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Impacts of human activities and climate variability on green and blue water flows in the Heihe River Basin in Northwest China

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Abstract

Human activities and climate factors both affect the availability of water resources and the sustainability of water management. Especially in already dry regions, water has become more and more scarce with increasing requirements from growing population, economic development and diet shifts. Although progress has been made in understanding variability of runoff, the impacts of climate variability and human activities on flows of both green water (actual evapotranspiration) and blue water (discharge accumulated in the river network) remain less well understood. We study the spatial patterns of blue and green water flows and the impacts on them of human activities and climate variability as simulated by the Soil and Water Assessment Tool (SWAT) for an inland Heihe river basin located in Northwest China. The results show that total green and blue water flow increased from 1980 to 2005, mainly as a result of climate variability (upward precipitation trends). Direct human activities did not significantly change the total green and blue water flow. However, land use change led to a transformation of 206 million m^3 from green to blue water flow, while farmland irrigation expansion resulted in a transformation of 66 million m^3 from blue to green water flow. The synchronous climate variability caused an increase of green water flow by 469 million m^3 and an increase of blue water flow by 146 million m^3 at the river basin level, while the geographical distribution showed an uneven change even with reductions of water flows in western sub-basins at midstream. The results are helpful to benchmark the water resources in the context of global change in the inland river basins in China. This study also provides a general approach to investigate the impacts of historical human activities and climate variability on green and blue water flows at the river basin level.

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1 Introduction

The impact of climate change on water availability has caused sustainability concerns around the world (Piao et al., 2010; Vörösmarty et al., 2000). With global warming, extreme weather events are now occurring more frequently, resulting in serious challenges to water supply (Vörösmarty et al., 2000, 2010; Oki and Kanae, 2006; Alley et al., 2003). Global climate change has already decreased water resources in many regions (Kundzewicz et al., 2008). In particular in arid regions, water use competition is intense among human, agriculture and ecosystems (Cheng et al., 2003; Vörösmarty et al., 2000). This influences socioeconomic sustainability and ecosystem health, and may lead to ecosystem degradation (Piao et al., 2010; Falkenmark et al., 2003; Cheng et al., 2006). Therefore, a comprehensive study on the available water resources in the context of global change is critical for an in-depth understanding of the variability of water resources for better water resources management.

In recent years, scholars have paid much attention to blue water resources assessment and management, but they have not paid sufficient attention to green water that is important for both human and ecosystems (Falkenmark, 1995; Cheng et al., 2006). Blue water is the water that is stored in rivers, lakes, aquifers and wetlands, while green water refers to the soil water from precipitation that is used for plant transpiration and soil evaporation (Falkenmark, 1995). Green water plays a critical role in producing food and maintaining natural ecosystems (Falkenmark et al., 1995, 2006). Rost et al. (2008) and Liu et al. (2009a, b) estimated green water accounted for more than 80 % of consumptive water use of global crop production. Furthermore, water use in other ecosystems (e.g. grassland and forest ecosystems) is dominated by green water (Rockström, 1999; Rost et al., 2008).

Water resources in a catchment is influenced not only by climate change but also by activities of humans (Wang et al., 2005). Actually, there is interaction among climate factors, human activities and water resources. Water vapour cycling is a critical part of the climate system; and climate change will also influence the spatial and temporal

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variability of water resources in a watershed (Chen et al., 2007; Ren, 2011). On the one hand, human activities (e.g. land use change and irrigation) will change the discharge generation mechanism; on the other hand, human activities (e.g. greenhouse gas emissions) will trigger global or regional warming, consequently influencing water resources distribution (Siriwarden et al., 2006; Thamapark et al., 2006). The impacts of human activities and climate factors may cause a water shortage or crisis, especially in arid and semi-arid regions (Xiao et al., 2004). Therefore, assessments of the joint impacts of human activities and climate variability and trends on water resources are needed to understand green and blue water variability and sustainability of freshwater use in arid regions.

Recently, several studies have investigated the impacts on water resources of human activities, including land use change (Postel et al., 1996; Gerten et al., 2008; Jewitt et al., 2008; Liu et al., 2009), water conservancy projects (Hayashi et al., 2008; Liu et al., 2013), and irrigation (Allen et al., 1998; Wang et al., 2003). Li et al. (1998) found that human activities mainly in terms of irrigation decreased runoff in downstream locations of the Tarim River Basin. Fang et al. (2001) found that the groundwater table declined and land subsidence had happened in several cities in the northern part of China due to groundwater over-exploitation. Williams (2009) estimated that water conservancy projects caused runoff to decrease by more than 55 % in the Nile River Basin. And Wang et al. (2003) found that cropland irrigation decreased runoff and changed overall water flows in the Hexi corridor (Heihe river basin, China). However, how human activities and climate factors synchronously impact on both green and blue water flow and their spatial distribution remains a rarely studied issue. In addition, many studies emphasize global change impacts on water resources in the future by establishing future scenarios (Xu et al., 2003; Wei et al., 2009), but few focus on the past.

