1980s where the green water coefficient is even lower than 65%. This sub-basin links upstream and mid-stream as most of the upstream discharge flows through Yingluo Canyon in this sub-basin onwards to mid- and downstream (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 the dominant land cover. Runoff seldom occurs as precipitation mostly 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 (Figure 8).

For the entire basin, the green water coefficient remained relatively stable over the whole time period (87% - 89% in the 1980s, 88% - 89% in the 1990s and 88% - 89%

in the 2000s; Figure 4). The green water coefficient is very high compared to previous studies on other locations, e.g. 58% in the Congo river basin and 61% in the west of Iran (Schuol et al., 2008; Faramarzi et al., 2009). The high green water coefficient in the Heihe river 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 a significant trend of change in the green water coefficient. The fluctuation of the green water coefficient also occurs upstream and mid-stream (Figure 4). Downstream, the green water coefficient increased from the 1980s to the 2000s.

## 4. 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 upstream hydrological stations indicated 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, the water resources distribution in time and space has been altered by human activities midstream. This has led to significant deviations of the green and blue water flows and transformations from what would be expected under natural conditions. 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 (Figure 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 operation of reservoirs. Clearly, human activities, especially the expansion of irrigated area, have already influenced the water cycling significantly in the Heihe river basin. However, the extent of the hydrological