Variability, change and prediction of hydro-climatic elements in the Hai River basin, China

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Abstract Many observational facts and studies have shown that the hydro-climatic conditions in the Hai River basin, which is the political and cultural centre of China, changed significantly over last half of the 20th century. This study attempts to evaluate the variability and change of hydro-climatic elements in the basin including precipitation, temperature, evapotranspiration and runoff, based on observations and a hydrological model, as well to predict the trends of these elements under a changing environment. Specifically, the temporal variations and sudden changes of precipitation, temperature, evapotranspiration and runoff during the last 50 years (1956–2005) in the basin are analysed using the moving-average method, linear regression method and Mann-Kendall method. For future conditions, the precipitation and temperature data are obtained from the average data set of 20 global climate models using the REA (reliability ensemble averaging) method, together with future land-use data based on national land-use planning documents, and evapotranspiration and runoff data obtained through hydrological model simulations. Thus, the prediction of the elements under a changing environment can be given. The results indicate that: (1) during 1956–2005, the temperature significantly increased and the estimated sudden change time was 1964, while the precipitation and evapotranspiration significantly decreased and the estimated sudden change time was 1961, the surface runoff also significantly decreased and the estimated sudden change time was 1963; (2) during 2021–2050, evapotranspiration will increase by 7.1%, surface runoff will decrease by 9.8% and the variation within a year may increase; runoff in flood seasons especially July and August may increase, but decrease in the remaining months. This study may provide decision support for integrated management and planning of water resources in the highly water-stressed basin.

Key words variability; change; prediction; hydro-climatic elements; Hai River, China

INTRODUCTION

The Hai River Basin (320 000 km^2) is the political and cultural centre of China and contains the cities of Beijing and Tianjin. In recent decades, climatic and environmental conditions of the basin have changed greatly, and global climate change and intense local human activity have greatly affected both the hydrological cycle and the quantity of water resources. Many observations and studies have shown that water resources in the basin decreased significantly over the last half of the 20th century (Zhang *et al*., 2007). The magnitude of the reduction of runoff in the basin has been the greatest among China's major rivers over the past 40 years. Simultaneously, groundwater has been seriously over-exploited, aquatic ecosystems have been seriously overdrawn, and there have been severe water security crises.

This study attempts to evaluate the variability and change of hydro-climatic elements in the basin, including precipitation, temperature, evapotranspiration and runoff, based on observations and a hydrological model, and predicts the trends of these elements under changing environment including climate change and human activities.

DATA AND METHODOLOGY

To evaluate the variability and change of hydro-climatic elements including precipitation, temperature, evapotranspiration and runoff in the basin during the last 50 years (1956–2005), we employ some trend analysis methods, such as the moving-average method, linear regression method and Mann-Kendall method, to analyse the temporal variations and sudden changes; a distributed hydrological model WEP-L (Water and Energy transfer Process in Large river basins) to obtain evapotranspiration and runoff series; meteorological observation data made throughout the basin; and data of river flow observed at the main hydro-stations.

To predict the trends of the hydro-climatic elements under changing environment due to climate change and/or human activities, we employ an average data set of 20 global climate models using the

Reliability Ensemble Averaging (REA) method to represent the future climate, a weather generator to temporally downscale the GCM data, the Reversed Distance Square method combined with the Theissen polygon method to spatially interpolate the GCM data, the national land-use planning documents to represent future human activities, and the WEP-L model to obtain future evapotranspiration and runoff data. The data and methods mentioned above are each described in the following sections.

Trend analysis method

To evaluate the temporal variations and sudden changes of the hydro-climatic elements: precipitation, temperature, evapotranspiration and runoff, during last 50 years (1956–2005) in the basin, we employ a trend analysis method combining moving-average, linear regression with Mann-Kendall method. Since these methods are widely used, their details are not given here.

WEP-L model

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

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). The areal averages of water and heat fluxes for all land uses in a calculation unit give the average fluxes in the calculation units. Land use is first divided into three groups: a water body group, 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. Runoff routings on slopes and in rivers are carried out by applying the one-dimensional kinematic wave approach from upstream to downstream. Multilayered aquifers are numerically simulated for groundwater flows in mountainous and plain areas separately considering groundwater exchange with surface water, soil moisture and streamflow.

