Attribution study of water resources changes in the highly water-stressed Haihe River Basin of China

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Abstract Many observational facts and studies have shown that the water resources amount in the Haihe River Basin of China decreased significantly over last half of the 20th century. Factors contributing to this situation consist of a variety of aspects, including natural variability of hydrological elements, climate change and human activities of high intensity which are further subdivided into two aspects in this study: land use change and water use change. The aim of this study is to attribute water resources amount changes in the basin in past 40 years to different factors including natural variability, climate change and human activities. To achieve this, we employ a climate model PCM (Parallel Climate Model), which has been used widely in hydrological studies and realistically portrays important features of observed climate and the amplitude of natural internal variability, a downscaling model SDSM (Statistical Down-Scaling Model) which is the first tool of its type offered to the broader climate change impacts community to downscale the global climate model output, a distributed hydrological model WEP-L (Water and Energy transfer Processes in Large river basins) (Jia et al., 2006) which has been successfully applied in several watersheds in Japan and China with different climate and geographic conditions, the fingerprint-based method (Hasselmann,1997) which is a kind of attribution method widely used in climate change study, a set of observed meteorological data over the basin and observed river flow data at main hydro-stations. Firstly, the temporal variation of annual water resources amount in the basin is analyzed using moving average method, linear regression method and Mann-Kendall method. In addition, the spatial variation of annual water resources amount is also analyzed using EOF (empirical orthogonal function) method. Secondly, through setting several different scenarios, water resources amount affected by different factors, including natural variability, climate change induced by greenhouse gas emission and human activities including water use and land use change are analyzed separately. Thirdly, fingerprint-based method is used to calculate the single strength of water resources amount change under different scenarios. Finally, impacts on water resources amount caused by different factors could be discriminated by comparing the single strengths. The research results indicate that natural variability and human activities may be the reasons, and human activities are the main reasons resulting in the water resources amount change in past 40 years in the Haihe River Basin, accounting for about 36% and 60% of the trend respectively.

Key words water resources change; fingerprint; attribution; climate change; human activities

INTRODUCTION

The Haihe River Basin (320,000 km^2) is the political and cultural center of China, inside which the cities of Beijing and Tianjin are located. With only 1.3% of the total water resources of China, the Haihe River Basin sustains 10% of the country's population, and 13% of the country's GDP. In recent decades, climatic and environmental conditions in the basin have been greatly modified, and global climate change and local human activities of high intensity have caused prominent impacts on both the hydrological cycle and the quality and quantity of water resources. Many observational facts and studies have shown that water resources in the Haihe River Basin decreased significantly over last half of the 20th century (Zhang, et al, 2007). The reduction in extent of runoff in the basin ranked first among China's major rivers over the past 40 years. Simultaneously, groundwater was seriously over-exploited, aquatic ecosystems were seriously overdrawn, and water security suffered severe crises. We consider here how local human activities or climate change or other reasons might account for the situation, and how to attribute factors to the observed water resources changes.

Current attribution methods are mostly based on the fingerprint method (Hasselmann, 1997). Attribution studies have been conducted for a number of measures of atmospheric and oceanic climatic conditions (Barnett et al., 2001, 2006; Hegerl et al., 2006; Hoerling et al., 2006; Zhang et al., 2007; Santer et al., 2007). A review of previous attribution studies is available from the International Ad Hoc Detection and Attribution Group (IADG, 2005). Most of the previous studies examined global or continental scale quantities. This study differs by attempting to perform attribution on a regional scale, which is generally more difficult (Karoly and Wu, 2005). Different from some exploratory work in western United States (Barnett et al., 2008), we attribute river runoff and water resources amount changes at a basin level in this study.

The aim of this study is to quantitatively discriminate among natural variability, climate change and human activities impacts on river runoff and water resources amount changes in the basin in past 40 years. Firstly, the temporal variation of river runoff and water resources amount in the basin is analyzed using moving average method, linear regression method and Mann-Kendall method. In addition, the spatial variation of the two variables is analyzed using EOF (empirical orthogonal function) method. Secondly, through setting different scenarios, the two variables affected by different factors including natural variability, climate change induced by greenhouse gas emissions as well as human activities including water use and land use change are analyzed separately. Finally, fingerprint-based method is used to calculate the signal strength of variables change under different scenarios, through comparing the signal strength of the changes under different scenarios with that of actual changes, water resources changes can be attributed to different factors.

METHODS, MODELS AND DATA SOURCES

To investigate possible attribution of water resources changes in the Haihe River Basin to different factors including climate change and human activities, we employ a climate model PCM (Parallel Climate Model), which has been used widely in hydrological studies and realistically portrays important features of observed climate and the amplitude of natural internal variability (Barnett T. P. et al., 2008), and two model simulations including no forcing run and anthropogenic forcing run separately, a downscaling model SDSM (Statistical Down-Scaling Model) which is the first tool of its type offered to the broader climate change impacts community to downscale the global climate model output to a hydrological suited terrain scale, a distributed hydrological model WEP-L (Water and Energy transfer Processes in Large river basins) (Jia et al.,2001,2005,2006) which has been successfully applied in several watersheds in Japan and China with different climate and geographic conditions to obtain river runoff and water resources amount data, the fingerprint-based method (Hasselmann,1997) which is a kind of attribution method widely used in climate change study, a set of observed meteorological data over the basin and observed river flow data at main hydro-stations. These are each described in the following sections.

Temporal and spatial variation analysis method

Temporal variation analysis method

There are several methods commonly used in trend analysis for hydro-meteorological time series, such as linear regression, cumulative average, moving average, second smooth, cubic spline function and Mann-Kendall rank correlation. In this study, the trend analysis of hydro-meteorological time series is conducted combining linear regression, moving average and Mann-Kendall rank correlation method. Since these methods are widely used, the details of these methods are not listed here limited to paper length.