In this study, we investigated the impacts of three main processes, i.e. land use change, irrigation expansion and climate variability, on the flows of green and blue water in the Heihe river basin over the period 1986 to 2005. Based on these results, we discuss implications for future research and water management. The Heihe river basin

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is the second-largest inland river basin in China. It is located in the northwest of China, and it has suffered from a serious water crisis in recent years (Cheng et al., 2003, 2006). Following the socio-economic development, water use in the midstream has increased sharply (Ma et al., 2011), and recently, human activities have changed the distribution of lakes and watershed and the inter-annual allocation of water resources in the Heihe basin (Xiao et al., 2004). So far, no efforts have been paid to the assessment of green and blue water in the context of global change. We here investigate the green and blue water dynamics and their natural and anthropogenic causes.

2 Methodology

2.1 The study area

The Heihe river originates in the Qilian Mountains, and discharges into the Juyanhai Lake. The area of the basin is 0.24 million km^2, with the majority located in China and a minor part in Mongolia (Fig. 1). The basin has an average altitude of over 1200 m with a length of 821 km for the major channel. Three sections are often distinguished: upstream from the Qilian Mountain to the Yingluo Canyon, midstream running from the Yingluo to Zhengyi Canyon, and downstream terminating in the Juyanhai Lake (Fig. 1). The average annual air temperature is 2–3 °C in the upstream, 6–8 °C in the midstream, and 8–10 °C in the downstream area. The average annual precipitation is 200–500 mm in upstream, 120–200 mm in midstream, and < 50 mm in most downstream regions (Cheng et al., 2003). The potential evaporation ranges from 1000 mm yr^{-1} in the upstream to 4000 mm yr^{-1} in the downstream area (Li, 2009). Precipitation occurs mainly in summer and autumn (> 70 % of annual precipitation between May and August; Ma et al., 2011), whereas spring is dry with snow and ice melting (4 % of total discharge; Li, 2009); there is much snow in winter (Cheng et al., 2003). The river discharge provides about 65 % of the blue irrigation water in midstream regions, while groundwater provides over 90 % in the downstream regions (Xiao et al., 2011). The main land cover

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types of the basin include desert (prevailing downstream), mountains (upstream) and oases (midstream); these three land covers together account for 98.6 % of the total basin area (Cheng, 2003).

2.2 Simulation experiments

To study climatic and anthropogenic impacts on green and blue water resources in the Heihe basin, we set up four simulation experiments as follows: *scenario A* fixes land use and climate conditions around 1986 (land use in 1986 and climate for 1984–1986); *scenario B* uses land use in 1986 and climate conditions for 2004–2006; *scenario C* uses land use in 2005 and climate conditions for 2004–2006; *scenario D* assumes all crops are irrigated in addition to scenario C (Fig. 2). Based on these scenarios, we analyse the impacts on green and blue water flows of climate variability (difference between B and A), land use change (difference between C and B), irrigation expansion (difference between D and C) and all factors (difference between D and A), respectively.

2.3 The SWAT model

In this study, we used the Soil and Water Assessment Tool (SWAT) to simulate green and blue water flow for the river basin of Heihe. The SWAT model is a semi-distributed water assessment model (Neitsch et al., 2004), which has been applied widely in different regions across the world (e.g. Schuol et al., 2008; Faramazi et al., 2009). We select the SWAT model for this study mainly due to two reasons. Firstly, it has been successfully used for assessments of water cycling processes under different environmental conditions (Faramazi et al., 2009; Schuol et al., 2008; Gassman et al., 2007); and secondly, it has been successfully tested to simulate hydrological processes in the Heihe river basin (Huang et al., 2004; Li et al., 2009), including the green and blue water flows (Zang et al., 2012).

We use the version of SWAT-2005 that works in Arcview-3.3. The study area was separated into 309 hydrological response units (HRUs) and 32 sub-basins with

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information on topography, land use type, soil attributes, and management. Evapotranspiration was estimated by the Hargreaves method (Hargreaves et al., 1985), surface runoff was calculated with an SCS Curve Number (CN) method (Neitsch et al., 2004), while snowmelt was computed by an energy balance approach (Neitsch et al., 2004). The actual evapotranspiration includes plant transpiration and soil evaporation. The SWAT model first calculates rainfall interception by plant canopy, then the maximum plant transpiration and soil evaporation using an approach similar to Ritchie (1972). The actual plant transpiration and soil evaporation are then calculated based on the soil moisture balance following Neitsch et al. (2004). The land use types influence surface runoff generation rate and evapotranspiration. In SWAT, different land cover types (urban, crop and forest) correspond to different parameters (e.g. for curve number) (Neitsch et al., 2004). Irrigation influences the discharge in water channels and transpiration of irrigated crop. We only worked on the part of the river basin located within China and did not include the Mongolia part due to the lack of data. We use the SUFI-2 approach from the SWAT-CUP interface (Abbaspour et al., 2007) to optimize parameters. The Nash–Sutcliffe coefficient (E_{ns}) (Nash et al., 1970) and the coefficient of determination (R^2) were used to evaluate the goodness of the calibration and validation process.