For the simulation of hydrological processes, evapotranspiration is computed with the Penman-Monteith equation, infiltration excess during heavy rain is simulated by a generalized Green-Ampt model, and saturation excess during the remaining periods is obtained via balance analysis of unsaturated soil layers. Taking account of the recharge from unsaturated soil layers and groundwater table rise 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 employing the kinematical wave method in a one-dimensional scheme.
Details of the model and its application are given by Jia *et al.* (2001, 2005b, 2006).

Observation data

Long time series (1956–2005) of meteorological observations including those of precipitation and temperature were provided by the China Meteorological Administration (CMA). Long time series (1980–2000) of river runoff used for validation of the hydrological model were provided by the main hydro-stations in the Hai River basin. Land-use data were downloaded from the website: http://www.geodata.cn/Portal/mdsearch/listMetadata.jsp?category=185&pn=2&isCookieChecked=true.

Future climate data

Global climate models perform differently in different regions. Much research shows that ensemble averages of climate models perform better than a single model. The GCM data used in this study are from the World Climate Research Programme’s (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model data set, which includes estimation results of more than 20 climate models provided by the Programme for Climate Model Diagnosis and Intercomparison (PCMDI). Based on the data set, the multi-model average data set under three emission scenarios A1B, A2 and B1,

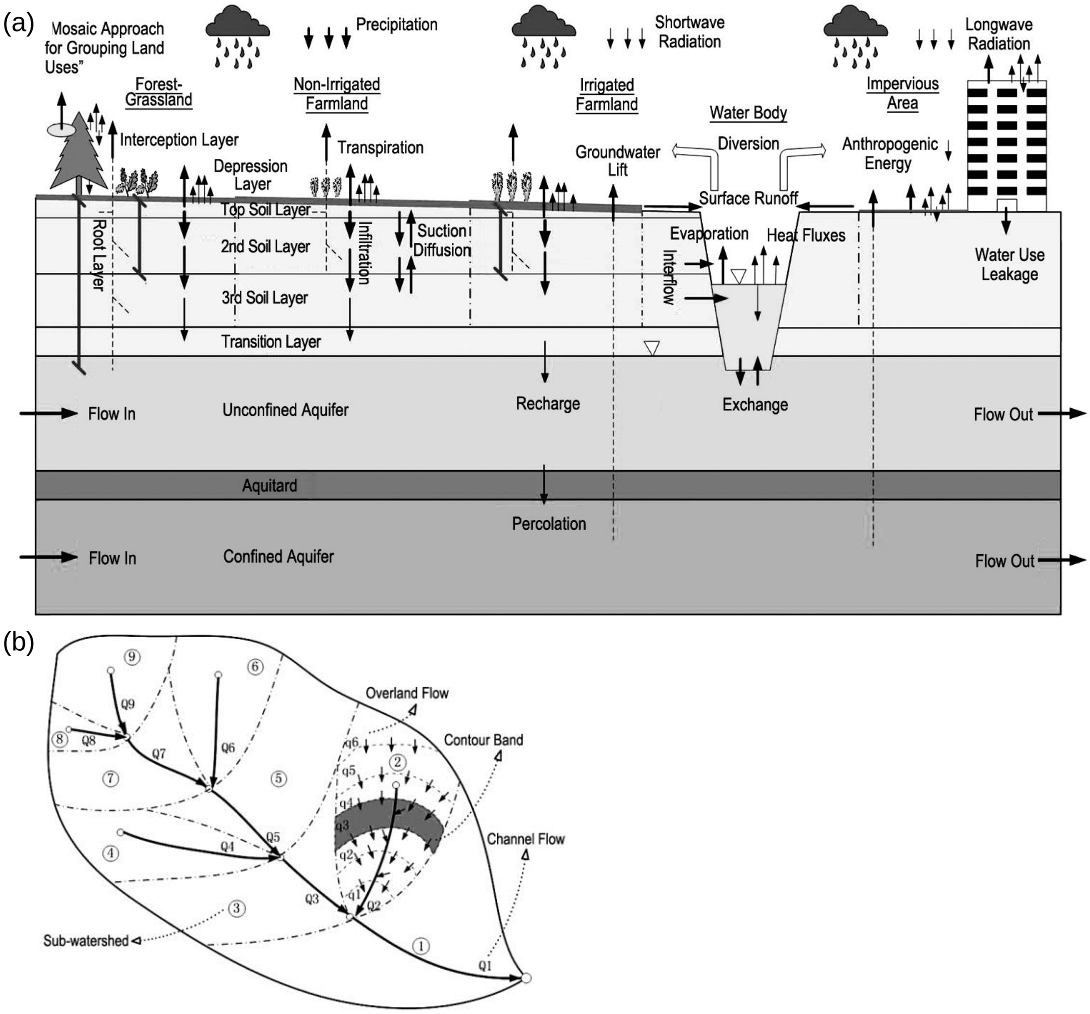

Fig. 1 Schematic illustration of the WEP-L model structure: (a) vertical structure within a contour band and (b) horizontal structure within a sub-basin.

which were provided by the Intergovernmental Panel on Climate Change (IPCC) in 2000, can be obtained employing the REA method. For more details about the data set and scenarios, please refer to National Climate Centre (2008).

Both temporal and spatial scale conversions of GCM estimation data are needed when coupling climate models with hydrological models, because the requirements for the temporal and spatial scale of precipitation and temperature data between climate models and hydrological models are inconsistent.

The temporal scale of the original GCM estimation data is monthly, while that of the hydrological model input is daily. We employ the weather generator BCCRCG-WG 3.00 to temporally downscale the GCM estimation data. This weather generator takes the whole of China as the study area, and the parameters are estimated using the observations of long time series at 672 meteorological stations, and thus can reflect the actual local climate (Liao *et al.*, 2004).

