Hydrological Responses to Climate Change in the Water Receiving Area of the Middle Route Project for South-to-North Water Transfer

XIA Jun[1,2], ZENG Sidong[2], ZHANG Liping[2] & DU Hong[2]

[1.] Key Laboratory of Water Cycle & Related Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

[2.] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China

Abstract Climate change will lead to a significant alteration in the temporal and spatial pattern variation in the regional hydrological cycle, and the subsequent lack of water, environmental deterioration, floods and droughts etc. And it is especially remarkable in semi-humid and semi-arid region. In this paper, the impacts of climate change on the hydrological cycle were analyzed for the Hai River Basin, a semi-humid and semi-arid basin and also the water receiving area of the middle route of South-to-North Water Diversion Project. Meanwhile it is the most vulnerable to climate change. Firstly, the linear regression and Mann-Kendall non-parametric test methods were used to analyze the change characteristics of the hydrological and meteorological elements for the period from 1960 to 2009. The results show a significant increase in temperature, while precipitation decreases slightly, and runoff decreases drastically over the past 50 years. Secondly, the applicability of SWAT (Soil and Water Assessment Tool) model based on the DEM (Digital Elevation Model), land use and soil type was verified in the basin. Results show the model performs well in this basin. Furthermore, the water balance model, Fu's theory and Koichiro's theory were used to calculate the actual evaporation, comparing to the simulated actual evaporation by SWAT model to validate the result for the lack of large-scale observed evaporation datasets. Possible reasons were also analyzed to explore the reasonable factor for the decline of the runoff. Finally the precipitation, temperature, runoff and evaporation response processes based on the IPCC AR4 multi-mode climate models and the verified SWAT model under different GHG emission scenarios (SRES-A2, A1B and B1) in the 21st century were discussed in three time periods: 2020s (2011–2040), 2050s (2041–2070), 2080s (2071–2099). Results show that there are systematic positive trends for precipitation and temperature while the trends for runoff and evaporation will differ among sub-areas. The results will offer some references for adaptive water management in a changing environment, also including adaptation of a cross-basin water transfer project.

Keywords climate change, the Hai River Basin, water cycle, SWAT model

ZENG Sidong (1987-), a Ph.D student of State key laboratory of Water Resources and Hydropower Engineering Science in Wuhan University, specialized in water system model including the physical, biogeochemical and human components and hydrological responses to climate change.
Email: zsdwhu@gmail.com

1. Introduction

Global warming has been aggravated by anthropogenic interference since the last century. And it is a global environmental issue concerned by both governments and scientists (IPCC, 2007). It is expected to raise the evaporation rate and increase humidity in the atmosphere, therefore accelerate the water cycle. As a main component of the climate system, climate change will affect the elements of water cycle, including precipitation, evaporation, infiltration, runoff, following with the change of distribution on spatial and temporal scales and the water available, the subsequent lack of water, *environmental deterioration, floods and droughts etc*. (*Fu et al*.2007, Bronstert *et al*. 2007). Meanwhile the change of hydrological processes will have certain influences on the feedback of water and energy from the earth to the atmosphere, which will intensify the change of water cycle. So it is important to evaluate the vulnerability, sensibility and suitability of regional water resources to the impact of climate change, which will provide a scientific reference for the integrated water resources management and local economy development.

China is located in the monsoon area, where the earth environment is complex in spatial and mutable in temporal, and it is sensitive and vulnerable to the external changes (Zhou *et al*. 2004). The Hai River Basin, one of the main areas of severe water shortage with water imbalance and water overloading, is extremely vulnerable to climate change in China (Liu *et al*. 2004). To address the water scarcity problem, the Middle Route Project for South-to-North Water Transfer has been established, which originates from the Danjiangkou Reservoir, linking the Yangtze River, the Huai River, the Yellow River and the Hai River, and finally bringing water northward into Beijing and Tianjin. And it will play an important role in relieving the water shortage in the Hai River Basin. Under the condition of global warming and the diversion project, the sustainable use of water resources, as well as the social economy and the ecosystem of this basin will encounter a huge challenge.

Now the assessment of hydrological response to climate change is basically following a paradigm that "climate scenario generation — hydrological simulation—hydrological response assessment" (Zhang *et al*. 2008, Chen *et al*. 2009). The most promising way of the paradigm is coupling climate models and hydrological models using the outputs of the former to drive the latter. Traditionally, the climate scenario was generated by the assumption of meteorological variables or the data via the atmospheric CO_2 concentration generated by GCMs rises up to a stable value. Currently, various climate models under SRES (Special Report on Emissions Scenarios) are used in the third and fourth assessment reports of IPCC. And the hydrological models chosen have been developed from concept lumped models to distributed physical models. Various combinations of climate models and hydrological models have been considered, from which comparative results were derived (Michael D. Dettinger *et al*. 2004, Tao *et al*. 2007, F.H.S. Chiew *et al*. 2009, Zhang *et al*. 2011). Wang *et al*. (2008) analyzed the water scarcity and adaption in the Hai River Basin using the water resource model developed by CAS. Yuan *et al*. (2005) studied the response to climate change in the basin coupling the VIC model and PRECIS (Providing Regional Climate for Impact Studies). Due to the uncertainty of GCMs, different models have different simulating results, especially for the simulated regional precipitation, which will increase the uncertainty of runoff simulation for the direct influence of precipitation (Zhang *et al*. 2008). Many researches have proved that the average result of multiple models is better than the result of a single model (Murphy J.M *et al*. 2004). Now the average simulating result of multiple climate models is used to drive the hydrological models for evaluation of climate change impact on hydrological processes.

Evaporation plays a significant role in linking the water balance and energy balance on the land surface, impacting the exchanges of land-air heat flux, momentum and water. And it is the major consumption of the precipitation to land. The evaporation paradox has put forward a new problem of the changing trend of evaporation under climate change (Brutsaert *et al*. 1998). Therefore, it is important to study the regional evaporation to recognize the discipline and control factors of the spatial and temporal pattern of water balance (Wolock and McCabe, 1999). And it is necessary to compute the actual evaporation and its changing characteristics more accurately. So in this study, the water balance, Koichiro (1979) and Fu's theory (Fubaopu 1981, Zhang *et al*. 2004) was used to compare the simulated actual evaporation by model simulation.

To study the hydrological responses to climate change, the changing characteristics of the hydrological and meteorological elements for the period 1960-2009 were analyzed firstly, including precipitation, runoff, mean temperature and evaporation. And possible factors such as hydraulic engineering were discussed. Then the SWAT distributed hydrological model was verified in this

basin. Finally the average outputs of multiple GCMs under different GHG emission scenarios (SRES-A2, A1B and B1) were used to drive the SWAT distributed hydrological model to simulate the hydrological processes for the future time period 2011-2099. Besides, possible changes of precipitation, temperature, runoff and evaporation in the 21st century were discussed.