This study is an expansion of our previous research. In Zang et al. (2012), we assessed the spatial and temporal distribution of the water flows of green and blue only under natural conditions, i.e. without considering human activities. The SWAT model was calibrated to simulate the green and blue water flows at the whole-basin level by using climate data from 1980 to 2004 and land use data for 2000 (Zang et al., 2012). The calibration and validation processes were performed successfully, as shown by high values of E_{ns} (> 0.87) and R^2 (> 0.9). Further information on the model simulation, parameters, calibration, and validation can be found in Zang et al. (2012). In the present study, we used the calibrated parameters derived from the previous study, and further investigated the impacts of human activities (land use change and irrigation expansion) and climate variability on the green and blue water flows. The impacts are assessed by comparing results from different scenarios with those under natural conditions. We expand the study period to cover 1978–2005, and land use maps for 1986 and 2005 are used in addition to that for 2000 in previous research.

2.4 Green and blue water flow and data

The actual evapotranspiration is green water flow, whereas the sum of surface runoff, lateral flows, and groundwater recharge is treated as blue water flow (Schuol et al., 2008). To account for the relative importance of the two flows, we defined the green water coefficient (GWC) as the ratio of green water flow to the total flow (green and blue water flows) (Liu et al., 2009a). The relative change rate (RCR = $[(V_i - V_0)/V_0] \times 100\,\%$) was applied to indicate the relative change of a variable. V refers to a variable (e.g. green water flow), 0 indicates the initial time period, and i the ending time period.

The data on daily climate, DEM and land use in 1986 were obtained from the Heihe Data Research Group (HDRG) (http://westdc.geodata.cn). We used climate data between 1980 and 2005 from 19 weather stations for our simulation: 7 upstream, 7 midstream, and 5 downstream stations. The irrigation area, irrigation depth, and irrigation parameters that need input the SWAT model were obtained from published literature (Ge et al., 2011; Wang et al., 2012) and the Ministry of Water Resources irrigation test web site (http://www.syzz.org.cn/about.asp?id=23). The irrigation districts data were obtained from the HDRG (http://westdc.geodata.cn), and the total irrigation area in the river basin is 1.88 million ha. In scenario D, we assume that all cropland within the irrigation districts is irrigated. The 1 km land use data for 1985 and 2005 were obtained from the institute of Geographic Science and Nature Resources Research, Chinese Academy of Sciences (CAS) (http://www.geodata.cn/Portal/aboutWebsite/aboutus.jsp?isCookieChecked=true) (see Table 2 for land use types). The soil data were obtained from the Harmonized World Soil Database (HWSD) (http://www.iiasa.ac.at) with a spatial resolution of about 1 km. This dataset includes 63 soil types for the Heihe river basin, and for each soil type soil parameters for two soil layers are available, i.e. 0–30 cm and 30–100 cm.

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3 Results

3.1 Impact of land use change

Impacts of land use change are assessed by comparing difference of results from land use in 1986 and 2005 (holding all other factors unchanged). According to our model simulation results (Table 1), at the river basin level, land use change has resulted in an increase of blue water flow by 206 million m^3 and a concurrent increase in green water flow by the same amount. These changes are simulated in particular for the midstream and a part of the downstream region (Figs. 4 and 5). The relative change rate in the sub-basins there was more than 50 % (Fig. 3). Irrigation water use and urban land use are the two main reasons that caused the hydrological variability in the SWAT model (Neitsch et al., 2004). In this section, the main reason for these changes was, that urbanization expanded fast in these sub-basins (Fig. 4; Table 2), accelerating surface runoff production. In our simulations, the total green and blue water flow did not change in response to the land use changes, but the green water coefficient is found to have decreased from 81–90 % to 71–75 %, in particular in the middle part of midstream (Fig. 7).

3.2 Impact of irrigation expansion

At the river basin level, irrigation expansion resulted in a decrease of blue water flow by 66 million m^3, according to our model (Table 1). Blue water flow decreased in particular in midstream regions (Fig. 3), where a large area of agriculture with many irrigation farmlands exists (Fig. 4). In an earlier study, irrigation expansion was shown to require a large amount of water from rivers and groundwater (Wang et al., 2003). Green water flow has increased by the same amount due to farmland irrigation (Fig. 5), because, compared to rainfed agriculture, irrigated agriculture consumed more water and thus increased actual evapotranspiration. As in the case of the isolated land use change effect, the total green and blue water flow did not change at the river basin level due to irrigation expansion, and the green water coefficient has increased from 71–75 % to 81–90 % in particular in the eastern part of the midstream area (Fig. 7).