GCM data at stations are spatially interpolated to the calculation units of the hydrological model combining the RDS method with the Theissen polygon method. Details of the method are given by Zhou *et al*. (2006).

Future land-use data

According to the relation between calculation units and the provinces in the basin, distributed land-use data for the basin in the future can be obtained using GIS tools based on the areas of different types of land use in provinces provided by National Land Use Planning Documents (2006–2020). Comparing with those in 2000, in the future, the areas of grassland and farmland will decrease by 12.4% and 1.8%, respectively, and the area of woodland and urban land will increase by 13.2% and 10%, respectively.

RESULTS AND DISCUSSION

WEP-L model application

The Hai River basin is located at 35°–43°N and 112°–120°E. It borders the Inner Mongolian Plateau to the north, the Yellow River to the south, the Bohai Sea to the east and Shanxi Plateau to the west. The basin belongs to the warm temperate zone and has a semi-humid and semi-arid climate. The winters are dry and cold, and there is low rainfall in the spring and heavy rainfall in the summer. The average annual precipitation is 548 mm, about 80% of which falls from June to September.

The entire Hai River basin in the WEP-L model is divided into 3067 sub-basins (Fig. 2(a)); each sub-basin in hilly and tableland areas is further divided into 1–10 contour bands, but no further division is performed for sub-basins on the plains because of the small topographic effects. According to the contour bands, the entire Hai basin is further discretized into 11 752 calculation units (Fig. 2 (b)).

The sensitivity of the main parameters was analysed, and parameters with high sensitivity were calibrated by trial and error. The 11 years of 1990–2000 were selected as the calibration period. The calibration parameters include the maximum depression storage depth of the land surface, soil saturated hydraulic conductivity, hydraulic conductivity of the unconfined aquifer, permeability of riverbed material, Manning roughness, snowmelt coefficient, and critical air temperature for the melting of snow. After model calibration and keeping all parameters unchanged, continuous simulations from 1980 to 2000 were performed to verify the model using observed monthly discharges at 12 main gauging stations in the basin. Verification results of the model indicate that the average errors in annual runoff are less than 15%, the Nash-Sutcliffe efficiency of the monthly runoff at the main gauge stations exceeds 60%, and coefficients of correlation between simulated and observed monthly runoff exceed 80%. A validation example for the four stations is shown in Fig. 3.