Spatial variation analysis method

The EOF (Empirical Orthogonal Functions) method is the method of choice for analyzing the variability of variables and finds the spatial patterns of variability which are referred to as the “EOFs”. EOF analysis has been extensively used to examine variability of scalar fields such as sea level pressure (SLP), sea surface temperature (SST), 500Z, etc.

Given the matrix F including measurements of some variable at several locations taken at several different times, that is, each row of the matrix is one map, and each column is a time series of observations or simulations for a given location. We form the covariance matrix of F by calculating $R = F^t F$, and then we solve the eigenvalue problem:

$$RC = C\Lambda \quad (1)$$

where Λ is a diagonal matrix containing the eigenvalues λ_i of R.

For each eigenvalue λ_i chosen we find the corresponding eigenvector c_i. These eigenvectors are the EOFs we are looking for. In what follows we always assume that the eigenvectors are ordered according to the size of the eigenvalues. Thus, EOF1, is the eigenvector associated with the biggest eigenvalue and explaining the variance most. Each eigenvalue λ_i gives a measure of the fraction of the total variance in R explained by the mode. This fraction is found by dividing the λ_i by the sum of all the other eigenvalues (the trace of Λ). The eigenvectors are orthogonal to each other. Details of the method are referred to in H.Bjornsson (1997).

Models

Climate model

The climate model selected in this study is the Parallel Climate Model version 2.1 (PCM; Washington et al. 2000) at a resolution of T42L26 which has been used widely in hydrological studies and realistically portrays important features of observed climate and the amplitude of natural internal variability. The natural variability of precipitation is characterized by run B07.20, the signal of climate change forced with anthropogenic forcing is obtained based on run B06.22. In run B07.20, all components (atmosphere, ocean, sea ice, land surface) are active, model time is 1890-1999, and there is no forcing, but fixed solar constant of 1367 was used. In run B06.22, all components (atmosphere, ocean, sea ice, land surface) are active, model time is 1870-1999, and the driven forcing consist of historical GHG (greenhouse gas), sulfate and ozone. Based on the simulation results of the two run (B07.20, B06.22), we can obtain precipitation and temperature data under natural variability and anthropogenic forcing scenarios, after downscaled and interpolated, the data can be supplied as input to hydrological model to obtain runoff and water resources amount. The details of the model and two runs are referred to website: http://www.earthsystemgrid.org/.

Statistical downscaling model

The statistical downscaling model SDSM enables the construction of climate change scenarios for individual sites at daily time–scales using grid resolution GCM output, and is the first tool of its type offered to the broader climate change impacts community. SDSM couples multiple regressions with stochastic weather generator. The statistical relationship between large-scale climatic factors (predictors) and local variables (predictands) is firstly established, then local change information can be simulated and climate change scenarios in the future can be obtained. Details of the model and application are referred to in Wilby (2007).

Hydrological model

The distributed hydrological model WEP-L was developed in a national key basic research project of China. The WEP-L model is based on the WEP model which has been successfully applied in several watersheds in Japan, Korean and China with different climate and geographic conditions. The WEP-L model adopts the contour bands as the calculation units to fit for large river basins and has been applied in the Yellow river basin in China. For details one is referred to in Jia et al. (2005).

The vertical structure within a calculation unit is shown in Fig.1(a),and the horizontal structure within a watershed is shown in Fig.1(b). Each calculation unit in the vertical direction, from top to bottom, includes nine layers, namely an interception layer, a depression layer, three upper soil layers, a transition layer, an unconfined aquifer and two confined aquifers. State variables include depression storage on land surface and canopies, soil moisture content, land surface temperature, groundwater tables and water stages in rivers, etc. To consider the subgrid heterogeneity of land use, the mosaic method is used which reflects composition of different land uses within a calculation unit. The areal average of water and heat fluxes from all land uses in a calculation unit produces the averaged fluxes in the calculation units. Land use is at first divided into three groups, namely a water body group, a soil-vegetation group and an impervious area group. The soil-vegetation group is further classified into bare soil, tall vegetation (forest or urban trees) and short vegetation (grass or crops). The impervious area group consists of impervious urban cover and urban canopy. In addition, for the convenience of describing soil evaporation, grass or crop root water uptake and tree root water uptake and reflecting surface soil moisture content change with changing root depth, the surface soil of soil-vegetation group is divided into 3 layers. Runoff routings on slopes and in rivers are carried out by applying one-dimensional kinematical wave approach from upstream to downstream. Numerical simulation of multilayered aquifers is performed for groundwater flows in mountainous and plain areas separately with the consideration of groundwater exchange with surface water, soil moisture and stream flow.

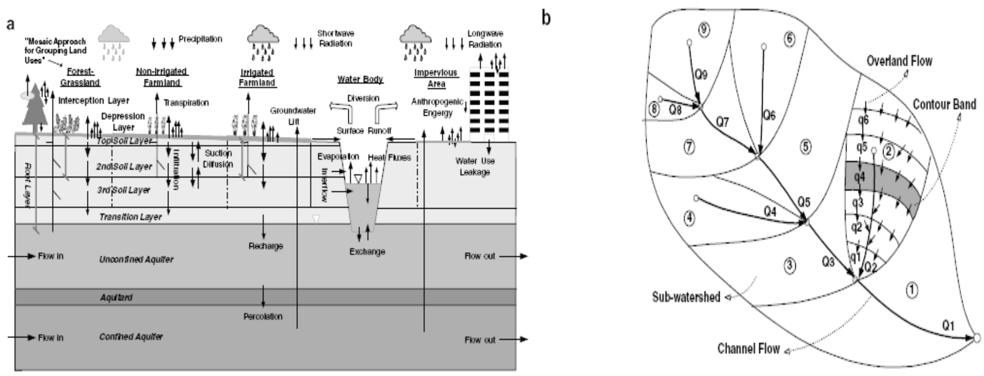


Fig.1. Schematic illustration of WEP-L model structure: (a) vertical structure within a contour band, and (b) horizontal structure within a sub-basin

For hydrological processes, evapotranspiration is computed by the Penman-Monteith equation, infiltration excess during heavy rains is simulated by a generalized Green-Ampt model, whereas saturation excess during the remaining periods is obtained by doing balance analysis in unsaturated soil layers. Taking account of the recharge from unsaturated soil layers and lifted groundwater as source terms, a two-dimensional numerical simulation of multilayered aquifers is performed for groundwater flow to consider the interactions between surface water and groundwater. Flow routing is conducted by using the kinematical wave method in a one-dimensional scheme. Snow melting process is simulated by the Temperature-index approach.