3.3 Impact of climate variability

Climate variability, assessed as the difference between the mid-1980s and the mid-2000s, has increased both blue and green water flow by 146 and 469 million m^3, respectively (Table 1), with little change in the green water coefficient (87–88 %). Spatially, although climate variability has led to an increase in blue and green water flows in most sub-basins, we can also find a clear decreasing trend of both flows in the western part of the midstream. The decrease was a result of a lower precipitation in the western midstream area, where precipitation has decreased significantly at $p < 0.10$ level from 1980 to 2005 (Fig. 8). Precipitation had increased in downstream areas; hence, blue and green water flows have increased there (Fig. 8).

3.4 Impact of all factors

In response to climate, land use and irrigation change, blue water flow has increased by 286 million m^3 in the entire river basin (Table 1). The spatial distribution of the changes in blue water flow varies largely, with decreases in western sub-basins, but increases in eastern sub-basins in midstream areas. The relative change rate of several midstream sub-basins exceeded 30 % (Fig. 3). The change patterns were found to be largely influenced by climate variability; for example, in the western part of midstream areas, precipitation showed a decreasing trend (Fig. 8); hence, both blue and green water flows decreased, though also influenced by other factors. As shown above, the accelerated urbanization and farmland irrigation are the other main reason that caused blue water flow variability, the increase of blue water flow probably influenced by urbanization development, and the decrease by irrigation expansion (Wang et al., 2003; Ma et al., 2008). Therefore, land use change contributed most to this increase, followed by the contribution from climate variability (Table 1).

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Green water flow showed an increasing trend with a 329 million m^3 higher flow over the entire river basin, mainly due to climate variability but also due to irrigation expansion (Table 1). Decreases (> 30 %) are found to prevail in most midstream sub-basins, while increases were simulated for most of sub-basins downstream (Fig. 5). The total water flows increased by 615 million m^3, caused almost exclusively by climate variability. Both land use change and irrigation expansion did not alter the amount of total water flows; instead, they influenced the allocation of water into green or blue flows.

4 Discussion

In this study, we applied the SWAT model to analyze the impacts of human activities and climate variability on green and blue water flows for an arid river basin in a spatially explicit way. We choose two time periods (around 1986 and around 2005) to analyze the green and blue water flow variability because these two periods reflect the sharp socio-economic changes in the past decades. Land use change and irrigation were used as indicators for human activities. The land use change was found to be a main factor that influences water resources variability. Between 1986 and 2005, the urban area has increased by 47 %, and the irrigated land had increased by 27 % (Table 2).

The total water flows have increased in the past 20 yr in the Heihe river basin, mainly as a result of increasing precipitation (Wu et al., 2010). However, land use changes – especially the urbanisation in the basin's midstream area – also have demonstrably led to increased blue water flow. Urban construction hardens the ground, decreases soil infiltration, and accelerates surface runoff generation (Ren et al., 2002; Hao et al., 2008); hence, it increases blue water flow. Meanwhile, the increasing runoff and the decreasing infiltration rate would reduce the soil moisture for evapotranspiration; hence, green water flow was reduced (Wouter et al., 2006; Ma et al., 2008). At the same time, cropland irrigation has caused green water flow to increase by 66 million m^3, and blue water flow to decrease by the same quantities (Table 1). On the one hand, irrigation from watercourses would decrease the river discharge; on the other hand, farmland

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irrigation would increase the water availability for crop evapotranspiration (Allen et al., 1998; Andrew et al., 2009).

The results imply that land use change towards urbanization has led to a major shift from green to blue water flow in the study area, while irrigation expansion had resulted in a shift from blue to green water flow. The transformation processes from blue to green water are as follows: blue water is brought through irrigation to crops or plants in different ecosystems and eventually evapotranspired as green water in terms of surface water evaporation and plant transpiration. The transformation processes from green to blue water are as follows: infiltration rate becomes smaller due to land use change e.g. with more urban areas; hence, less water flow can get to unsaturated soils but terminates in water bodies in terms of surface runoff. Actually, as the hydrological processes are very complex, we cannot define the accurate transformation processes between green and blue water flow by one model (SWAT). The green and blue water transformation is a multi-directional loop system, but the model represents one-direction flow processes only with no feedback to the atmosphere (Neitsch et al., 2004). Further research is needed to study the mechanism of green and blue water mutual transformation, especially to strengthen the research of local water vapour cycle contributions to green and blue water transformation. Moreover, the limited number and uneven distribution of weather stations represent an important source that influences the accuracy of results. Also, previously we have validated the runoff based on measured data (Zang et al., 2012); however, a lack of measured evapotranspiration hinders a validation for green water flow.