2. Study area and data

The Hai River Basin (shown in Figure 1), located between 112-120 ºE and 35-43 ºN, is a semi-arid basin with an area of approximately 317,800 km2 , which consists of mountains (60%) and plateaus (40%) in the west and a wide plain in the east. It contains several sub-areas from the north to south as follows: Luanhe, Beishanhe, Yongdinghe, Daqinghe, Ziyahe and Zhangweihe. For the lack of data, Luanhe, Yongdinghe and Zhangweihe were analyzed in this study. It has a temperate continental monsoon climate, exhibiting an annual distribution of precipitation which is reduced from the southeast to northwest. According to historical records the mean annual temperature and

precipitation are 1.5-14ºC and about 539mm respectively.

The Hai River Basin is the center of the politics, economy and culture in China. Meanwhile it is an area suffering most from imbalance in supply and demand of water resources due to the high development and over-use of water resources. And the lack of water resources not only hinders the development of the national economy but leads to severe environmental problems. So it is necessary to study the hydrological response to climate change, which will offer some reasonable references for water management and planning, environment protection and social sustainable development.
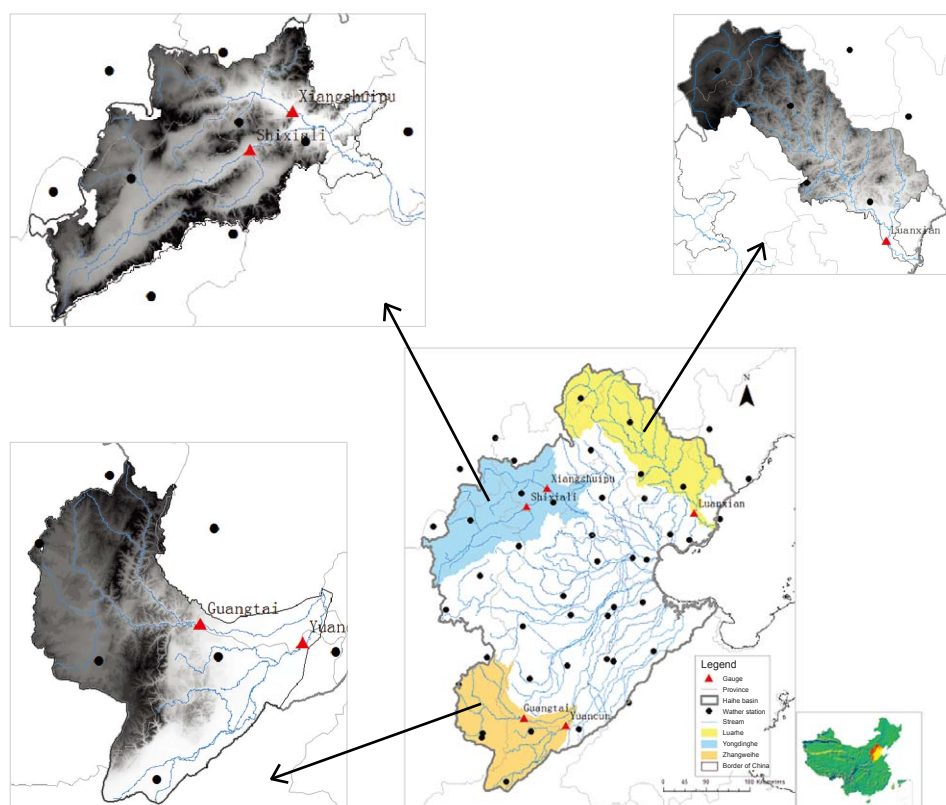

Figure 1 The distribution of meteorological stations, rainfall stations and hydrological stations in the Hai River Basin.

The datasets used in this study mainly contain the observed datasets, GIS and GCMs as follows: (1) Daily precipitation and temperature data from 1960 to 2009 were collected from 39 meteorological stations in the Hai River Basin and downloaded from CMA. And monthly stream flow dataset from 1960 to 2009 from 50 hydrological stations were also included (Figure 1). (2) The dataset of average output of multiple GCMs was downloaded from China's National Climate Center (NCC), which was interpolated into the same resolution (1 ° × 1 °) from the 23 GCMs with different resolution ratios involved in the World Climate Research Programme's (WCRP's) coupled model inter-comparison project phase 3 (CMIP3) multi-model dataset and then tested in East Asia. (3) The GIS dataset of the basin, including the digital elevation model (DEM) with the resolution of 500m×500m used in this study, were downloaded from the GTOPO30 public domain provided by the U.S. Geological Survey (USGS). Land use and soil type were also included with the resolution of 1km×1km from CAS.

3. Methodology

Trend analysis. Several parametric and non-parametric test are used to detect the trend of hydrological and meteorological elements, such as linear regression methods, Mann-Kendall test, Moving average and Spearman test *etc*. Mann-Kendall non-parametric test recommended by WMO may eliminate the impact of distribution characteristics of time series to a certain extent. Some people discussed the impact of auto-correlation coefficient to Mann-Kendall test result (Yue and Wang, 2002). So the auto-correlation in time series needs to be removed, which is done in the following procedure (Chu *et al*. 2010).

(1) Calculate the 1st order auto-correlation coefficient:

$$\rho = \frac{Cov(x_i, x_{i+1})}{Var(x_i)} = \frac{\frac{1}{n-2}\sum_{i=1}^{n-1}(x_i - \bar{x})(x_{i+1} - \bar{x})}{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

$\{x_i\}$ is the given time series and ρ is the auto-correlation coefficient.

(2) Remove the auto-correlation from the original time series:

$$x_i' = x_i - \rho x_{i-1}$$

(3) Then the Mann-Kendall test was used to detect the trend and abrupt using the new series.

Global Circulation Models (GCMs). Despite its great uncertainties, GCMs are still the most scientific and rational method to generate future climate scenarios at present (NCC 2008, Benioff *et al*. 1996). GCM is a simple description of the earth system using Mathematical-Physical Equation based on physical processes including several components. From the 1980s, many GCMs were developed, such as GISS, VCAR, UKMO, OSU, GFDL, CCC and CUS etc.

all around the world (Zhang *et al*. 2008). And more than 20 GCMs were used to simulate the climate change for the past time and the future time periods involved in the IPCC Fourth Assessment Report. Due to the uncertainty of the GCMs, different models usually have different simulating results, which will increase the uncertainty of the evaluation of the climate change impacts. Many researches have proved that the average result of multiple models is better than the result of a single model. China's National Climate Center has done interpolation from the 23 GCMs of the World Climate Research Programme's (WCRP's) coupled model inter-comparison project phase 3 (CMIP3) multi-model dataset involved in the IPCC AR4 into the same resolution, tested the simulation effects in East Asia, and finally obtained the results of multi-model assemble. The estimates of future climate scenarios adopted the regional development scenarios which emphasized economic growth (A2, with high emissions), global co-development scenarios which emphasized economic growth (A1B, with medium emissions) and global sustainable development scenarios (B1, with low emissions) of the IPCC Fourth Assessment Report (IPCC, 2007).