For anthropogenic components, the water use in every calculation unit is deduced by using population and water use per capita. The water use per capita is decided according to statistics of water use in a watershed. Water use leakage is deduced from water use and the leakage rate of water supply system. The sewerage is equal to water use subtracted by leakage, and it is set as one part of the lateral inflow to the channel. The groundwater lift is divided into the domestic water, industrial water and the irrigation water. The domestic water is calculated according to the annual regional domestic water lift and the population distribution, and the industrial water is deduced based on the GDP distribution. The irrigation water is calculated based on the annual lift, irrigation area and irrigation rule.

Fingerprint-based attribution method

Two important concepts in the fingerprint-based attribution method are fingerprint and signal strength. The fingerprint is defined as the leading EOF （Empirical Orthogonal Functions）of the data set (model or observation). Given the fingerprint, the signal strength S is calculated as the least-squares linear trend of the projection of a data set (model or observation) onto the fingerprint:

$$S = trend(F(x) \bullet D(x,t)) \tag{2}$$

where $D(x,t)$ are the regional time series either from a model run or observations, “trend” indicates the slope of the least squares best-fit line.

Given a variable for attribution, the basic idea is to reduce the problem of multiples dimensions (n) to a univariate or low-dimensional problem. In this low-dimensional space, the fingerprint of the variable change can be obtained which is used to further calculate the signal strength. Attribution of the variable change can be conducted through comparing the signal strengths of different scenarios with the actual signal strength calculated by observations. Details of the method can be found in Hegerl et al. (1996, 1997), Tett et al. (1999), Allen and Tett (1999), and Barnett et al.

(2001).

In this study, due to the different units for each variable, we normalized each variate by its own standard deviation before the EOF was computed. Each individual variate time series was also normalized by the fraction of area it represented relative to the entire area represented by the variate, so that time series representing larger areas would contribute proportionally more.

Scenarios setting

The scenarios in the study are set as follows:

For the attribution of river runoff and water resources change, we set five scenarios including natural variability, anthropogenic forcing, artificial water use, land use change, and human activities of high intensity (combining artificial water use with land use change). For attributing river runoff and water resources amount change to natural variability and anthropogenic forcing, the original climate model output precipitation and temperature data is firstly downscaled using SDSM, and then interpolated to the calculation units of hydrological model combining RDS (Reversed Distance Square method) with the Theissen polygon method (Zhou, et al., 2006). River runoff and water resources amount data can be obtained through hydrological model simulations. For attributing river runoff and water resources amount change to artificial water use, land use change, and human activities of high intensity, river runoff and water resources amount data is directly obtained through changing the hydrological model run conditions.

Data sources

Observed meteorological data of long time series (1961-2000) including precipitation and temperature is provided by CMA (China Meteorological Administration). River runoff data of long time series (1961-2000) which is used for the validation of hydrological model is provided by main hydro-stations in the Haihe River Basin. The downscaling model SDSM can be obtained on the website: https://co-public.lboro.ac.uk/cocwd/SDSM/. SDSM calibration data is from NCEP reanalysis data which can be obtained on the website: http://www.cdc.noaa.gov/. The climate model data of two runs can be obtained on the website: http://www.ipcc-data.org.

The water use data is obtained from the integrated water resources planning of the Haihe River Basin. Land use data can be downloaded at the website: http://www.geodata.cn/Portal/mdsearch/listMetadata.jsp?category=185&pn=2&isCookieChecked=true.

RESULTS AND DISCUSSIONS

WEP-L model application

Description of study area

The Haihe River Basin is located between 35°~43°N and 112°~120°E. It neighbors the Inner Mongolian Plateau in the north, and the Yellow River is the borderline in the south. It faces the Bohai Sea to the east and borders Shanxi Plateau in the west. The Haihe basin belongs to the warm temperate zone with a semi-humid and semi-arid climate. The winters are dry and cold, with low rainfall in the spring and heavy rainfall in the summer. The average annual precipitation is 548 mm, about 80 percent of which falls during June to September. Its area is 317,800 km^2, of which 189,000 km^2 is mountainous and the remainder is plain (Fig.2).

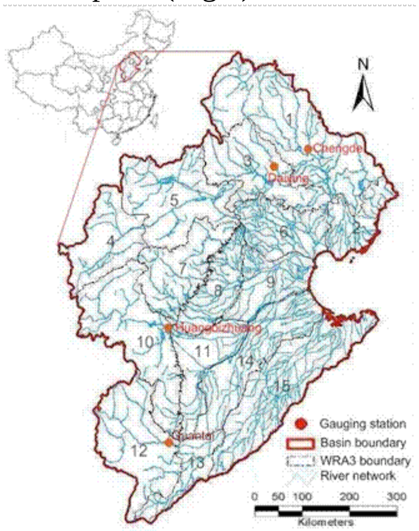


Fig.2. Description of the Haihe River Basin

Notes: the number 1~15 represents the ID of level-3 water resources areas (WRAs)

Subdivision of calculation units

The whole Haihe River Basin in WEP-L model is divided into 3,067 sub-watersheds (Fig. 3(a)), each of which is assigned with a Pfafstetter code. Each sub-watershed in hilly and tableland areas is further divided into 1-10 contour bands, but no further division is performed for sub-watersheds in plain areas because of little topographic effects, i.e., one sub-watershed is taken as one contour band. According to the contour band, the whole Haihe basin is further discretized into 11,752 calculation units (Fig.