responses to human intervention has never been assessed quantatively. The current study provides a first step for such an assessment by quantifying the green and blue water flows under natural conditions. Third, although the two upstream discharge stations represent 85% of the annual discharge flows, they represent a small proportion of the entire region. Using only these two stations may work satisfactorily for simulating green and blue water flows under natural situations, but more hydrological stations are still needed in the next step to study the effects of human activities on hydrological flows. Last but not least, the lack of soil moisture and actual evapotranspiration data hampers the validation of 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 provide a theoretical reference for 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 $H_20$ 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 [ ℃] | -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 June 21 [mm $H_2O$ ℃-$day^{-1}$] | 5.85-6.27 | 6.02 |
| v__SMFMN | Melt factor for snow on December 21 [mm $H_2O$ ℃-$day^{-1}$] | 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;Yang et al., 2008). 'v_', 'r_' means an 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.

## Figure Legends

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

**Figure 2**. Comparisons between the observed and simulated (expressed as 95% prediction uncertainty band) discharge for the Zhamushike and Yingluo canyon hydrological stations in Heihe river basin

**Figure 3**. The total amount of water flow (the best simulation and long term average annual values) and its relative change rate in the Heihe river basin

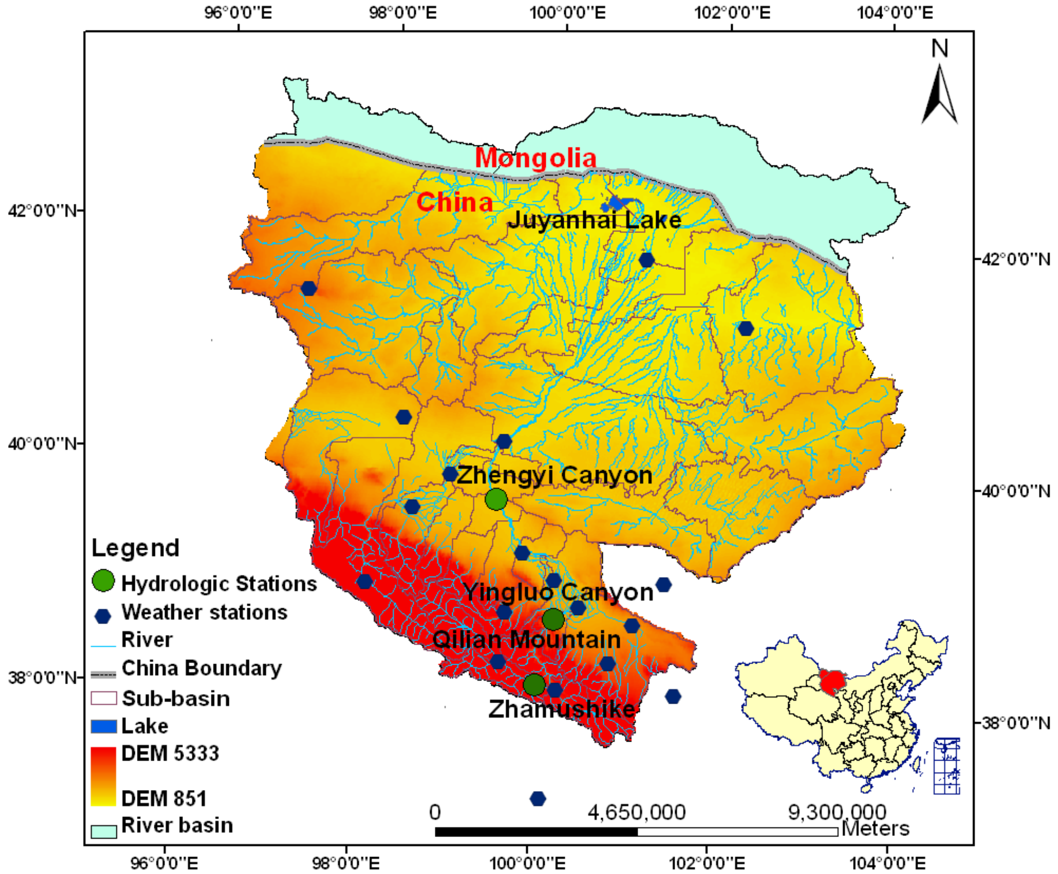
**Figure 4**. The total water flow and green water coefficients from the 1980s to the 2000s in the Heihe river basin (G is green water coefficient)