Downscaling technology. For the coarse resolution of GCMs and the simplification of hydrologic cycle in climate models, it is not yet possible to interpret the mechanism of water cycle and make reliable predictions of regional hydrologic changes directly from GCMs (Arora 2001). Consequently, downscaling is used to link the climate models and hydrological models. And it can be grouped into four main types: dynamical downscaling, weather typing approaches, stochastic weather generators and transfer functions. Although the dynamical downscaling

is based on physical mechanism, it's not widely used for its complex. Contrarily because of the parsimony and "low–tech" advantages of statistical downscaling over dynamical downscaling, the use of statistical downscaling is now widespread. In this paper, The BCCRCG-WG 3.00, developed by Beijing Climate Center and the Regional Climate Group at the University of Gothenburg, was used to process the temporal downscaling, and the bilinearity interpolation was used to do spatial downscaling. Many experiments of the downscaling have shown that the simulated series of daily average precipitation, monthly average raining days and average precipitation during these days have reasonable precision and high accuracy (Liao *et al.* 2004). In the study, the monthly grid data from the GCMs was interpolated into the 39 meteorological stations, and then the BCCRCG-WG 3.00 was used to generate daily datasets for driving the SWAT model.

Hydrological model. The distributed SWAT model (Soil and Water Assessment Tool) was chosen to characterize the hydrological processes in the Hai River Basin. SWAT was developed with a strong physical basis by Agricultural Research Service of the United States Department of Agriculture in the early 1990s. It has been widely used in simulation of hydrologic processes and hydrologic responses to climate change and LUCC in large complex watersheds with varying soils, land use and management conditions over long periods of time (Darren *et al.* 2009, Zhang *et al.* 2010). Some studies show it performs well in this basin (Wang *et al.* 2008). SWAT provides two methods for runoff calculation: SCS method and Green-Ampt Model. In this paper, SCS method was chosen for the lack of sub-hourly precipitation data. And the Penman-Monteith and Muskingum approach were chose to calculate the potential evaporation (PET) and river flow concentration respectively.

Evaporation calculation. For the lack of observed large scale evaporation dataset, several experimental methods were used to calculate the actual evaporation. In this study, water balance model, Fu's theory and Koichiro's theory was used to calculate the actual evaporation, comparing to the result from SWAT model.

(1) Water balance model. It is a basic method for evaporation. The water balance equation can be characterized as following in a closed basin without regard for transfer with other basin at a multi-year time scale.

$$E=P-R$$

Where E is Evaporation (mm), P is Precipitation (mm) and R is runoff (mm).

(2) Fu's theory-based on Budyko's coupled water and energy balance hypothesis. Budyko noted that the average annual evaporation from a catchment is determined by a balance between the energy available for evaporation and the amount of available water (Budyko, 1963, 1974). On the basis of Budyko hypothesis, Fu (1981) derived a formula as follows:

$$E = E_m \left\{ 1 + \frac{P}{E_m} - \left[1 + \left(\frac{P}{E_m} \right)^w \right]^{\frac{1}{w}} \right\}$$

Where m is w model parameter and E_m is the potential evaporation. E_m can be obtained by Hargreave-Samani as following:

$$E_m = aQ_o(T+17.8)(T_{max}-T_{min})^b$$

Where a, b are parameters and T, Tmax, Tmin are the mean temperature, maximum temperature and minimum temperature (^{o}C).

(3) Koichiro's theory-was brought forward by Koichiro (1980) using heat balance equation as following:

$$E = \frac{3100P}{3100 + 1.8P^2 \exp\left(-\dfrac{34.4T}{235+T} \right)}$$

Where E is monthly actual evaporation (mm), P is monthly precipitation (mm) and T is monthly mean temperature (^{o}C).

4. Results and analysis

Trend analysis of history hydrological and meteorological factors
(1) Trend analysis of precipitation and temperature.

The changing trend of annual precipitation, the linear regression result and the 5-year moving average process (Figure 2) shows a slight decrease in the basin. According to the Mann-Kendall test, the decrease trend for precipitation is not significant at the 95% confidence level; meanwhile there is no distinct mutation.

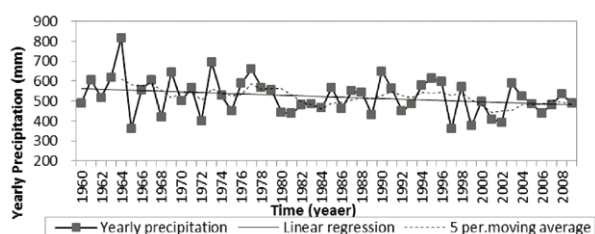While the temperature increase significantly during the

Figure 2 the change trend of precipitation in the basin during the past 50 years.

Figure 3 the change trend of temperature in the basin during the past 50 years.

past 50 years, according to the Mann-Kendall trend test, the result is 5.48 for temperature, and has a mutation at 1992.

Because of the complex underlying surface and strong uneven human activities, the distribution of regional water resources in the basin is uneven. Many studies show that the hydrological and meteorological factors are various from the south to north. Figure 4 and Figure 5 show the Mann-Kendall trend results of precipitation and temperature. From Figure 4, in most area of the basin, the precipitation decreases slightly except for Wutai Mountain in the western part during the past 50 years at the 95% confidence level. Figure 5 shows that in most
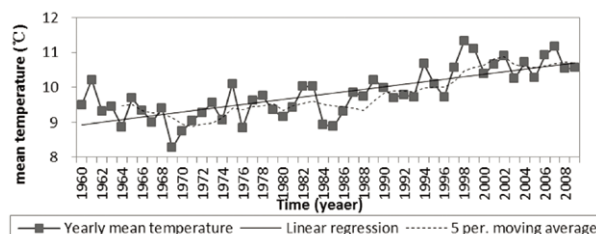
area the temperature in the basin increases significantly. Furthermore, temperature increase is more pronounced in the northern part than that in the southern part and precipitation decreases generally more in the eastern part.
(2) Trend analysis of runoff