3(b)). The details of the basin subdivision and coding are described in Luo et al. (Luo, etc, 2003).

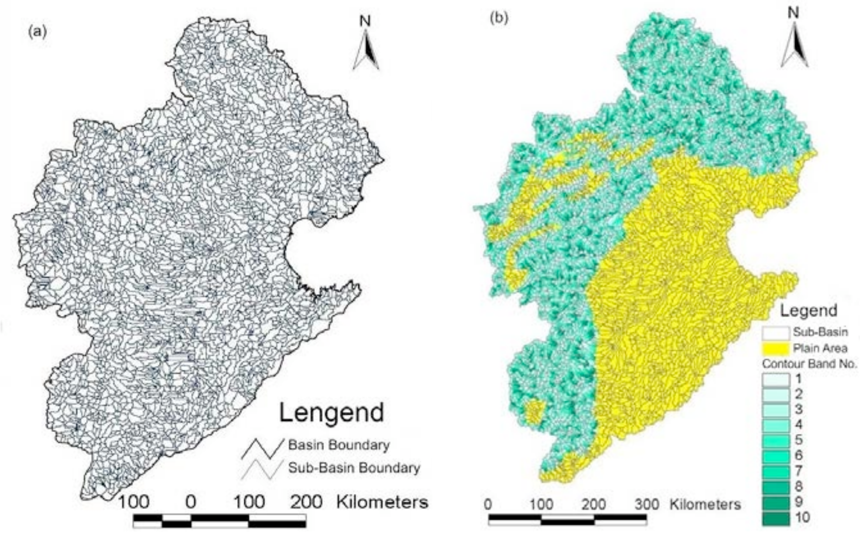


Fig.3. Subdivision of calculation units: (a) Subdivision of sub-basins; and (b) Subdivision of contour bands in mountainous area

WEP-L model calibration and validation

The main parameters in the WEP-L model include soil parameters, groundwater aquifer hydraulic conductivity and specific yield, vegetation parameters, roughness of overland and river channel and infiltration coefficient of river bed.

The WEP-L input data includes following categories: 1) river network, subdivision and coding of sub-basins, subdivisions of contour bands; 2) meteorological and hydrological data; 3) information of land cover elements including land use, soil, geohydrology, vegetation, topography, reservoir, etc.; 4) information of social and economic elements including population, GDP, irrigation area, food yield, etc.; 5) water use data.

Sensitivity of parameters is analyzed, and then parameters with high sensitivity are calibrated on a basis of “try and error”. 11 years (1990-2000) is selected as calibration period. The calibration parameters include maximum depression storage depth of land surface, soil saturated hydraulic conductivity, hydraulic conductivity of unconfined aquifer, permeability of riverbed material, Manning roughness, snow melting coefficient, and critical air temperature for snow melting. After the model calibration, keeping all parameters unchanged, continuous simulations from 1980 to 2000 are performed to verify the model by using observed monthly discharges at 23 main gage stations in the basin. Simulation results of model indicate that average errors of annually runoff are less than 10%, Nash-Sutcliffe efficiency of monthly runoff at main gage stations is over 60%, and correlation coefficients between simulated and observed monthly runoff exceed 80%. A validation example at four stations is shown in Fig.4. Nash-Sutcliffe efficiency and multi-yearly errors of simulated monthly runoff at Guangtai, Huangbizhuang, Chengde and Daiying station are 0.4 and 6.5%, 0.68 and 5.3%, 0.72 and -0.6%, 0.66 and -3.0%, respectively.