**Figure 5**. The green/blue water flows (the best simulation and long term average annual values) per unit area (mm $year^{-1}$) from the 1980s to the 2000s in the Heihe river basin

**Figure 6**. The blue water flows (the best simulation and long term average annual values) (million $m^3$ $year^{-1}$) from the 1980s to the 2000s in the Heihe river basin

**Figure 7**. The green water flows (the best simulation and long term average annual values) (million $m^3$ $year^{-1}$) from the 1980s to the 2000s in the Heihe river basin

**Figure 8**. The green water coefficient (the best simulation and long term average annual values) from the 1980s to the 2000s in the Heihe River basin

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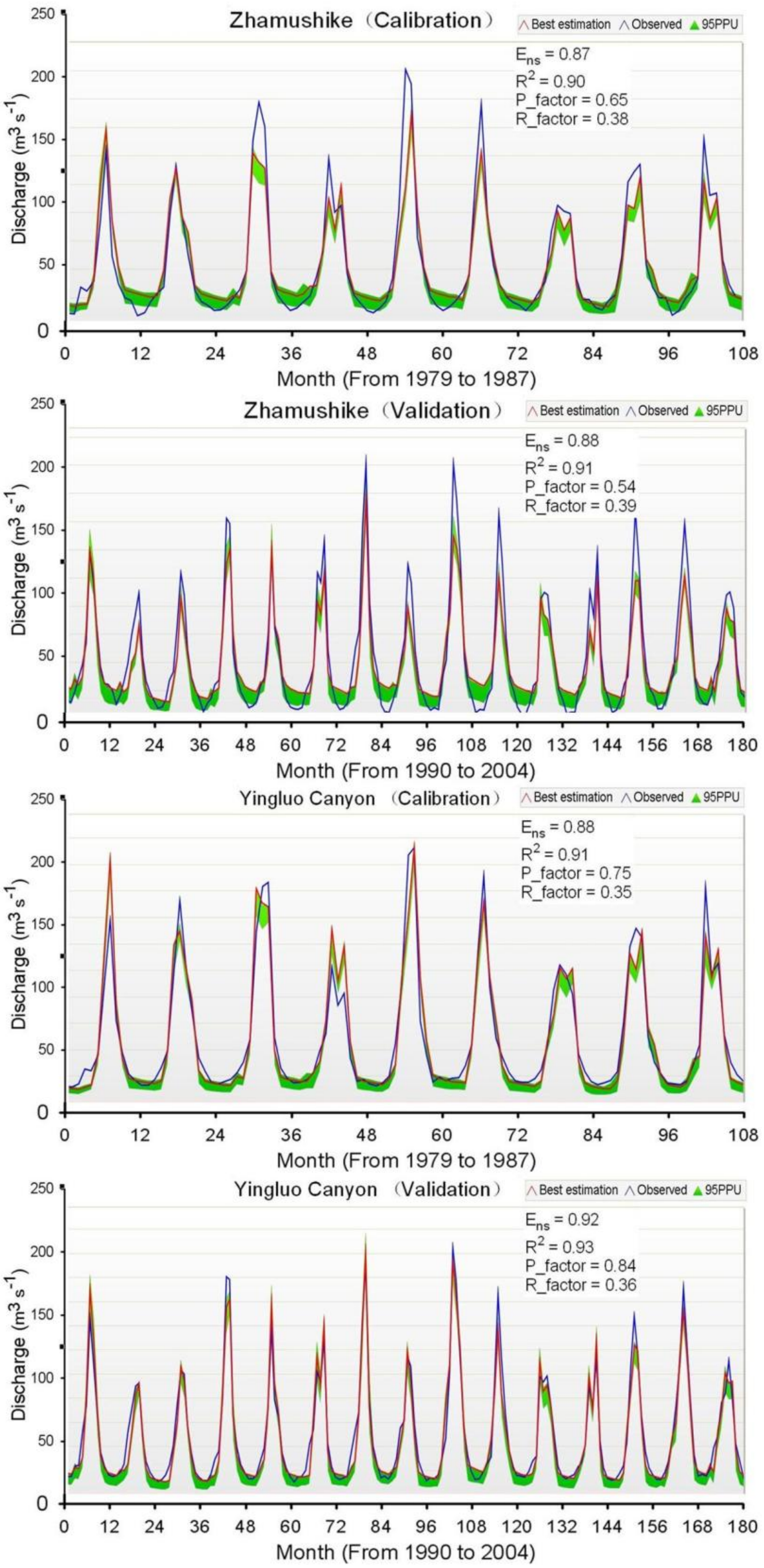


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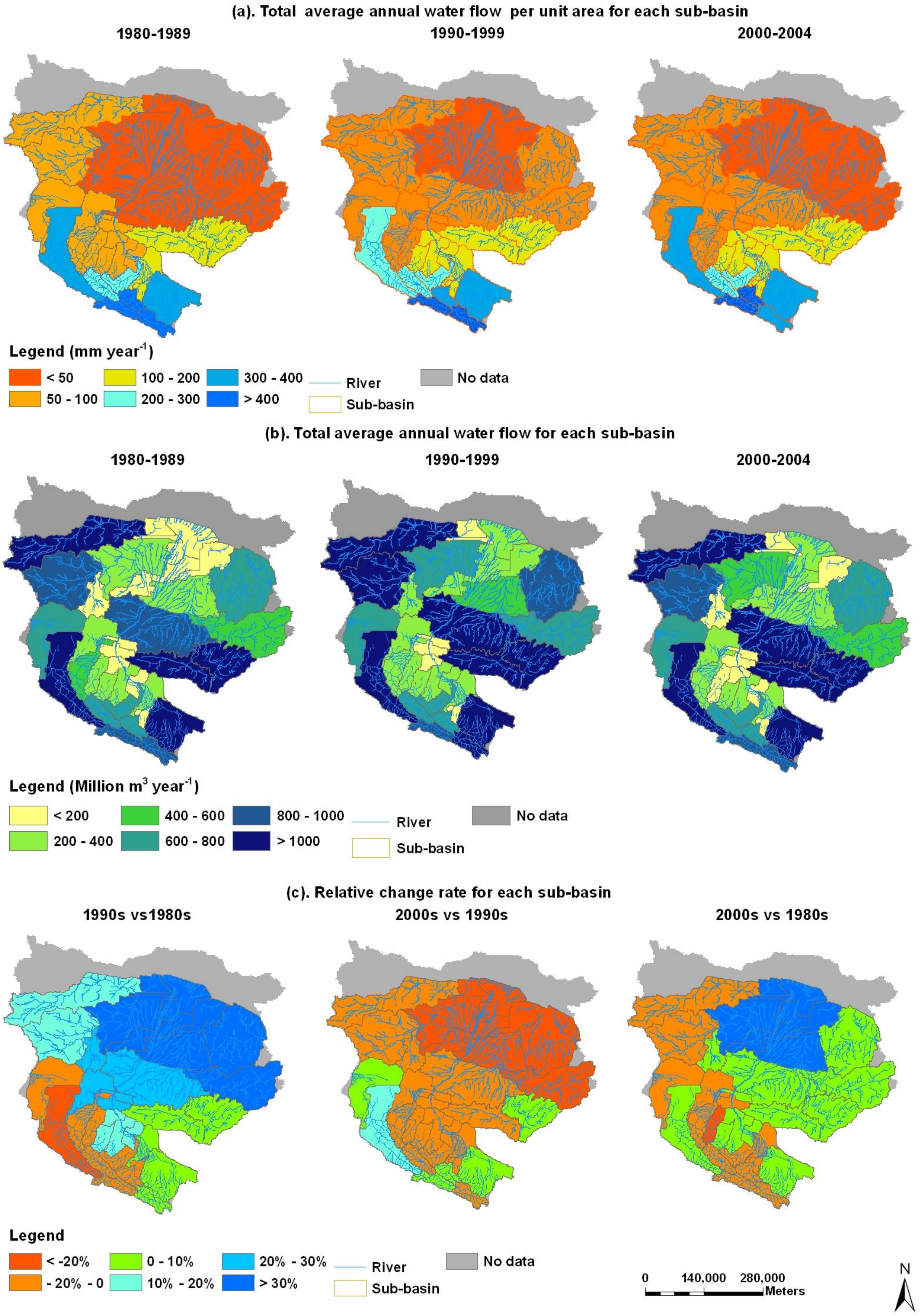