Trend of runoff from five stations in the three sub areas were detected as the following Table 1, they are Luanxian, Shixiali, Xiangshuipu, Guantai and Yuancun station. From the table below, the results show a significant decrease and mutations for all the select stations. Moreover, Figure 6 shows the changing trend based on Mann-Kendall test distribution in the basin. From the result show in the figure,
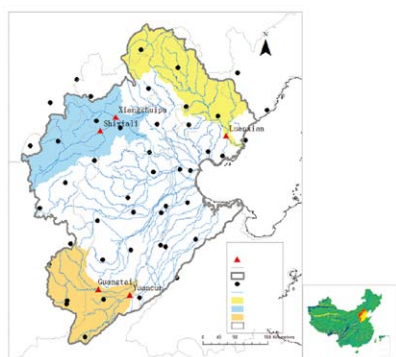

Figure 4 Trend of precipitation based on MK test.
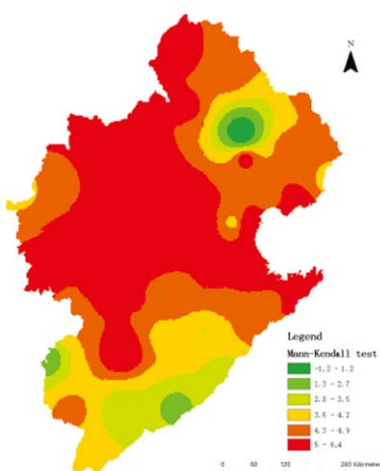
Figure 5 Trend of temperature based on MK test.
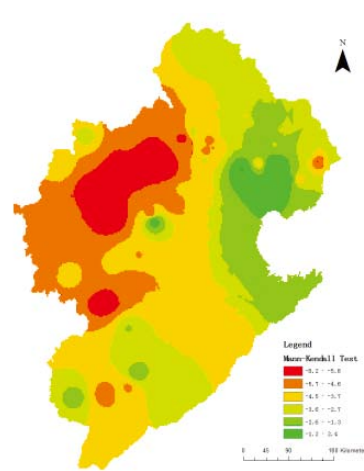
Figure 6 Trend of runoff based on MK test.

Table 1 Change trend of runoff

Station	Multi-year mean annual flow (m^3/s)	Mann-Kendall Trend	Mutation (year)	Subarea
Luanxian	86.93	-4.47	1992	Luanhe
Shixiali	10.54	-7.60	1982	Yongdinghe
XiangShuipu	9.38	-6.84	1987	Yongdinghe
Guantai	26.85	-4.27	1975	Zhangweihe
Yuanchun	44.98	-3.13	1978	Zhangweihe

we can see that the runoff reduction in the Yongdinghe sub area is more than that in other sub areas.

(3) Water balance analysis of the three sub-areas

Table 2, 3 and 4 show the decadal characteristics of water balance analysis and annual mean temperature in the three sub areas. Here the evaporation is calculated by Water balance model. From Table 1, precipitation, temperature and evaporation increase during the years 1991-2000 in Luanhe. From Table 3, 4, precipitation, evaporation and runoff all decrease while the temperature increases in Yongdinghe and Zhangweihe. The runoff in Luanhe decreases dramatically during 1981-1990 while increases during 1991-2000, which may do with the project of water transferring from the basin to Tianjin in the 1980s and suspended in the 1990s. In Yongdinghe, the runoff reduces tardily, which maybe relates to the reduction of precipitation. The runoff in Zhangweihe has a significant mutation in the 1980s, which is consistent with the changing trend of precipitation. Besides, water assumption of large scale irrigation such as Hongqi irrigation canal, Yuejin irrigation canal and Renminshengli irrigation canal is another reason for the reduction of the runoff in

Zhangweihe sub area.

Model calibration and validation

The spatial complex of the water cycle in Hai River basin is affected by both climate change and human activities, and Liu *et al*. (2004) show that the main factor in different sub areas are different by analyzing the water resources in the basin. In this study, the hydrological processes in three sub areas (Luanhe, Yongdinghe and Zhangweihe) were simulated and analyzed.

There are many parameters in the SWAT model, and they can be divided into two categories: one is the physical parameters that can be observed or measured, such as the soil physical parameters and the LUCC parameters; another one is the experimental parameters that should be calibrated in the model, such as runoff curve (CN2), soil available water content (SOL_AWC), compensation coefficient for soil evaporation (ESCO), ground water evaporation coefficient (GW_REVAP) and decline coefficient (ALPHA_BF) etc. The calibration should follow several principles below: taking upstream priority over downstream; considering water

Table 2 Water balance analysis in Luanhe

years	Annual precipitation(mm)	Mean temperature($^\circ$C)	Evaporation(mm)	Runoff (mm)
1961-1970	502.89	6.6	404.46	98.43
1971-1980	509.62	6.7	404.78	104.84
1981-1990	462.43	7.0	417.93	44.51
1991-2000	513.82	7.4	446.32	67.50

Table 3 Water balance analysis in Yongdinghe

years	Annual precipitation(mm)	Mean temperature($^\circ$C)	Evaporation(mm)	Runoff (mm)
1961-1970	428.75	6.2	386.82	41.94
1971-1980	429.45	6.4	390.37	39.08
1981-1990	406.37	6.7	374.31	32.07
1991-2000	402.93	7.4	375.46	27.47

Table 4 Water balance analysis in Zhangweihe

years	Annual precipitation(mm)	Mean temperature($^\circ$C)	Evaporation(mm)	Runoff (mm)
1961-1970	617.71	12.0	478.86	138.85
1971-1980	571.69	11.8	461.20	110.49
1981-1990	535.30	12.1	460.31	74.99
1991-2000	533.28	12.3	458.97	74.32

balance before adjusting flow duration curve; adjusting the surface flow before considering the soil water, evaporation and underground runoff (Zhang *et al*. 2010). Considering the complexity of the structure of the SWAT model, we use both automatic calibration methods and manual calibration approaches. To test the applicability of the SWAT model in this basin, Nash-Sutcliffe coefficient (ENS) (Nash and Sutcliffe, 1970), relative error(R) and correlation coefficient(r) were chosen as model performance indicators.

In this basin, the three sub areas were calibrated with the years from 1961 to 1990, and the period from 1991 to 2000 was used as validation data. Figure 7 and Figure 8 show the simulated and observed hydrographs comparatively for the station Luanxian and Yuancun. From Table 5, we can see

that the model performs well with Nash-Sutcliffe coefficient 75.1%, 67.7%, 89.1% in calibration period and 96.1%, 91.3%, 91.5% in validation period in the three sub areas and can be used to evaluate the hydrological response to climate change.