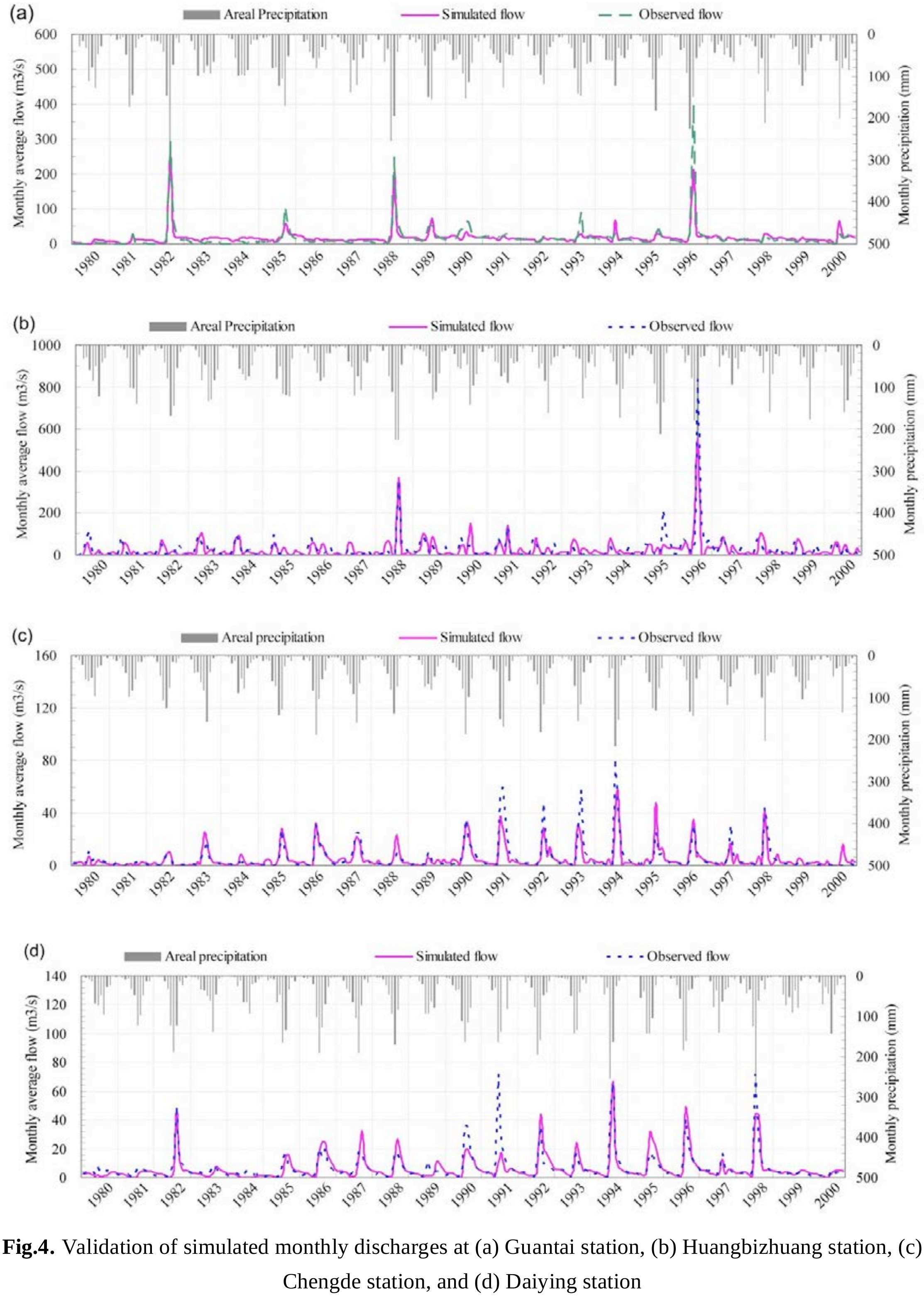


Fig.4. Validation of simulated monthly discharges at (a) Guantai station, (b) Huangbizhuang station, (c) Chengde station, and (d) Daiying station

It should be noted that the WEP-L (Water and Energy transfer Process in Large river basins) model not only can simulate the natural water cycle but also the artificial water cycle, including water abstraction, water use, water consumption, and water drainage, and therefore could reflect local human activity impacts on water resources. Thus we consider that once validated by observed discharge data, the WEP-L model is applicable to attribution study.

Temporal variation of hydro-meteorological variables

We select 26 meteorological stations in the Haihe River Basin, and the distribution of the selected stations is shown in Fig.5.

Based on the observed 1961-2000 time series of annual precipitation and average temperature at 26 stations, the temporal variation of annual precipitation and average temperature as well as temperature change rate is analyzed as listed in Table1.

As can be seen from Table 1, except for the annual temperature at Yushe station slightly decreased, the annual temperature at the other 25 stations all increased, among which 21 stations increased significantly at 95% confidence level. The average change rate at 26 stations reached 0.32 °C/10a, the biggest change rate occurred at Wutaishan station and reached 0.84 °C/10a. It can also be seen that, among the 26 stations, the annual precipitation at 21 stations decreased during 1961-2000, and the annual precipitation at Shenxian and Wutaishan decreased significantly at 95% confidence level. At Beijing, Duolun, Weichang, Weixian and Datong, the annual precipitation slightly increased but not significantly. The average decrease rate at 26 stations is -2.58 mm/a, the biggest decrease occurred at Wutaishan and reached -7.66 mm/a. During the 5 stations where annual precipitation increased, Beijing increased most and the increase rate reached 2.06 mm/a.

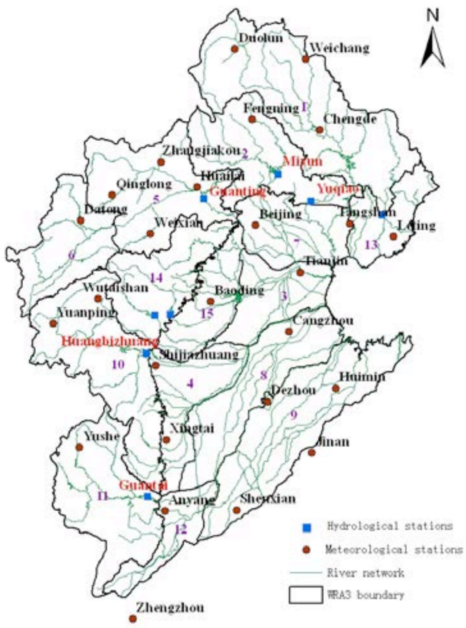


Fig.5. Distribution of selected hydrological and meteorological stations

Table 1 Observed annual average temperature trend in 1961-2000 at 26 stations

Station name	Latitude	Longitude	MK value for T	T change rate（°C/10a）	MK value for P	P change rate（mm/a）
Anyang	36.12	114.36	3.61	0.30	-0.58	-2.13
Beijing	39.92	116.28	4.43	0.48	0.21	2.06
Duolun	42.17	116.45	4.33	0.46	1.30	1.14
Jinan	36.67	116.98	2.91	0.27	-0.40	-2.90
Shijiazhuang	38.02	114.41	3.38	0.34	-0.07	-0.94
Zhangjiakou	40.77	114.88	5.15	0.53	-0.07	-0.41
Baoding	38.85	115.5	4.03	0.36	-1.37	-2.82
Chengde	40.96	117.93	1.14	0.08	-0.70	-0.88
Fengning	41.22	116.63	4.15	0.36	-0.61	-0.60
Huailai	40.4	115.5	4.03	0.39	-1.05	-1.0
Huimin	37.5	117.53	2.75	0.24	-1.17	-3.03
Leting	39.42	118.9	3.17	0.28	-1.28	-3.39
Qinglong	40.4	118.95	2.96	0.25	-0.84	-2.55
Shenxian	36.03	115.58	0.33	0.02	-2.03	-4.68
Tianjin	39.1	117.16	2.35	0.18	-0.65	-1.65
Tangshan	39.66	118.15	2.80	0.25	-0.54	-2.69
Weichang	41.92	117.75	3.87	0.34	1.17	1.41
Wutaishan	39.02	113.53	3.26	0.84	-2.98	-7.66
Weixian	39.82	114.56	3.31	0.44	0.26	0.19
Zhengzhou	34.71	113.65	1.35	0.13	-0.86	-1.73
Yuanping	38.72	112.7	3.89	0.39	-0.31	-1.62
Yushe	37.07	112.98	-0.13	-0.05	-1.86	-4.25
Cangzhou	38.32	116.83	2.80	0.27	-0.47	-1.88
Dezhou	37.42	116.31	3.34	0.35	-1.29	-3.93
Datong	40.1	113.33	1.89	0.21	0.62	0.66
Xingtai	37.07	114.5	5.01	0.47	-0.93	-3.49

Note: MK value in red means the change trend is significant at 95% confidence level, while in black means not significant.