Our results provide insights into the impacts of climatic and human factors on green and blue water variability throughout the Heihe river basin and can help policymakers to better manage the water resources in the context of global and regional climate change. As for the green water coefficient, the decreasing trend due to urbanization and the increasing trend due to irrigation are likely to apply in other river basins as well, although the impact magnitudes will certainly differ among regions. Future studies will have to investigate this in an intercomparative mode for a selection of river basins

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where transformations of both blue and green water flows are likely to have taken place. The present study demonstrates a general scenario analysis approach to study the impacts of historical human activities and climate variability on green and blue water flows at the river basin level, which we hope can serve as a guideline for follow-up studies for other river basins.

Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci-discuss.net/10/9477/2013/ hessd-10-9477-2013-supplement.zip.

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Table 1. The increase or decrease of blue water flow, green water flow and total water flows due to land use change, irrigation expansion, climate variability and all the above factors combined in the Heihe river basin (million m^3).

Variables	Impact of land use change	Impact of irrigation expansion	Impact of climate variability	Impact of all factors
Blue water flow	206	−66	146	286
Green water flow	−206	66	469	329
Total water flows	0	0	615	615

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Table 2. The land use area (km^2) and relative change rate of the Heihe river basin from 1986.

Land type	Land area in 1986	Land area in 2005	Relative change rate from 1986 to 2005
Forest high	1609	1848	15 %
Forest middle	3738	4187	12 %
Forest low	671	683	2 %
Forest mixed	53	24	−55 %
Grass high	4586	4813	5 %
Grass middle	7329	7402	1 %
Grass low	27 173	23 336	−14 %
River	171	136	−20 %
Lake	352	316	−10 %
Reservoir	87	67	−23 %
Glacier	184	181	−2 %
River shoal	785	422	−46 %
Town	75	110	47 %
Village	324	245	−24 %
Mining	99	120	21 %
Gobi and desert	133 540	139 158	4 %
Saline	6385	5916	−7 %
Swamp	680	589	−13 %
Bare land	4094	3829	−6 %
Bare Rock	35 611	32 378	−9 %
Others	4408	4811	9 %
Dry land	161	137	−15 %
Irrigated land	5280	6687	27 %

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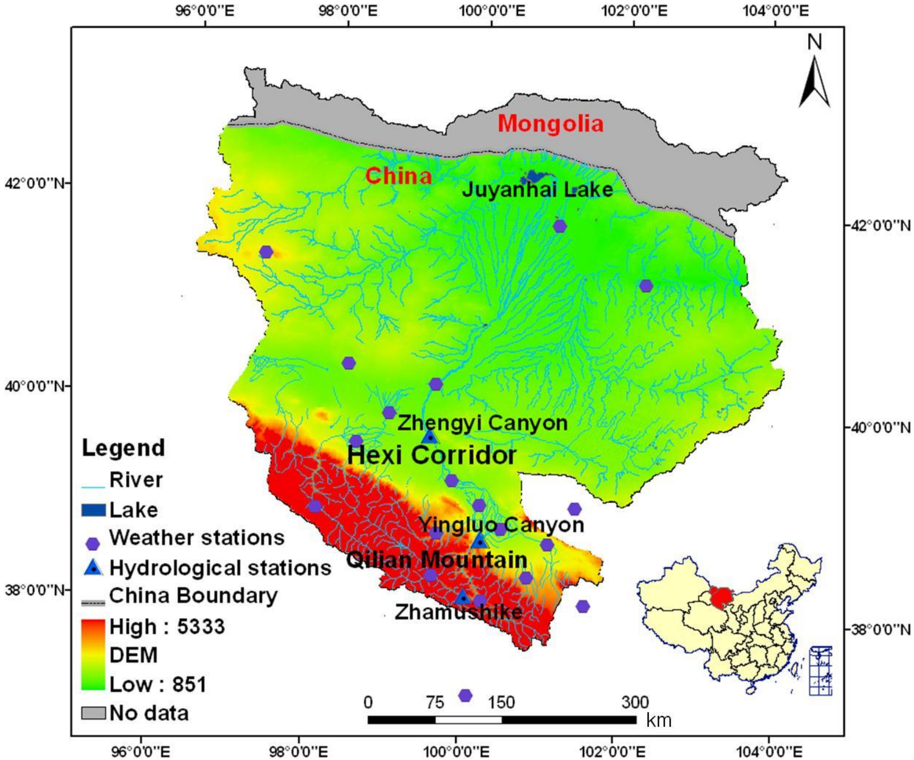

Fig. 1. The Heihe river basin with rivers, lakes, hydrological and weather stations indicated. The location of the Heihe river basin in China is shown in the inset.