Furthermore, water balance model, Fu's theory and Koichiro's theory were used to calculate the evaporation comparing the result by the SWAT model. Table 6, 7 and 8 show the results in the three sub areas. From the results below, we can see the ET by Koichiro's is less than that of other 3 methods. And the simulated ET by SWAT is close to Water balance model. The ET by Fu's theory and Koichiro's theory is close to the results of SWAT and Water balance model in Zhangweihe sub area, which is not the same with that in Luanhe and Yongdinghe sub areas.
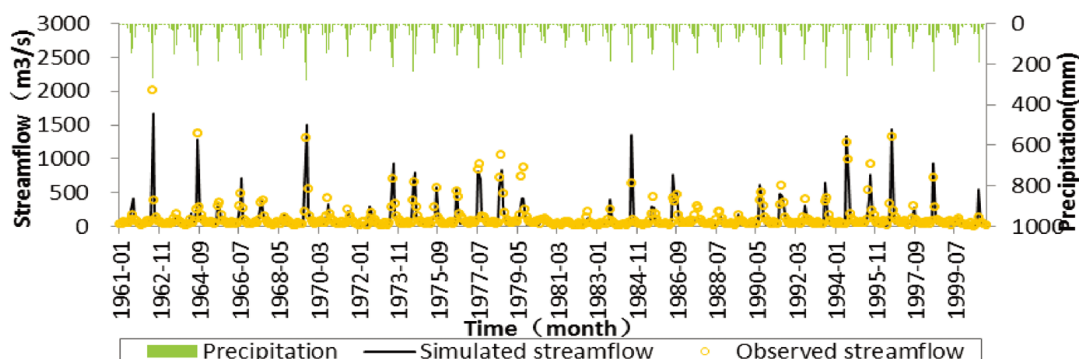
Figure 7 Comparison between observed and simulated monthly hydrographs at the Luanxian station from 1961 to 2000.
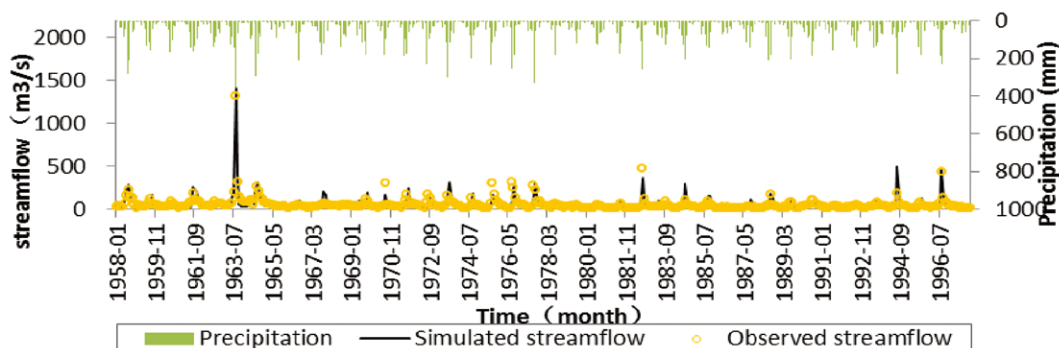
Figure 8 Comparison between observed and simulated monthly hydrographs at the Yuancun station from 1961 to 2000.

Table 5 Model performance during the calibration and validation periods

Subarea	Calibration(1961-1990)			Validation(1991-2000)		
	E_{NS}	R	r	E_{NS}	R	r
Luanhe	75.1%	5.3%	0.88	96.1%	5.8%	0.98
Yongdinghe	67.7%	5.6%	0.89	91.3%	11.4%	0.97
Nanyunhe	89.1%	2.6%	0.96	91.5%	14.5%	0.98

Table 6 Comparison of 4 methods for ET in the Luanhe River (mm)

years	SWAT	Water balance	Fu	Koichiro
1961-1970	414.20	404.46	392.08	352.17
1971-1980	427.48	404.78	394.66	356.02
1981-1990	407.33	417.93	369.02	344.99
1991-2000	430.62	446.32	397.77	371.12

Table 7 Comparison of 4 methods for ET in the Yongdinghe River (mm)

years	SWAT	Water balance	Fu	Koichiro
1961-1970	390.71	386.82	346.70	318.56
1971-1980	394.03	390.37	350.10	326.53
1981-1990	373.22	374.31	337.15	321.18
1991-2000	381.25	375.46	334.44	321.62

Table 8 Comparison of 4 methods for ET in the Zhangweihe River (mm)

years	SWAT	Water balance	Fu	Koichiro
1961-1970	474.19	478.86	440.71	460.71
1971-1980	465.98	461.20	420.41	450.27
1981-1990	443.51	460.31	398.93	437.45
1991-2000	417.10	458.97	395.97	436.44

Climate change impact and hydrological responses

(1) Analysis of precipitation and temperature for the three climate change scenarios

The precipitation and mean temperature in the basin under three climate scenarios (A1B, A2,B1) are characterized in the three periods of 2020s (2011-2040), 2050s (2041-2070) and 2080s (2071-2099). The reference period is 1961-1990. The results are showed in Figure 9, Figure 10 and Table 9. According to the results, temperature and precipitation under the three scenarios increase in the 21st century over the reference periods and both have a positive trend. And the precipitation will have an average increase by 4.88%, 17.83% and 24.22% at the periods 2020s, 2050s and 2080s, respectively. And the temperature will increase by 1.06, 2.13 and 3.25 at the periods 2020s, 2050s and 2080s, respectively. Generally, both temperature and precipitation increase with SA2>SA1B>SB1 at the end of the 21st century in the basin.
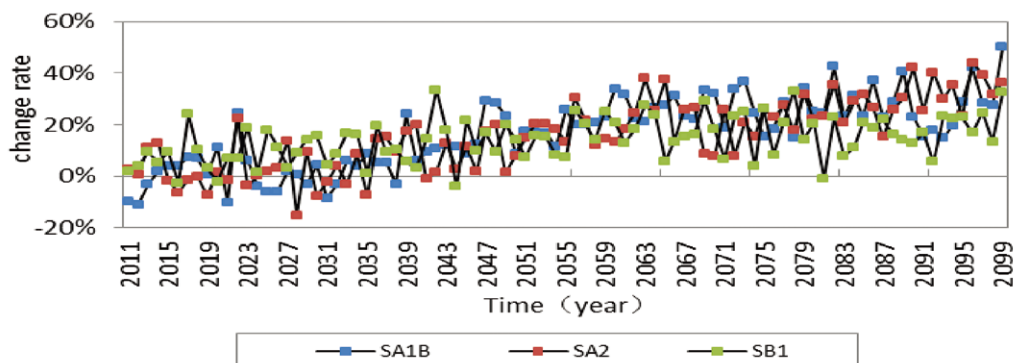
Figure 9 Changing rate of precipitation over the reference for the 21st century under SA1B, SA2 and SB1.
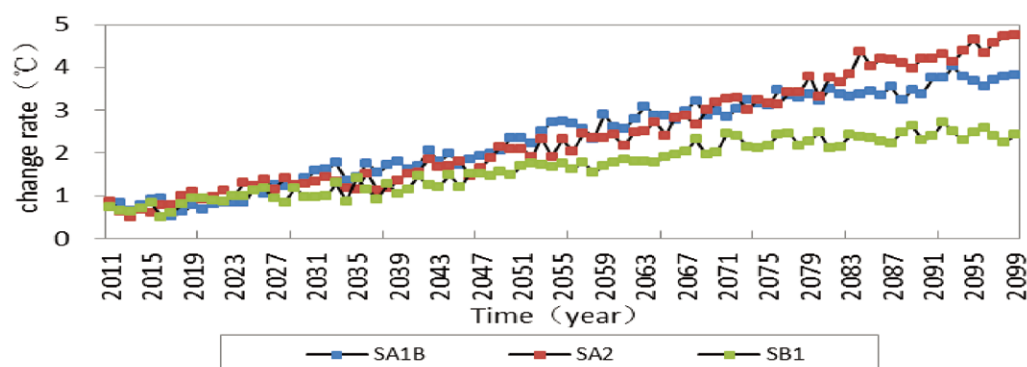
Figure 10 Changing rate of temperature over the reference for the 21st century under SA1B, SA2 and SB1.