We select 8 hydrological stations in the basin and the temporal variation of annual runoff at each station is analyzed as listed in Table 2 based on the observed 1961-2000 runoff time series.

As can be seen from Table 2, except for the annual runoff at Yuqiao increased since 1980, the annual runoff at the other 7 stations all decreased significantly and the decrease degree all above 20%, especially at Guantai, the annual runoff decreased 40.9% comparing with the annual average.

The temporal variation of annual average temperature, precipitation, river runoff and water resources amount for 15 WRA3s and the whole basin is analyzed as listed in Table 3 based on the simulated 1961-2000 runoff and water resources amount time series using hydrological model. Limited to the paper length, only the trend line and 5-year moving average process line of annual average temperature, precipitation, river runoff and water resources of the whole basin is shown in Fig.6.

Table 2 Observed annual runoff trend in 1961-2000 at 8 stations

Station name	Annual average R/10^8m^3			Change since 1980/%	MK value
	Whole series (1961-2000)	Before 1980	After 1980		
Luanxian	32.6	42.0	23.1	-29.0	-2.21
Yuqiao	6.52	5.08	7.95	22.0	3.57
Miyun	10.13	12.65	7.62	-24.8	-2.42
Guanting	7.37	10.72	4.02	-45.5	-5.38
Wangkuai	5.57	6.94	4.21	-24.5	-2.28
Xidayang	4.11	5.09	3.12	-24.0	-2.80
Huangbizhuang	13.10	18.06	8.13	-37.9	-4.50
Guantai	9.52	13.42	5.63	-40.9	-3.57

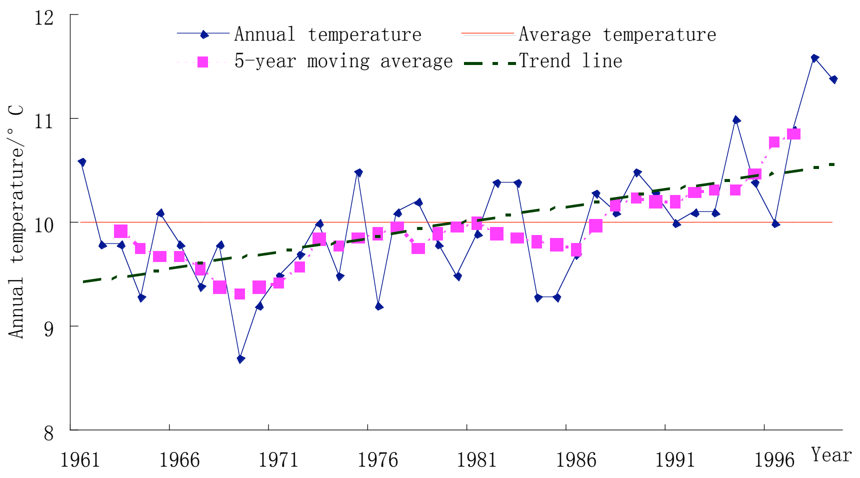
Note: MK value in red means the change trend is significant at 95% confidence level.

Table 3 Temporal variation of actual annual average temperature, precipitation, river runoff and water resources amount for 15 WRA3s and the whole basin in 1961-2000

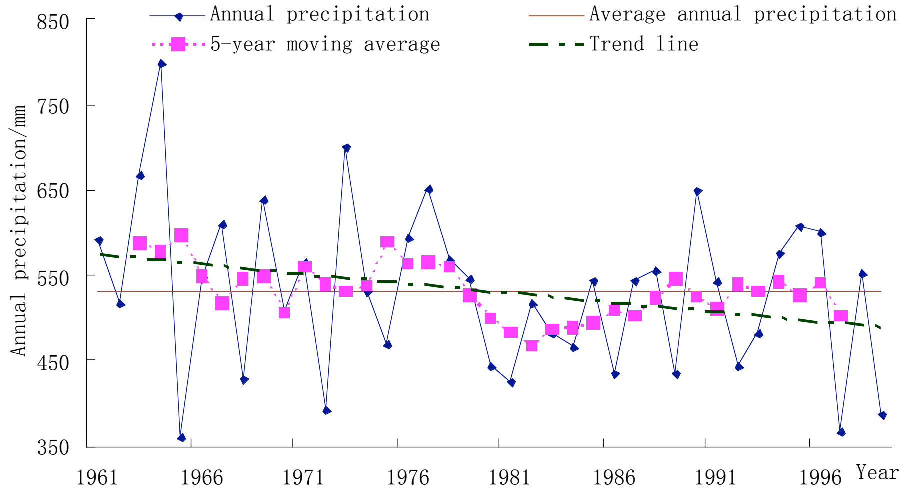
WRA3 ID	MK value for T	T change rate (°C/10a)	MK value for P	P change rate (mm/a)	MK value for R	R change rate (mm/a)	MK value for W	W change rate (mm/a)
1	3.19	0.32	-0.30	-0.33	0.71	0.31	0.76	0.55
2	3.54	0.34	-1.58	-3.55	-1.05	-0.54	-2.92	-2.51
3	3.66	0.33	-0.47	-0.73	-0.16	-0.07	-0.23	-0.10
4	2.77	0.35	-1.19	-1.38	-1.20	-0.08	-2.14	-0.59
5	2.80	0.27	-0.72	-1.00	-1.71	-0.05	-3.01	-0.50
6	3.47	0.34	-0.65	-1.68	0.66	0.05	-0.52	-0.66
7	3.29	0.35	-0.89	-2.02	-1.37	-0.93	-1.54	-1.65
8	3.59	0.39	-0.82	-1.74	-0.35	-0.48	-0.35	-0.48
9	3.38	0.31	-1.17	-2.56	-0.81	-0.42	-0.81	-0.42
10	3.52	0.36	-1.24	-2.06	-1.73	-0.67	-2.29	-1.50
11	3.66	0.37	-0.54	-2.07	-0.62	-0.62	-0.62	-0.62
12	2.47	0.22	-2.14	-3.65	-2.00	-0.68	-2.87	-1.73
13	2.21	0.24	-1.14	-3.18	-0.74	-0.23	-1.44	-1.40
14	3.03	0.27	-1.37	-3.86	-1.32	-0.24	-2.04	-0.84
15	2.59	0.23	-1.28	-3.90	-1.20	-0.26	-2.94	-2.54
Haihe basin	3.15	0.30	-1.35	-2.18	-1.08	-0.27	-2.14	-1.46