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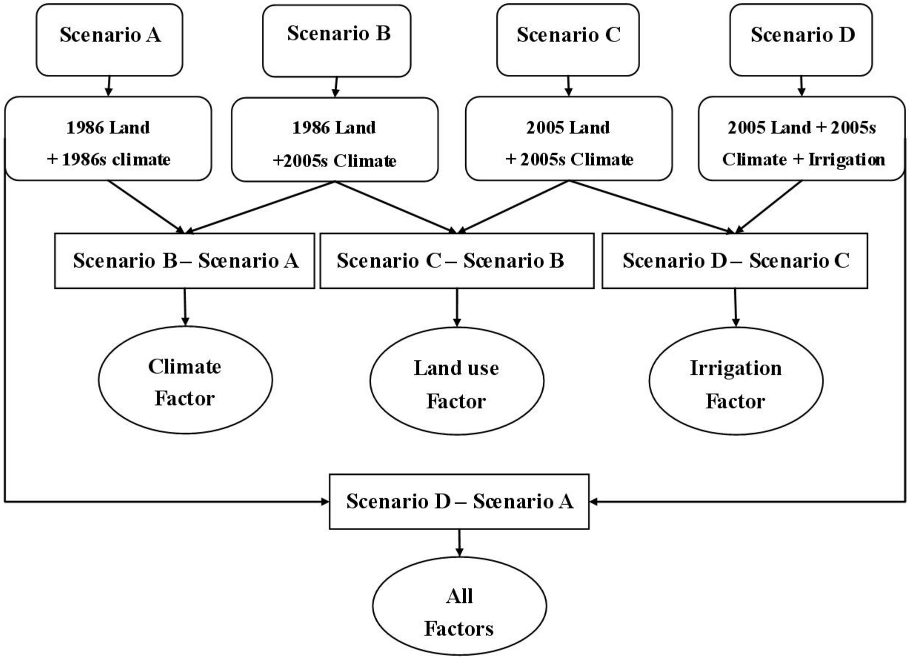

Fig. 2. The scenarios setup and research framework. 1986s is the average of 1984 to 1986; 2005s is the average of 2004 to 2006.

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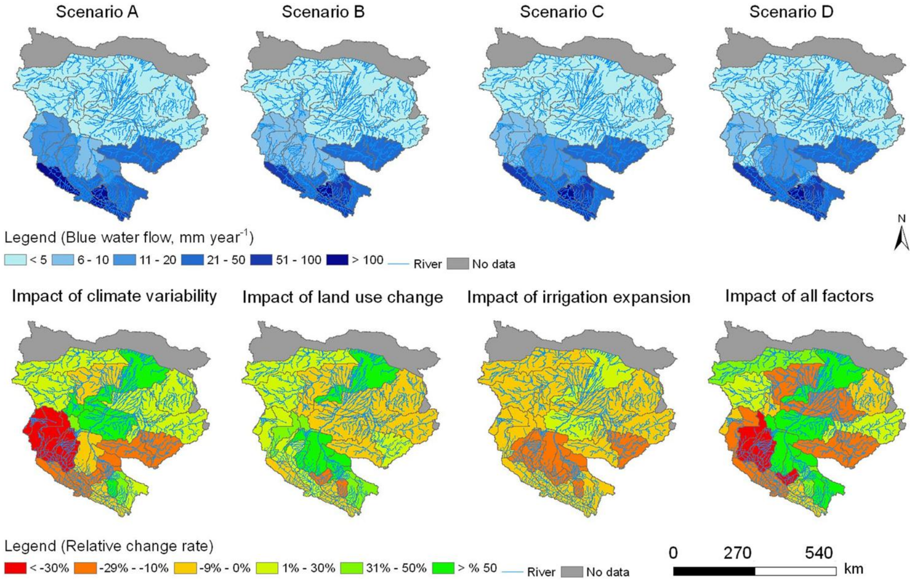

Fig. 3. The blue water flow in the Heihe river basin in different scenarios. The impacts are assessed with relative change rate. The impacts of climate variability, land use change and irrigation expansion are assessed by comparing results between Scenario B and A, Scenario C and B, and Scenario D and C, respectively. The impacts of all factors together are assessed by comparing results between Scenario D and A.