Table 9 changing rate of precipitation and temperature for the 21st century under SA1B, SA2 and SB1

Periods	Precipitation change(%)				Temperature change(°C)			
	A1B	A2	B1	Average	A1B	A2	B1	Average
2011-2020	1.17	1.19	6.29	2.88	0.75	0.78	0.73	0.75
2021-2030	0.79	2.33	10.54	4.55	1.07	1.21	0.99	1.09
2031-2040	4.47	7.61	9.51	7.20	1.62	1.31	1.11	1.35
2020s	2.14	3.71	8.78	4.88	1.15	1.10	0.94	1.06
2041-2050	15.41	7.60	15.35	12.79	1.94	1.78	1.41	1.71
2051-2060	20.53	17.87	15.98	18.13	2.56	2.22	1.70	2.16
2061-2070	27.09	22.56	18.05	22.57	2.90	2.68	1.94	2.51
2050s	21.01	16.01	16.46	17.83	2.47	2.23	1.68	2.13
2071-2080	24.97	21.76	18.18	21.64	3.20	3.30	2.31	2.94
2081-2090	29.69	28.02	14.47	24.06	3.39	4.03	2.33	3.25
2091-2099	27.16	33.94	19.82	26.97	3.76	4.45	2.45	3.55
2080s	27.27	27.91	17.49	24.22	3.45	3.93	2.37	3.25

(2) Assessment on hydrological response

Based on the WCRP's coupled model intercomparison project phase 3 (CMIP3) multi-model dataset with the data from 1961 to 1990 as the reference period, the future monthly precipitation and temperature in the basin were downscaled to daily data and used to drive the calibrated SWAT model under the three scenarios SA1B, SA2 and SB1. Figures. 11, 12 and 13 show the runoff changing rate over the reference periods for the 21st century in the three sub areas.
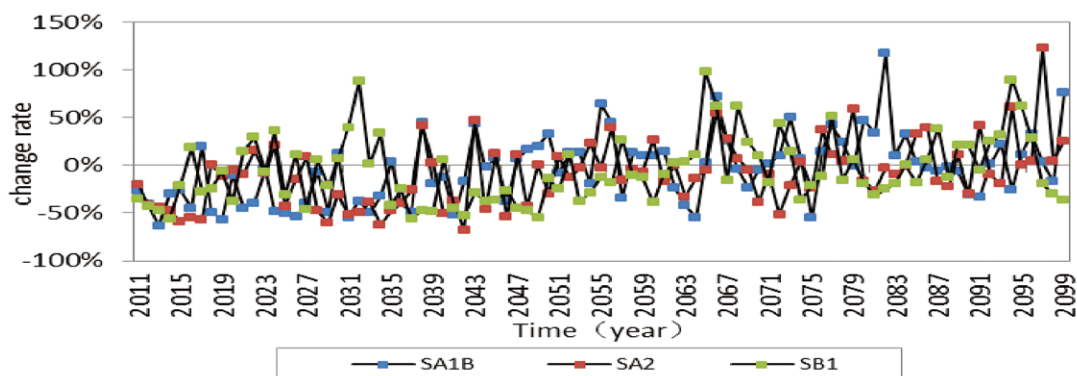

Figure 11 Changing rate of runoff over the reference for the 21st century under SA1B, SA2 and SB1 in the Luanhe River.
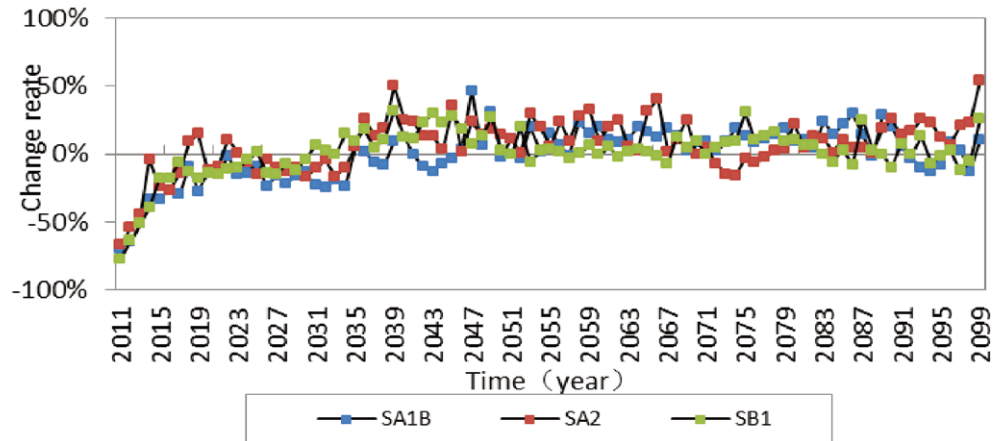
Figure 12 Changing rate of runoff over the reference for the 21st century under SA1B, SA2 and SB1 in Yongdinghe.
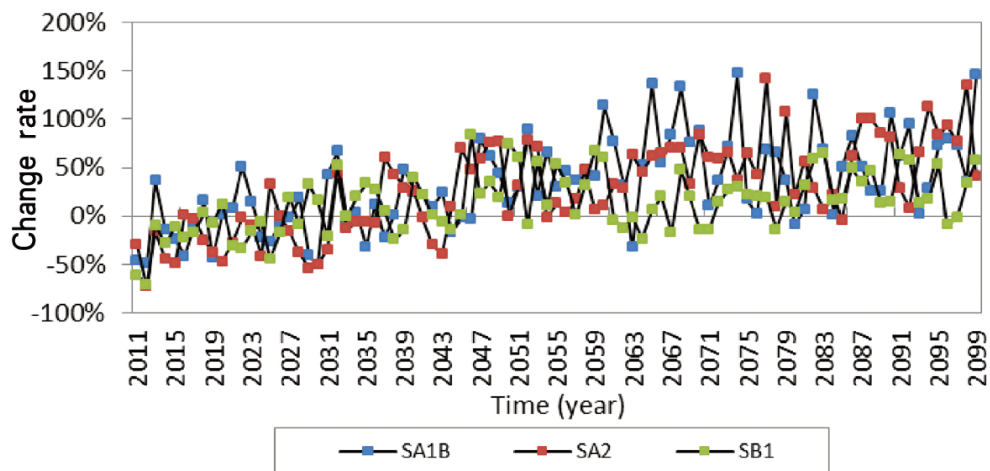