Note: MK value in red means the change trend is significant at 95% confidence level, while in black means not significant.

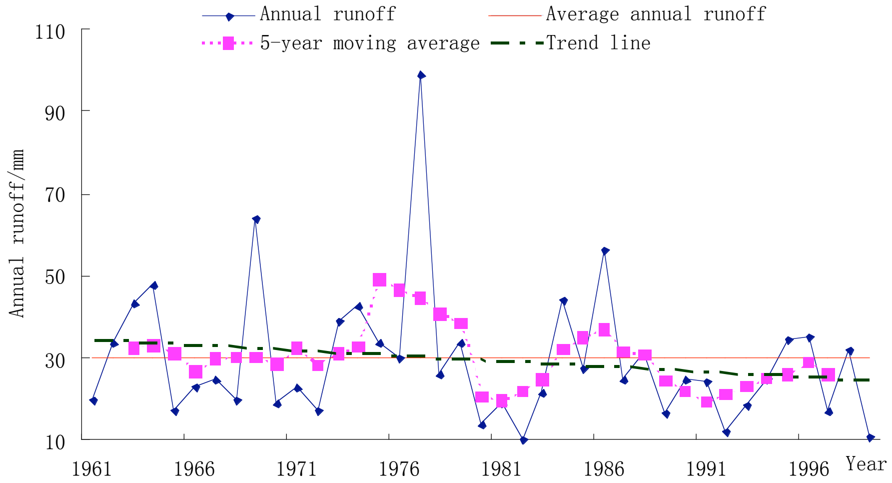
(a)


12
11
10
9
8
Annual temperature
Average temperature
5-year moving average
Trend line
Annual temperature/° C
1961
1966
1971
1976
1981
1986
1991
1996
Year

(b)


850
750
650
550
450
350
Annual precipitation
Average annual precipitation
5-year moving average
Trend line
Annual precipitation/mm
1961
1966
1971
1976
1981
1986
1991
1996
Year

(c)


110
90
70
50
30
10
Annual runoff
Average annual runoff
5-year moving average
Trend line
Annual runoff/mm
1961
1966
1971
1976
1981
1986
1991
1996
Year

(d)

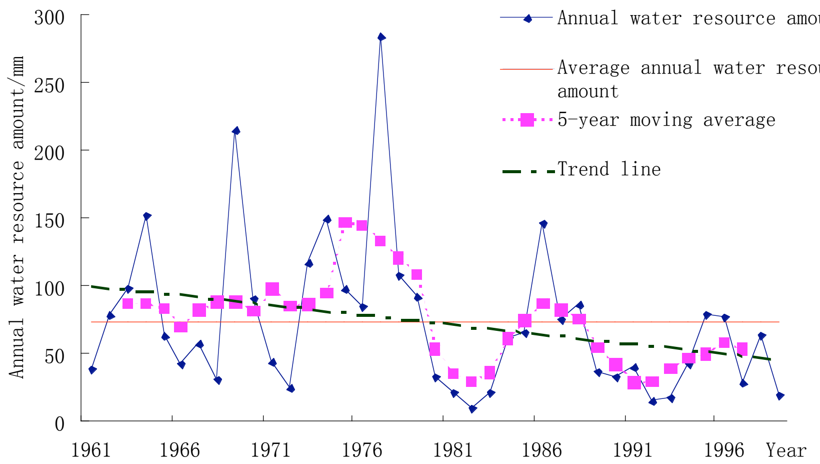


Fig.6 Temporal variation of annual average temperature (a), precipitation (b), runoff (c) and water resources amount (d) of the Haihe River Basin

Spatial variation of hydro-meteorological variables

Based on the 1961-2000 time series of annual runoff and water resources amount simulated by hydrological model in 15 WRA3s, the spatial variation patterns of the river runoff and water resources amount, which are defined as the leading EOF of the data sets, can be obtained as shown in Fig.7.

(a) (b)

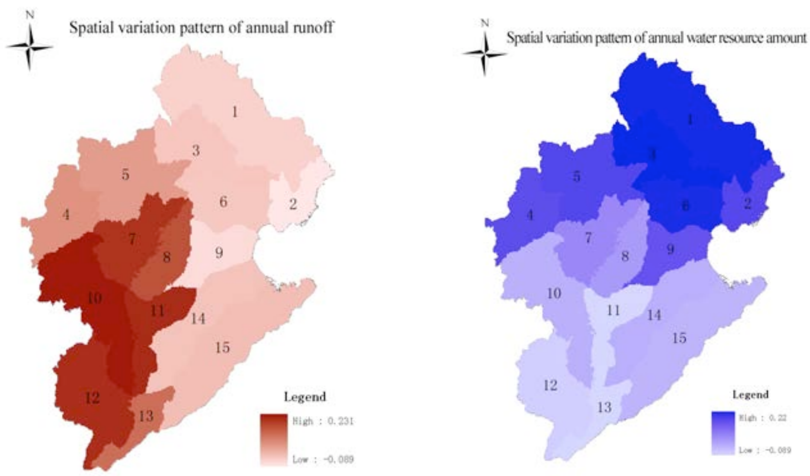


Fig.7 Spatial variation of annual runoff (a) and water resources amount (b) of the Haihe River Basin