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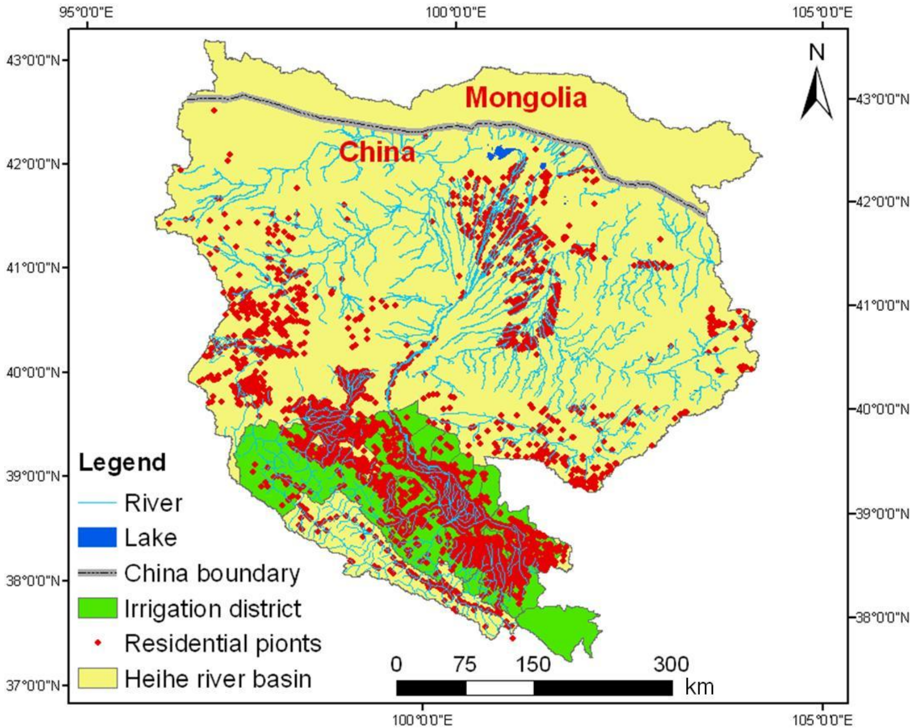

Fig. 4. The distribution of irrigation district and residential points in the Heihe river basin.

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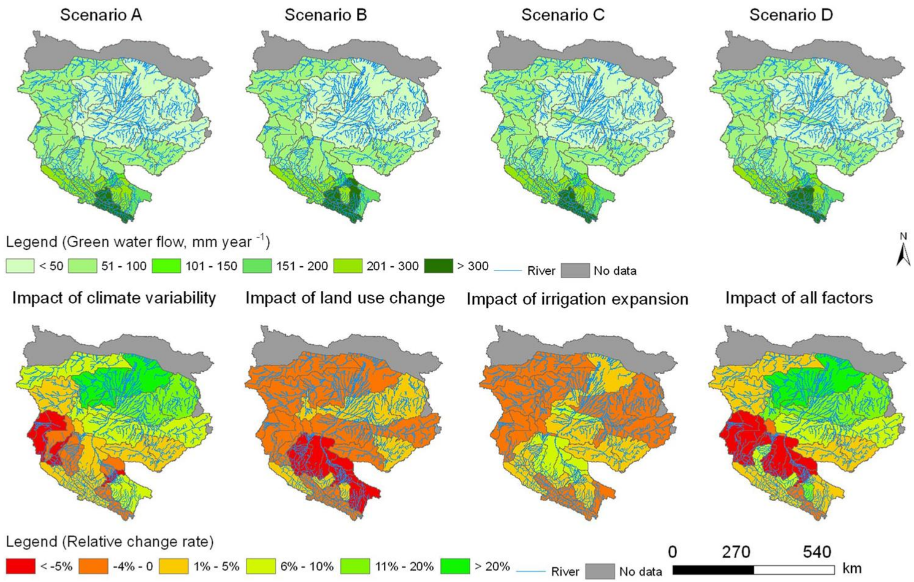

Fig. 5. The green water flow in the Heihe river basin in different scenarios. Details as in Fig. 3.

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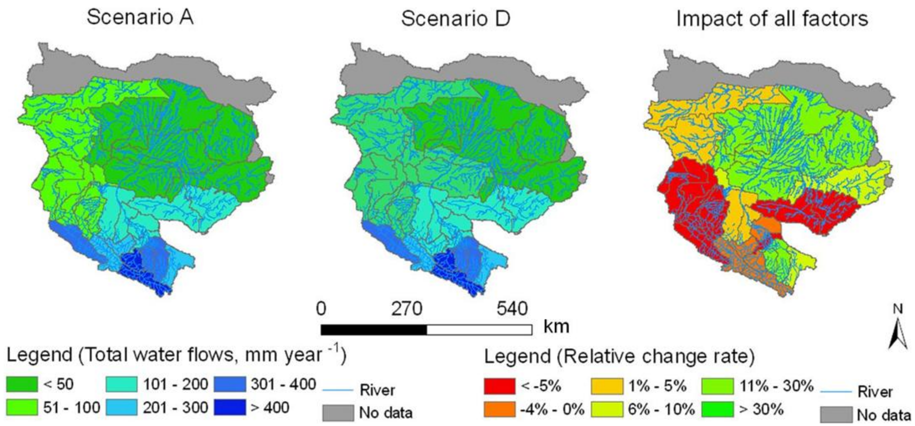

Fig. 6. Impacts of all factors (human activities and climate variability) on the total water flows in the Heihe river basin.