Variability and change of hydro-climatic elements

The temporal variation of annual precipitation, temperature, evapotranspiration and runoff in the basin during 1956–2005 is shown in Fig. 4. Based on a significance test and sudden change test, the results indicate that during 1956–2005 in the basin, the decrease trend of precipitation is significant at 0.05 level and the sudden change happened in 1961, the increase trend of temperature is significant at 0.05 level and the sudden change happened in 1964, the decrease trend of evapotranspiration is significant at

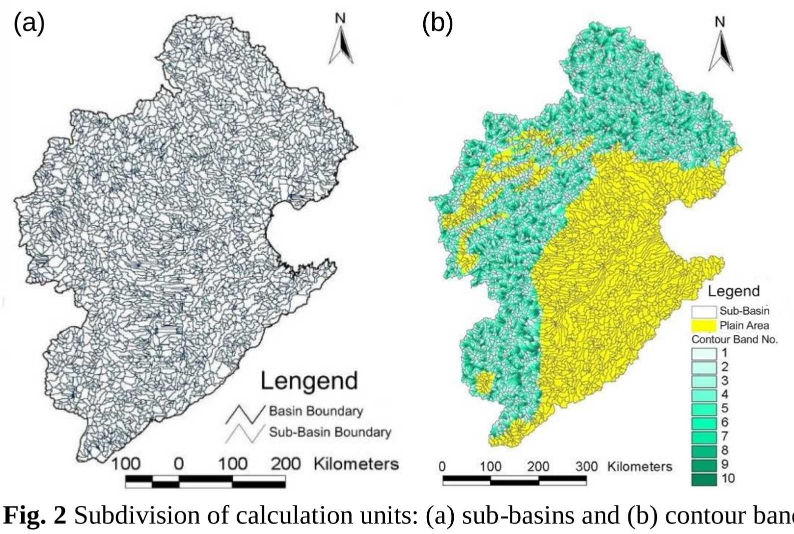

Fig. 2 Subdivision of calculation units: (a) sub-basins and (b) contour bands in mountainous area.