**Figure 3**. The total amount of water flow expressed by annual averages and its relative change rate in the Heihe river basin (based on best estimation of variables)

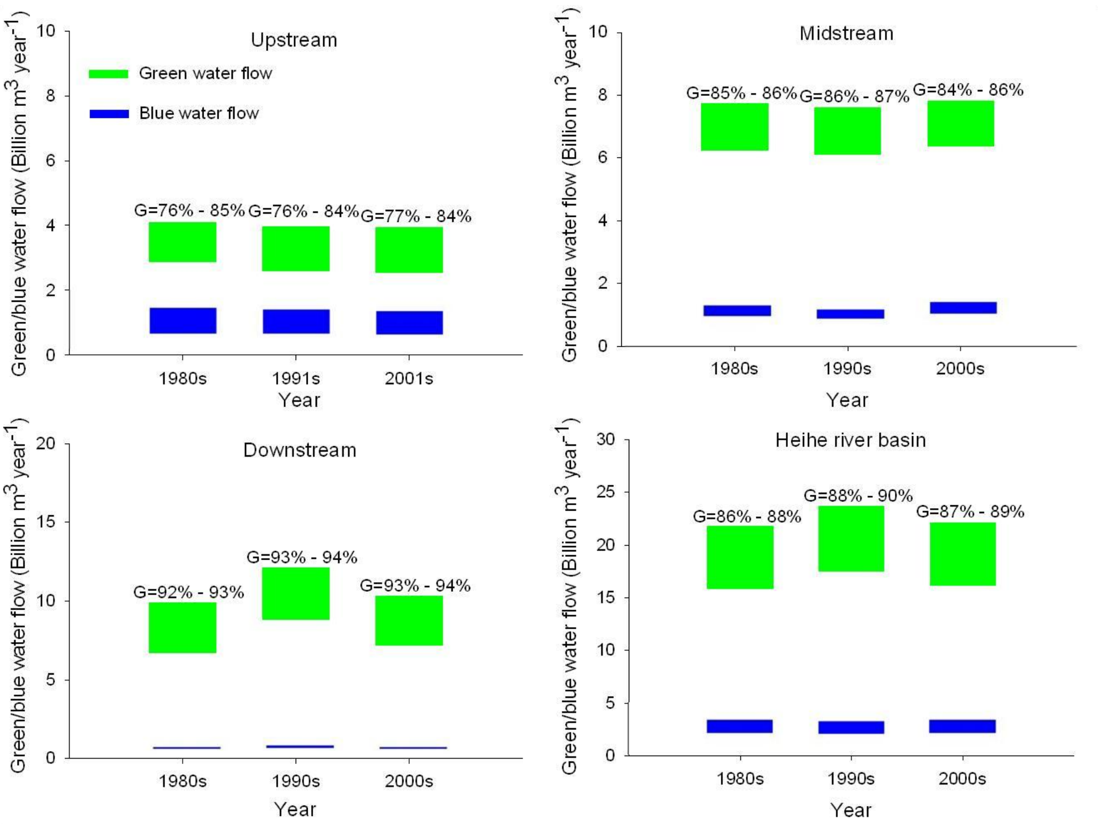



**Figure 4**. The total water flow and green water coefficients from the 1980s to the 2000s in the Heihe river basin (G is green water coefficient)

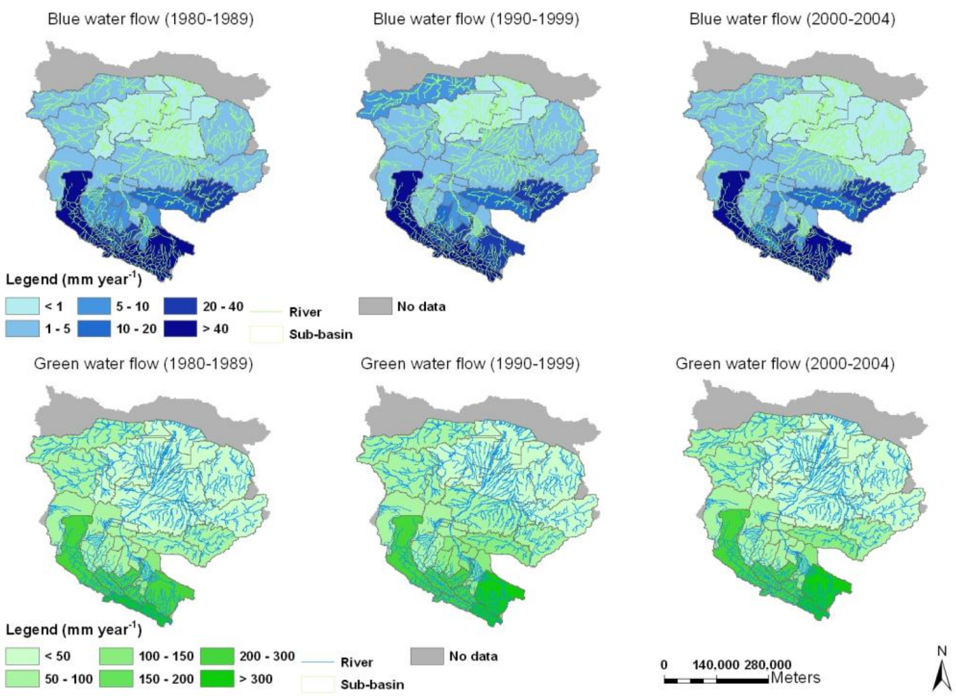



**Figure 5**. The annual average green/blue water flows (per unit area (mm year$^{-1}$) from the 1980s to the 2000s in the Heihe river basin