Fig. 13 Changing rate of runoff over the reference for the 21st century under SA1B, SA2 and SB1 in the Zhangweihe.

Furthermore, the trends for precipitation, evaporation, temperature and runoff at the time periods 2011-2099 in the three sub areas were analyzed in the following tables. In the tables, precipitation, temperature, evaporation and runoff are abbreviated as P, T, E and R, respectively. From the tables, we can see the precipitation and temperature hold a positive trend under all the three scenarios in the 21st century. Meanwhile the precipitation and temperature both increase comparing to the reference periods except for the precipitation in Yongdinghe during the 2020s under SA1B. According to the results, evaporation increases compared with the reference period under all the scenarios in all the three sub areas. Moreover, it shows a positive trend in Luanhe and Yongdinghe (northern part of the Hai River basin), while in has a negative trend in Zhangweihe (southern part of the Hai River basin). Runoff in Luanhe and Zhangweihe show an increasing tendency, while it decreases

after an increase in Yongdinghe sub area. Comparing to the reference periods, runoff decreases averagely by 22.9%, 11.9% and 7.3% under all the three scenarios during 2020s in Luanhe, Yongdinghe and Zhangweihe sub areas, respectively. During 2050s, runoff decreases by 5.9% and 9.5 under SA2 and SB1, while increases by 3.0% under SA1B in Luanhe. In Yongdinghe and Zhangweihe, runoff increases generally by 11.3% and 35.4% under the three scenarios during 2050s. During 2080s, runoff increases averagely by 8.3%, 7.9% and 47.9% in Luanhe, Yongdinghe and Zhangweihe sub areas, respectively. Moreover, runoff changes are more pronounced in the southern part than that in the northern part of the Hai River basin in mid-late 21st century compared with the baseline period. Furthermore, runoff increases with SA2>SA1B>SB1 in Yoninghe and Zhangweihe, while in Luanhe with SA1B>SA2>SB1 at the end of the 21st century.

Table 10 changing rate (%) of P, T, E, R under SA1B, SA2 and SB1 in Luanhe

Periods	SA1B				SA2				SB1			
	P	T	E	R	P	T	E	R	P	T	E	R
2011-2020	-0.1	0.73	5.9	-32.7	-2.0	0.76	3.7	-34.1	2.3	0.75	7.2	-28.0
2021-2030	1.4	1.08	7.5	-32.4	3.1	1.24	5.5	-16.8	9.8	1.02	9.6	-0.1
2031-2040	3.8	1.63	8.0	-24.5	1.8	1.34	8.0	-32.2	4.0	1.13	4.1	-5.0
2020s	**1.7**	**1.1**	**7.1**	**-29.9**	**1.0**	**1.1**	**5.7**	**-27.7**	**5.4**	**1.0**	**7.0**	**-11.0**
2041-2050	10.9	2.02	10.5	2.0	3.5	1.84	6.7	-20.8	0.1	1.44	7.9	-38.8
2051-2060	14.7	2.66	12.8	10.9	11.9	2.31	10.5	5.3	10.9	1.75	13.6	-14.6
2061-2070	13.6	3.01	15.5	-3.8	11.6	2.80	13.2	-2.2	18.5	2.02	13.6	25.0
2050s	**13.1**	**2.6**	**12.9**	**3.0**	**9.0**	**2.3**	**10.1**	**-5.9**	**9.8**	**1.7**	**11.7**	**-9.5**
2071-2080	16.1	3.28	13.9	14.3	10.3	3.44	9.7	-0.5	12.4	2.37	14.4	-0.5
2081-2090	15.6	3.48	14.3	15.1	13.9	4.22	15.4	-2.5	9.3	2.38	9.0	-1.9
2091-2099	17.4	3.88	16.4	8.1	17.7	4.61	12.7	25.9	15.7	2.53	14.7	16.5
2080s	**16.4**	**3.5**	**14.9**	**12.5**	**14.0**	**4.1**	**12.6**	**7.6**	**12.5**	**2.4**	**12.7**	**4.7**

Table 11 changing rate (%) of P, T, E, R under SA1B, SA2 and SB1 in Yongdinghe

Periods	SA1B				SA2				SB1			
	P	T	E	R	P	T	E	R	P	T	E	R
2011-2020	2.5	0.81	5.0	-35.7	2.1	0.82	3.6	-22.1	4.0	0.75	5.9	-31.7
2021-2030	-0.4	1.10	1.2	-14.4	2.5	1.25	4.6	-7.2	8.4	1.01	10.1	-9.0
2031-2040	-3.4	1.65	-3.0	-7.5	6.5	1.36	4.4	9.9	5.6	1.11	5.7	11.0
2020s	**-0.4**	**1.2**	**1.1**	**-19.2**	**3.7**	**1.1**	**4.2**	**-6.5**	**6.0**	**1.0**	**7.2**	**-9.9**
2041-2050	9.1	1.95	10.5	5.4	4.3	1.82	5.1	16.0	6.7	1.42	7.5	18.3
2051-2060	10.0	2.58	9.2	11.0	8.3	2.23	8.9	17.1	7.4	1.72	8.8	2.4
2061-2070	9.1	2.93	10.8	12.2	10.5	2.72	12.5	16.3	4.4	1.96	5.4	2.6
2050s	**9.4**	**2.5**	**10.2**	**9.5**	**7.7**	**2.3**	**8.8**	**16.5**	**6.2**	**1.7**	**7.2**	**7.8**
2071-2080	9.7	3.22	9.0	11.5	0.5	3.35	0.9	-1.7	12.3	2.33	12.4	11.3
2081-2090	17.5	3.42	20.6	16.6	15.2	4.05	13.3	9.6	7.6	2.34	10.7	1.8
2091-2099	8.0	3.80	10.4	-2.2	15.5	4.48	17.4	21.9	9.6	2.48	11.9	2.6
2080s	**11.7**	**3.5**	**13.3**	**8.6**	**10.4**	**4.0**	**10.5**	**9.9**	**9.8**	**2.4**	**11.7**	**5.2**