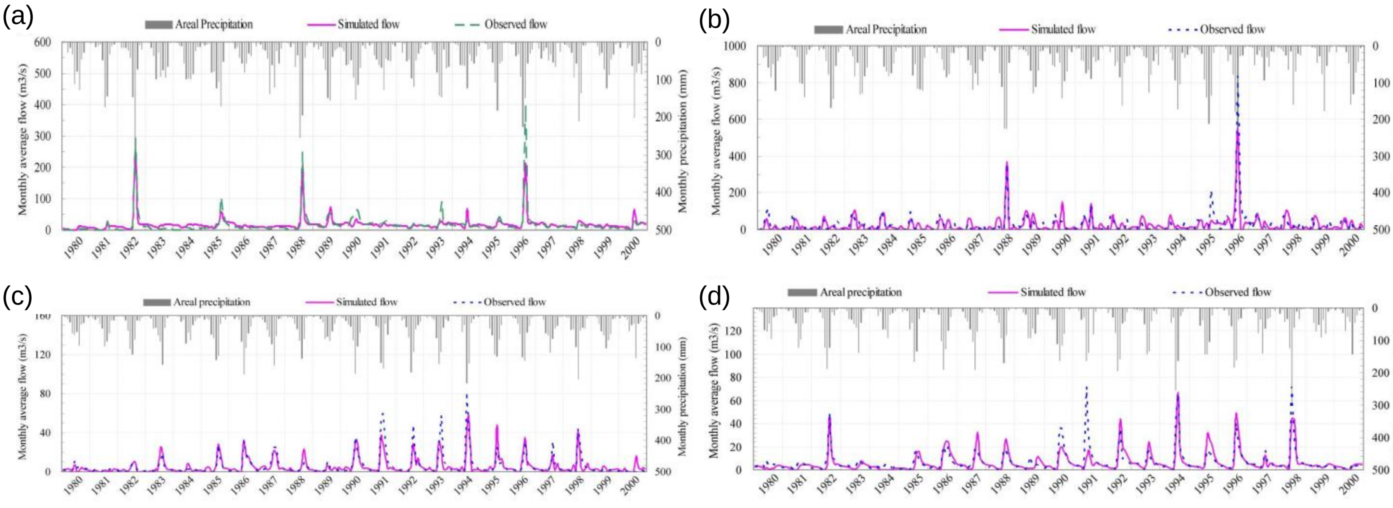

Fig. 3 Validation of simulated monthly discharge at: (a) Guantai, (b) Huangbizhuang, (c) Chengde and (d) Daiying.

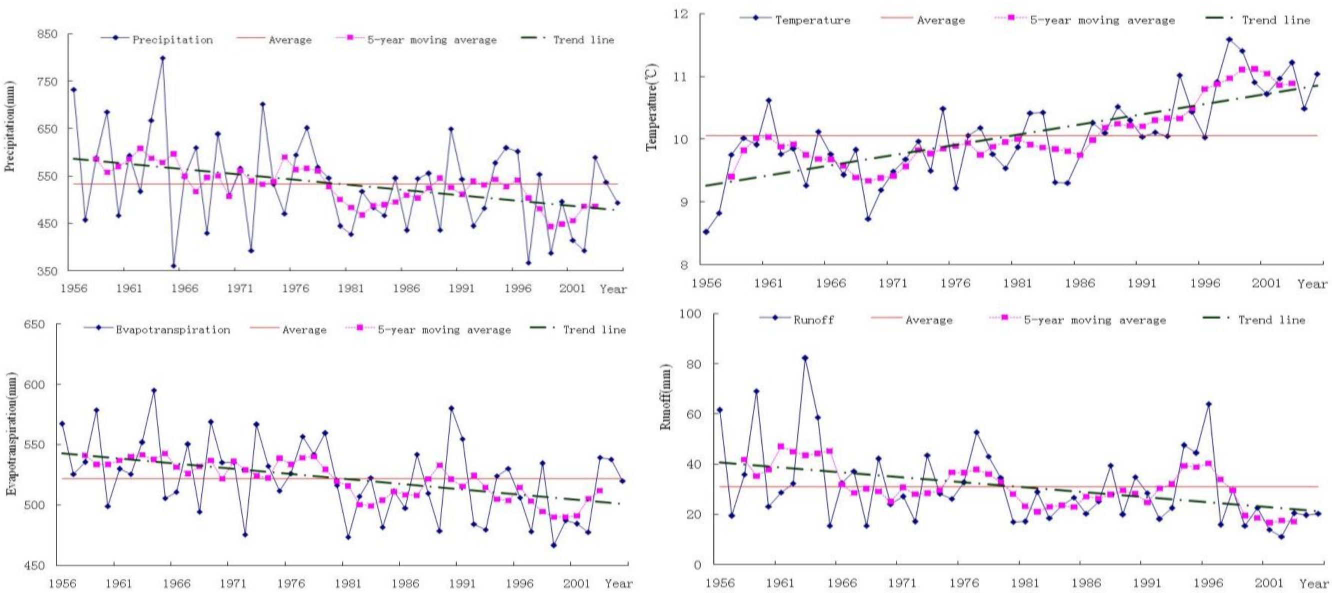

Fig. 4 Temporal variation of hydro-climatic elements in the Hai River basin during 1956–2005.

0.05 level and the sudden change happened in 1961, which is consistent with that of precipitation, the decrease trend of runoff is significant at 0.05 level and the sudden change happened in 1963 which is two years later than that of precipitation.

Prediction of hydro-climatic elements

Prediction of the hydro-climatic elements for the future 30 years (2021–2050) under three scenarios is shown in this section. A comparison of the average annual characteristic values of the main hydro-climatic elements under historical conditions (1956–2005) with three scenarios in the future is shown in Table 1.