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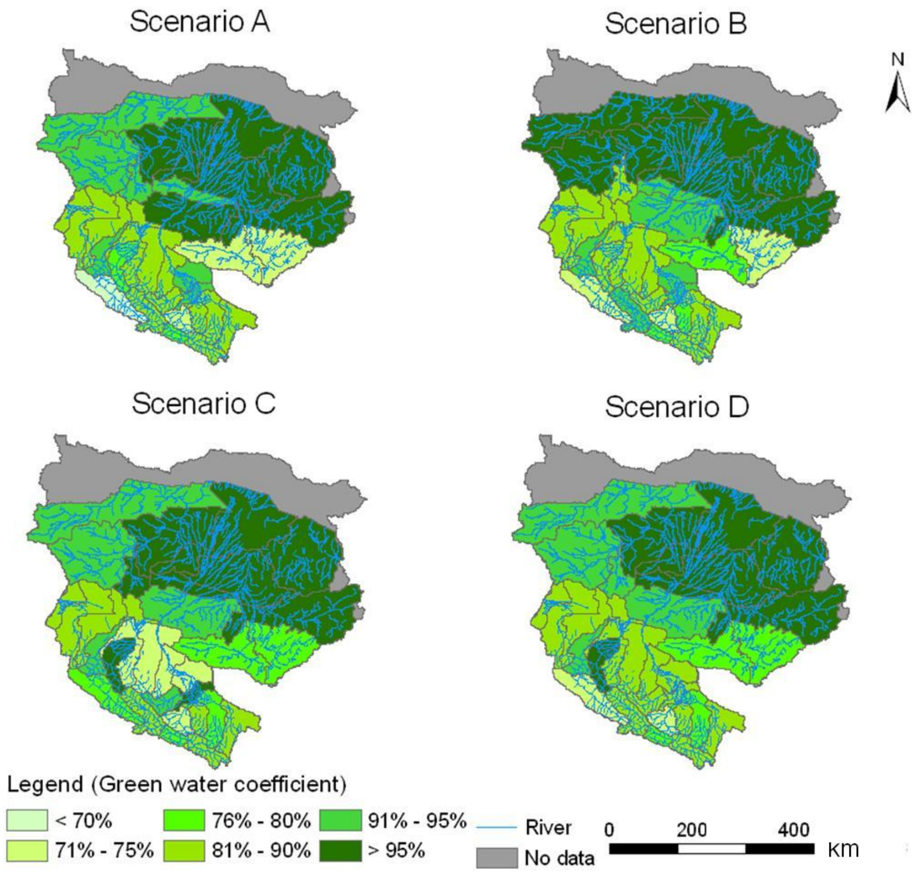

Fig. 7. The green water coefficient in the Heihe river basin in different scenarios.

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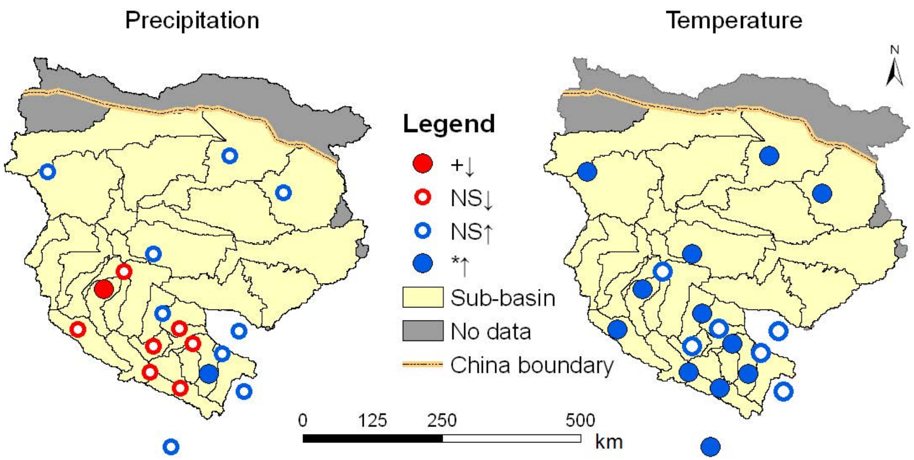

Fig. 8. The variability of precipitation and temperature in the Heihe river basin from 1980 to 2005. ↑ indicates increasing trend; ↓ decreasing trend, * significant at $p < 0.05$; + significant at $p < 0.10$; NS, not significant.