Table 12 changing rate (%) of P, T, E, R under SA1B, SA2 and SB1 in Zhangweihe

Periods	SA1B				SA2				SB1			
	P	T	E	R	P	T	E	R	P	T	E	R
2011-2020	4.7	0.68	7.5	-17.1	1.9	0.75	8.4	-32.2	6.1	0.69	9.7	-21.0
2021-2030	2.7	1.02	5.5	-5.9	-2.8	1.14	1.9	-20.4	7.8	0.93	10.8	-8.9
2031-2040	6.8	1.59	2.6	14.1	10.0	1.23	6.9	13.6	7.4	1.08	6.7	11.9
2020s	**4.7**	**1.1**	**5.2**	**-3.0**	**3.0**	**1.0**	**5.7**	**-13.0**	**7.1**	**0.9**	**9.1**	**-6.0**
2041-2050	7.0	1.87	3.8	23.4	7.3	1.68	2.9	27.0	12.0	1.37	8.2	24.0
2051-2060	14.5	2.45	4.7	52.0	8.5	2.11	4.8	28.0	11.6	1.63	6.8	36.6
2061-2070	14.7	2.77	2.7	70.2	14.8	2.54	4.8	55.4	1.7	1.85	3.1	2.3
2050s	**12.1**	**2.4**	**3.7**	**48.5**	**10.2**	**2.1**	**4.2**	**36.8**	**8.4**	**1.6**	**6.0**	**21.0**
2071-2080	8.6	3.12	1.6	45.0	12.4	3.12	1.5	60.9	7.0	2.24	5.8	12.7
2081-2090	15.5	3.30	4.8	54.5	12.3	3.84	1.3	53.7	12.2	2.27	5.9	34.9
2091-2099	15.0	3.62	2.9	66.1	16.0	4.26	3.6	71.9	10.7	2.35	6.8	31.9
2080s	**13.0**	**3.3**	**3.1**	**55.2**	**13.6**	**3.7**	**2.1**	**62.2**	**10.0**	**2.3**	**6.2**	**26.5**

5. Discussions and conclusions

In line with global change, China's climate has witnessed significant change in the last 50 years. These changes include increased average temperatures, reduced annual precipitation in North China, and rising sea-levels, glacier retreat in Northeast China and significant increases in Southern and Northwestern China. Extreme weather and climatic events are projected to become more frequent in the future and water resource scarcity will continue across the country. Coastal and delta areas will face greater flood and storm risks from sea level rise and typhoon generation. The term risk driven by climate change describes the potential outcome of the interaction of the vulnerable situations of societies and human-ecosystems exposed to climatic stressors such as mean and extreme events and their sequences. The concept of climate risk comprises a combination of the probability of the occurrence of specific physical hazards arising from these climatic stressors, and the consequences associated with these hazards (see the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation).

"Current water management practices may not be robust enough to cope with the impacts of climate change on water supply reliability, flood risk, health, agriculture, energy and aquatic ecosystems "(IPCC Technical Paper VI.

2008). Major problems and challenges on water resources management in China include the contradiction between water demands and water supply due to mismatching of available water resources (*i.e.*, more water in South and less water in North) with natural land resources and social-economic structure. Moreover, natural disasters of floods and droughts also strengthen national and regional water stress.

In this study, the change characteristics of hydrological elements were analyzed for the Hai River Basin. Temperature and runoff show significant increasing trends, while the precipitation decreases slightly during the periods 1961–2009 in the most regions of the basin. The reduction may be related to impact of climate change, such as the increase of evaporation in the basin, also large scale irrigation and water diversion etc. For example, the increasing temperature and LUCC may lead to the increase of evaporation. Large scale irrigation water pumping in the irrigated district from the river will directly cause the reduction of discharge. A water diversion project is another major reason, for instance, the project transferring water from the Luanhe River to Tianjin will reduce the stream flow.

Then the SWAT model, which was used to simulate the hydrological process in the basin, performs well in this basin with a preferable simulating result.

Furthermore, three methods to calculate the evaporation were used for comparing the results by SWAT model. Based on the calibrated hydrological model, the average results of WCRP's multiple models are used to drive the model to evaluate the hydrological responses to climate change under the scenarios SA1B, SA2 and SB1. And precipitation, temperature, evaporation and runoff were analyzed under the three scenarios for the periods 2011-2099. We can get the conclusions as follows.

(1) The precipitation and temperature increase comparing with the reference and hold a positive trend. Meanwhile, the increasing level is with SA2>SA1B>SB1 at the end of the 21st century in the basin.

(2) The evaporation in the basin increases comparing with the reference periods. The changing trend is different with sub areas in the basin. It holds a positive trend in the northern part of the basin, while it has a negative trend in the southern part.

(3) Runoff in the basin holds a positive trend in Luanhe and Zhangweihe, while it decreases after an increase in Yongdinghe. Generally, the water volume in the basin falls in the early periods of the 21st century while it increases in the mid-late of the 21st century, comparing with the reference periods.

(4) Major challenges of impact of climate change to water sector in Hai River Basin are how to take adaptive water management to changing environment. As we known, water resources in China are under two significant sources of pressure. One of them is climate change and another is from development pressure. These pressures are linked and the future long term viability of China is heavily dependent on the wise management of both these pressures to ensure long term sustainability of water (and energy) resources. Water resources are very important for continued development, human health, and food for the Chinese people, and our ability to manage this resource is an important priority at the highest level. For this reason, the China Central Government has adopted the following three adaptation priorities: (1) *The red line I* is water resources development controlled by *Total Water Resources Quantity*; (2) *The red line II is of* water use efficiency improved by *Water Demand Management; and* (3) *The red line III, i.e.* water resources protection by *Water Quality Management* (control of waste water *etc*.). These include a strong part of water governance that needs to be further improved in China.

Also, the results achieved in this study can offer some references for local water resources management in the Hai River Basin. While for further studies, the uncertainties brought by climate scenarios, hydrological modeling, downscaling processes and other factors should be considered to achieve better reliability and higher accuracy. Simulated precipitation for the future time periods by GCMs is still the most important for the evaluation of hydrological response to climate change. Downscaling technology is another factor to affect the input of hydrological model. Some studies show the uncertainties by hydrological model for the evaluation. But it is still very scarce. And the analysis of uncertainties is necessary for the further works. In this paper, the anthropogenic impacts such as LUCC, hydraulic engineering are not considered. And it is necessary to take into account the impacts to evaluate the hydrological response to climate change.

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