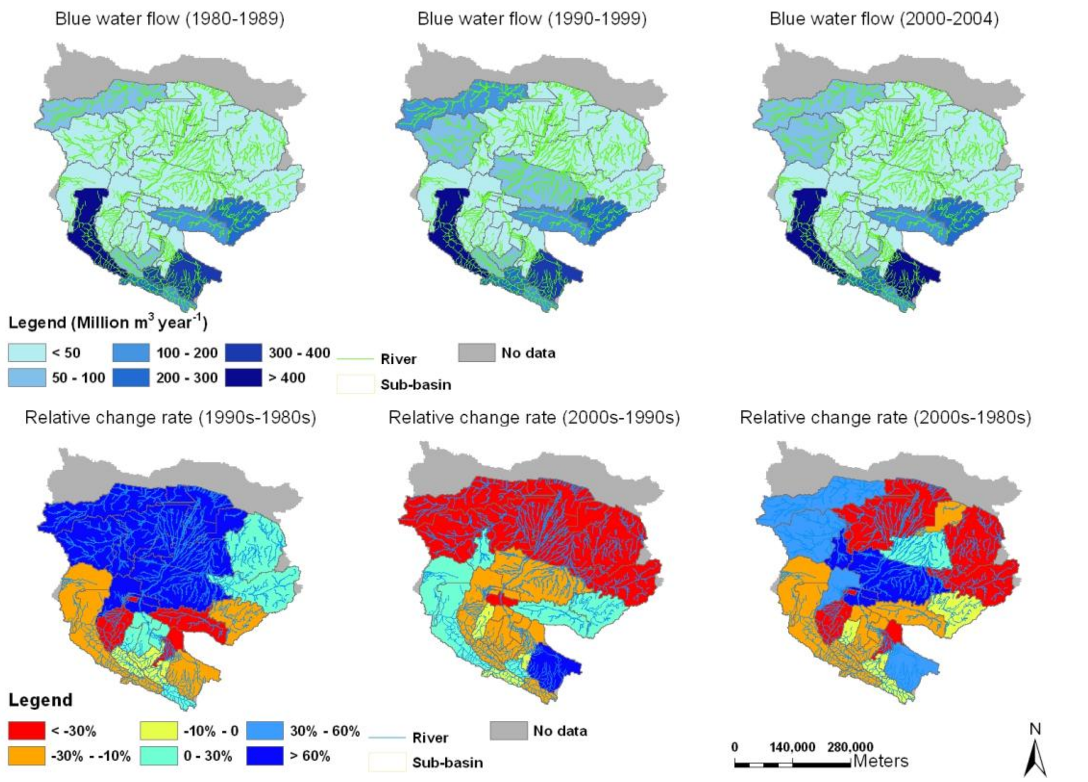
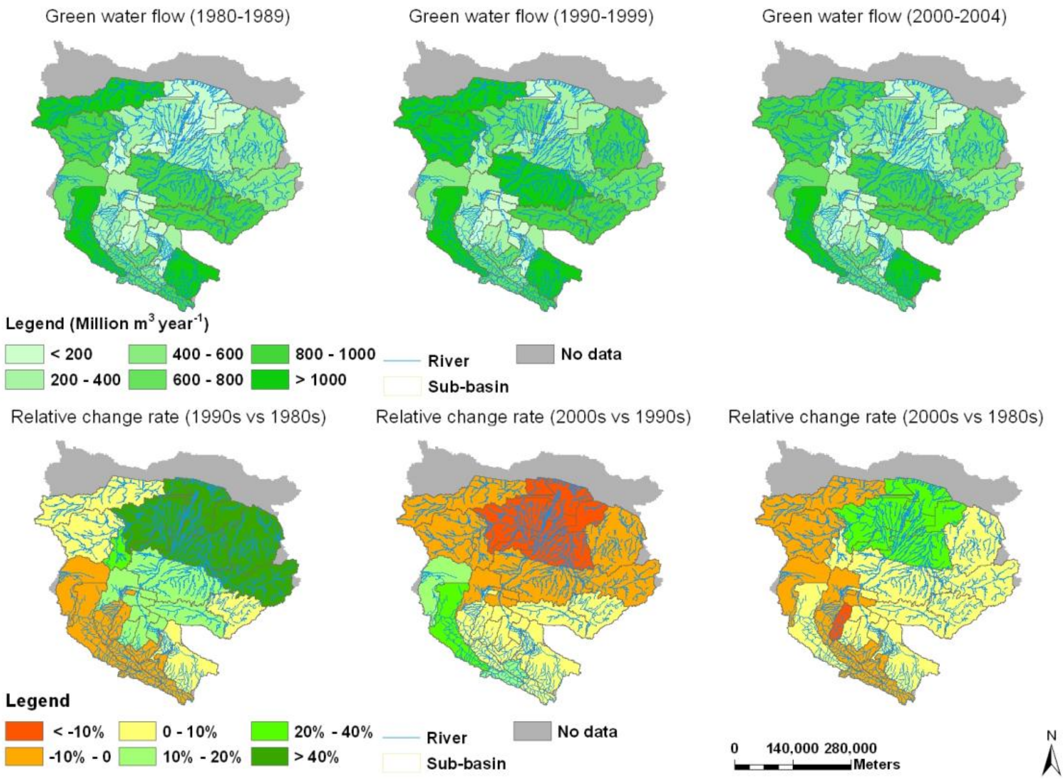