From Table 1 we can see that, from the view of average annual change, and comparing with the historical average, in the future 30 years under A1B, A2 and B1 scenarios, the precipitation will appreciably increase by 3.7%, 3.8% and 6.8%, respectively, and the extremes will not obviously vary; the temperature will increase by about 1.4°C, 1.2°C and 1°C, the evapotranspiration will generally

Table 1 Comparison of average annual characteristic values of the hydro-climatic elements under historical conditions with three scenarios in the future.

Scenario	P (mm)			T (°C)			E (mm)			R (mm)		
	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min
History	532.5	799.4	360.5	10.1	11.6	8.5	522.0	594.9	466.5	31.0	82.3	11.0
A1B	552.2	770.9	352.5	11.5	12.8	10.2	557.0	656.7	460.6	26.7	71.6	12.8
A2	552.9	785.8	369.2	11.3	12.8	10.1	556.1	660.2	467.7	27.1	61.3	11.2
B1	568.6	806.1	381.8	11.1	12.2	10.1	563.6	677.7	471.0	30.0	97.9	14.7

increase by 6.7%, 6.5% and 8.0%; whereas, the runoff will decrease by 13.8%, 12.5% and 3.2% respectively.

The average monthly changes of the elements are shown in Fig. 5. From the view of monthly average change, except the precipitation in May, September and October which will slightly decrease, precipitation in the other months will increase, especially in February and April; temperatures in all 12 months will increase, and temperature in February has the smallest increase; evapotranspiration in all 12 months will generally increase, and evapotranspiration in January, February, November and December will have larger increases; surface runoff in flood seasons, especially July and August, will increase, while in the remaining months, surface runoff will generally decrease.