Attribution analysis and discussion

Based on the runoff and water resources amount data, we can estimate the fingerprints and signal strengths of both runoff and water resources amount changes under the five study scenarios using the fingerprint-based attribution method, thus attribute the water resources changes to different factors. The attribution results are listed as follows:

For annual runoff change, the observed signal strength is -0.0014, while the signal strength of natural variability, anthropogenic forcing, water usage, land use change and human activities is -0.0007, 0.0008, -0.0008, -0.0007 and -0.001 separately (Fig.8). We can see that the signal strength of anthropogenic forcing is not consist with observed signal strength, thus the factor may not be the reasons resulting in the runoff change in past 40 years in the Haihe River Basin. Among the factors that have consist signal strengths with observed signal strength, natural variability of runoff accounts for 32% of the runoff change, water usage accounts for 36%, land use change accounts for 32%,while human activities combining water usage and land use change account for 59% of the runoff change. Thus, we conclude that natural variability and human activities may be the reasons, and human activities are the main reasons resulting in the runoff change in past 40 years in the Haihe River Basin.

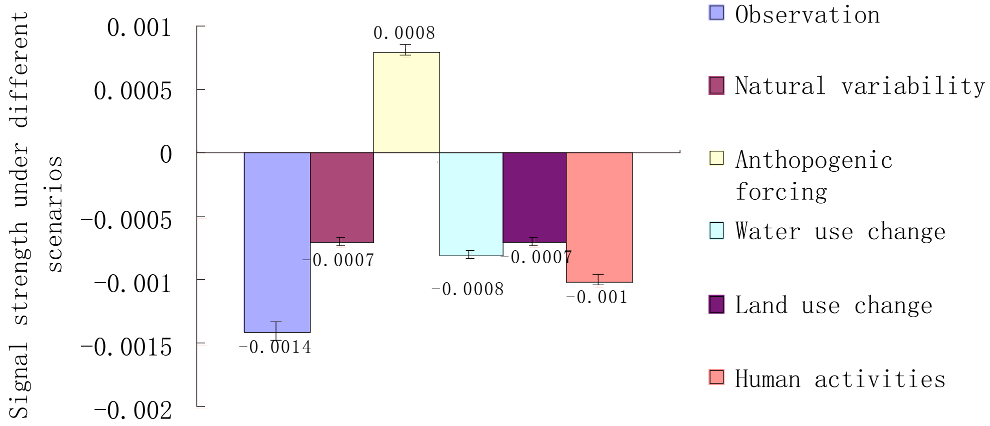


Fig.8 Signal strength under different scenarios for annual runoff change

For annual water resources amount change, the observed signal strength is -0.0079, while the signal strength of natural variability, anthropogenic forcing, water usage, land use change and human activities is -0.001, 0.0009, -0.0013, -0.0005 and -0.0015 separately (Fig.9). We can see that, the signal strength of anthropogenic forcing is not consist with observed signal strength, thus the factor may not be the reasons resulting in the water resources amount change in past 40 years in the Haihe River Basin. Among the factors that have consist signal strengths with observed signal strength, natural variability of water resources amount accounts for 36% of the water resources amount change, water usage accounts for 46%, land use change accounts for 18%,while human activities combining water usage and land use change account for 60% of the water resources amount change. Thus, we conclude that natural variability and human activities may be the reasons, and human activities are the main reasons resulting in the water resources amount change in past 40 years in the Haihe River Basin.

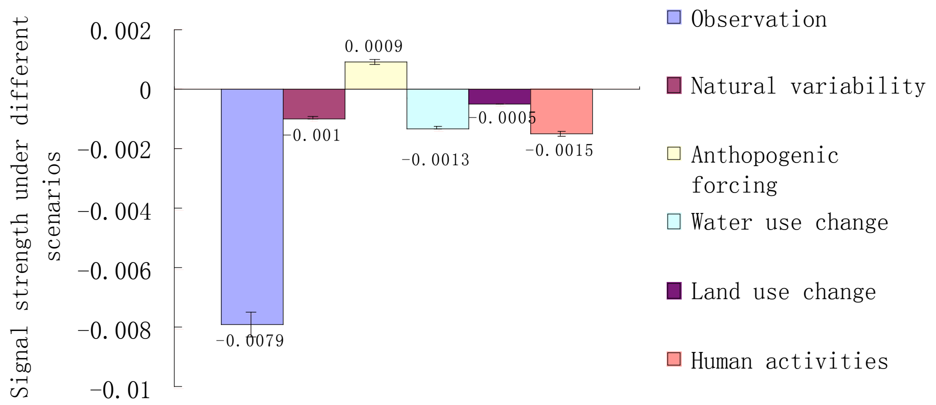


Fig.9 Signal strength under different scenarios for annual water resources amount change

CONCLUSION

In large river basins that were greatly affected by climate change and human activities of high-intensity like the Haihe River Basin, it is of great importance and significance to discriminate and quantitatively estimate climate change impacts and human activities impacts on hydrological variables such as runoff and water resources amount.

In this study, we apply fingerprint-based attribution method to attribute water resources changes to natural variability, climate change induced by greenhouse gas emission as well as human activities including water use and land use change, and obtain some primary results. During the past 40 years in the Haihe River Basin, natural variability and human activities may be the reasons, and human activities are the main reasons resulting in the water resources amount change in past 40 years in the Hai river basin, accounting for about 36% and 60% of the trend respectively.

These results warn people that it is urgent and necessary to protect and cherish water resources for our life and sustainable development while developing economy. In the future, to ensure the sustainable development of economy, society and environment, more great efforts should be made to realize sustainable management and effective use of water resources.

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