**Figure 6**. The averaged annual blue water flows (million $m^3$ $year^{-1}$) from the 1980s to the 2000s in the Heihe river basin

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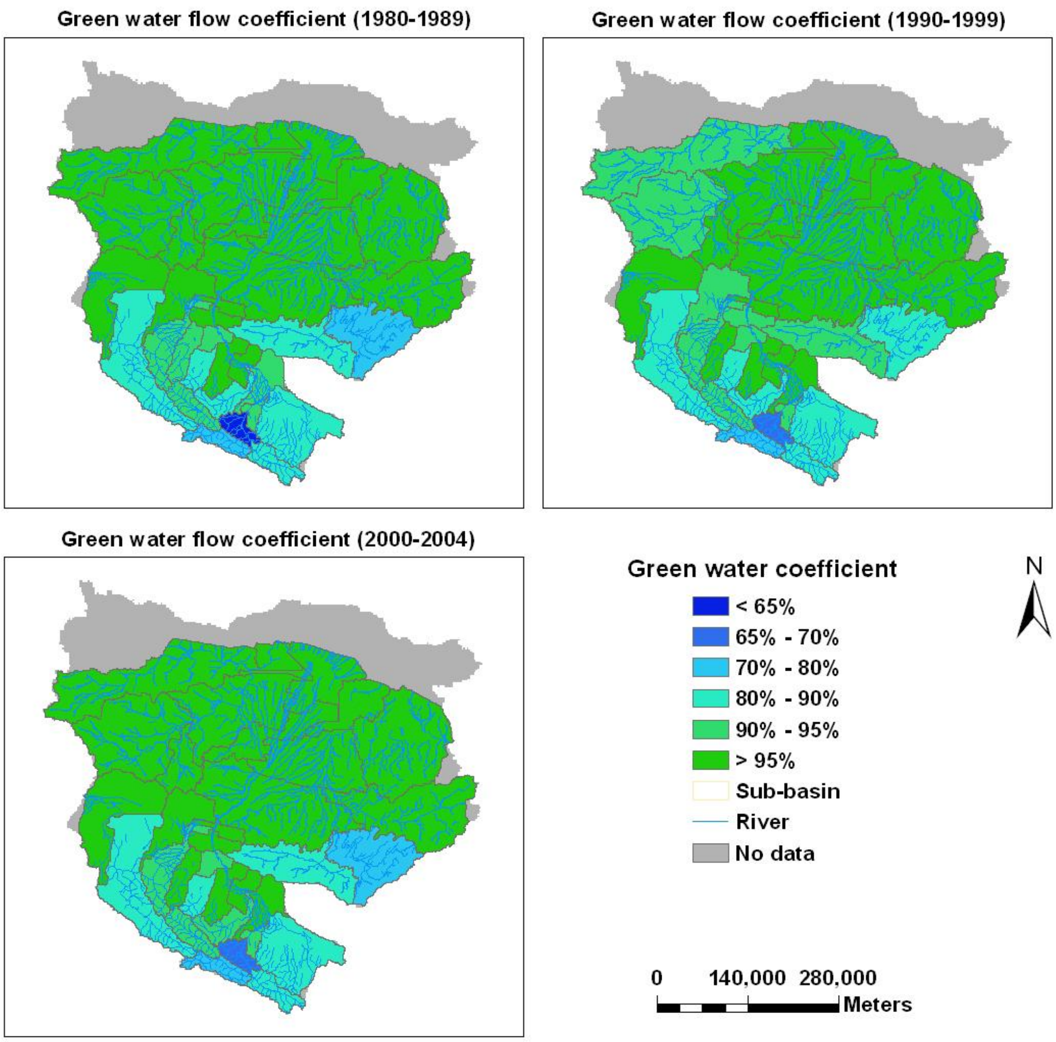


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