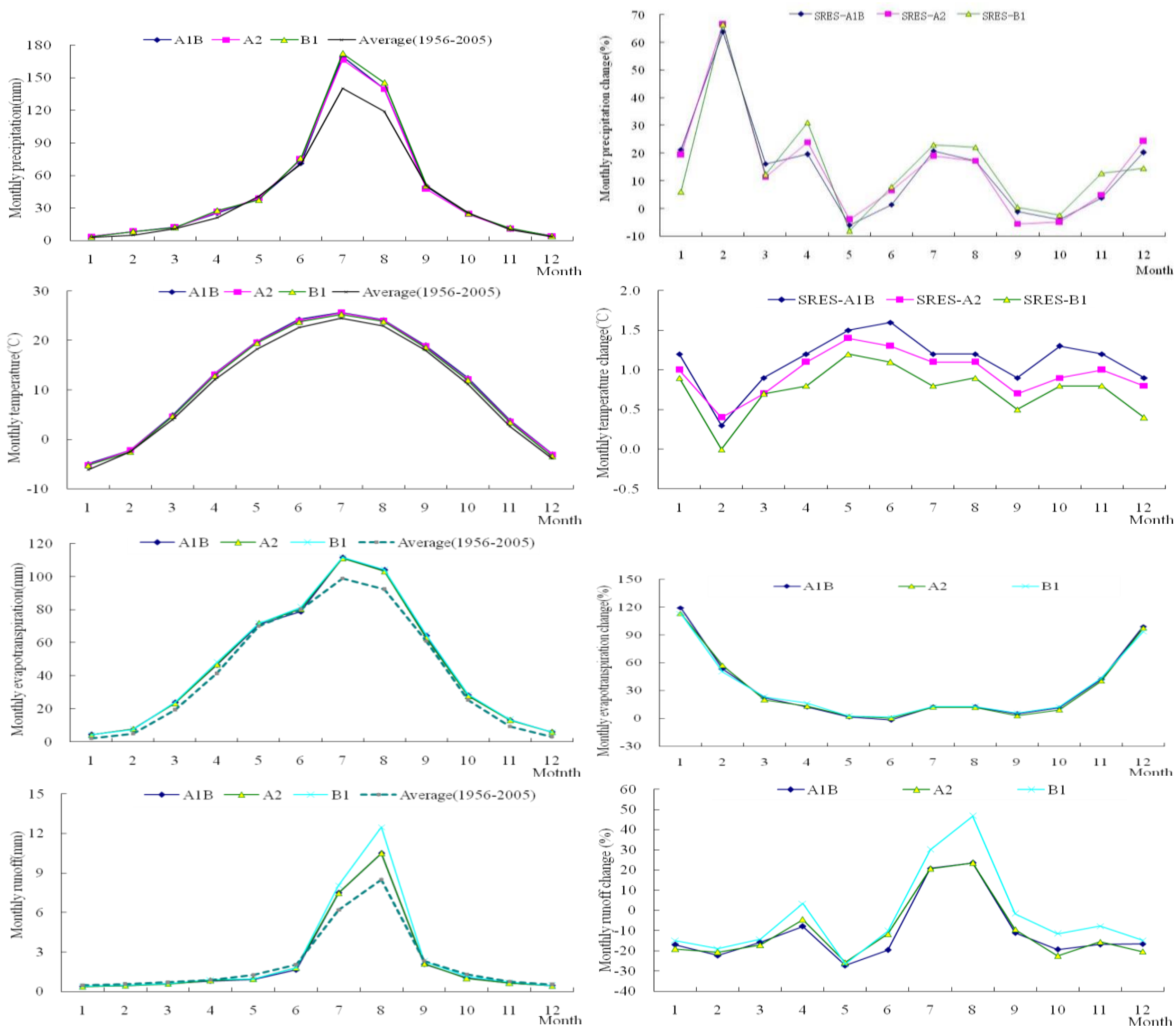

Fig. 5 Average monthly change of the hydro-climatic elements in the Hai River basin in 2021–2050.

CONCLUSION

This study evaluates the variability and change of hydro-climatic elements in the Hai River basin based on observations and the WEP-L model, as well as predicting the trends of these elements in the future 30 years (2021–2050) under different climate scenarios. The results indicate that, during the past 50 years (1956–2005) in the basin, the temperature significantly increased and the estimated sudden change time is 1964, while the precipitation and evapotranspiration significantly decreased and the estimated sudden change time is 1961; the surface runoff also significantly decreased and the estimated sudden change time is 1963. In the future, precipitation, temperature and evapotranspiration in the basin will increase by 4.8%, 1.2°C and 7.1% respectively, surface runoff will decrease by 9.8% and the variation within a year may exacerbate runoff in flood seasons, especially July and August, while runoff decreases in the remaining months.

It should be noted that many uncertainties arise during this study, and are inherent to such work. For example, the uncertainties for the parameters of the hydrological model, validating the hydrological model using runoff data only limited to the data obtained, the prediction results are based on the GCM estimation data which has great uncertainties especially for the estimated precipitation. Therefore, further work is required to quantify the uncertainties, where possible, in this research.

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REFERENCES

Jia, Y. W., Ni, G. H., Kawahara, Y. & Suetsugi, T. (2001), Development of WEP model and its application to an urban watershed. *Hydrol. Processes* **15**, 2175–2194.

Jia, Y. W., *et al.* (2005a) Distributed hydrologic modeling in a partially urbanized agricultural watershed using WEP model. *J. Hydrol. Engng ASCE* **10**, 253–263

Jia, Y. W., Wang, H., Ni, G. H., Yang, D. W., Wang, J. H. & Qin, D. Y. (2005b) *Theory and Practices of Distributed Watershed Hydrological Models*. China Water Resources and Hydropower Publishing, Beijing.

Jia, Y. W., H. Wang, *et al.* (2006) Development of the WEP-L distributed hydrological model and dynamic assessment of water resources in the Yellow River Basin. *J. Hydrol.* **331**, 606–629.

Liao, Y. M., *et al*. (2004), Simulation of precipitation in the China Weather Generator. *J. Geogr. Sci.* **59**(5), 689–698.

National Climate Centre (2008) Climate change estimation dataset in China, Version 1.0: Manual.

Zhang, J. Y., *et al*. (2007) *Study of Climate Change Impacts on Hydro-cycle and Water Resources*. Science Press, Beijing.

Zhou, Z. H. *et al*. (2006) Station-based temporal and spatial interpolation in large basin. *Hydrol.* **26**(1), 6–11