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Simulating Hydrologic Changes with Climate Change Scenarios in the Haihe River Basin*[1]

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ABSTRACT

Climate change scenarios, predicted using the regional climate modeling system of PRECIS (providing regional climates for impacts studies), were used to derive three-layer variable infiltration capacity (VIC-3L) land surface model for the simulation of hydrologic processes at a spatial resolution of 0.25° × 0.25° in the Haihe River Basin. Three climate scenarios were considered in this study: recent climate (1961-1990), future climate A2 (1991-2100) and future climate B2 (1991-2100) with A2 and B2 being two storylines of future emissions developed with the Intergovernmental Panel on Climate Change (IPCC) special report on emissions scenarios. Overall, under future climate scenarios A2 and B2, the Haihe River Basin would experience warmer climate with increased precipitation, evaporation and runoff production as compared with recent climate, but would be still likely prone to water shortages in the period of 2031-2070. In addition, under future climate A2 and B2, an increase in runoff during the wet season was noticed, indicating a future rise in the flood occurrence possibility in the Haihe River Basin.

Key Words: climate change, regional climate modeling system, runoff, VIC-3L model

Climate change has shown substantial impact on hydrosphere and biosphere including such important aspects as water availability and quality, floods, and droughts. The effect of climate variability on economic vitality and life of people has indicated that future climate change is of considerable global, national and regional importance (Yu *et al.*, 2000). Hydrologists and meteorologists have realized the importance of modeling the hydro-climatology of large river basins so as to understand the basin-scale hydrological cycle and to ultimately manage water resources (Yu *et al.*, 1999; Liu *et al.*, 2004; Chen *et al.*, 2004). Some hydrological models, such as the semi-distributed land use-based runoff processes (SLURP) model, the hydrological bureau water balance-section (HBV) model, and the macro-scale probability distributed model (Macro-PDM), have been developed and applied to study the effects of future climate change on runoff and water resources (Su and Xie, 2003). The three-layer variable infiltration capacity (VIC-3L) model was applied in this research to simulate future water resources at the Haihe River Basin in China at a spatial resolution of 0.25° × 0.25° in response to climate change scenarios predicted using the regional climate modeling system of PRECIS (providing regional climates for impacts studies).

MATERIALS AND METHODS

Haihe River Basin

The Haihe River Basin is located in North China, which is the political, economic and cultural center of China with a GDP (gross domestic product) of US $378 billion (RMB ¥3 130 billion, using a conversion rate of US $1.00 = RMB ¥8.28) and irrigable land of 140.0 million ha, 32.3% and 42%,

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respectively, of the national totals (Xia *et al.,* 2003). It has a drainage area of 3.182×10^5 km^2, a mean annual precipitation of 520.4 mm and a mean annual runoff depth of 120.1 mm. However, the Haihe River Basin is a region with a tremendous conflict in the water supply and demand. For example, the water volume per capita is merely 305 m^3, 1/7 of the national average and 1/24 of the world average (Chen, 1985; Chen, 1994; Chen and Xia, 1999; Xia *et al.,* 2003).

The lack of water resources in the Haihe River Basin has not only hindered the development of the national economy, but has also resulted in such severe environmental problems as the serious reduction of the water supply from mountainous areas, subsidence of the land surface due to over-exploitation of groundwater, degradation of rivers and lakes and water pollution (Xia *et al.,* 2003).

VIC-3L model

Liang *et al.* (1994) developed the two-layer variable infiltration capacity (VIC-2L) model, which included two different time scales (fast and slow) for runoff to capture the dynamics of runoff generation. The upper soil layer of the model was designed to represent the dynamic response of soil to rainfall events, and the lower layer was used to characterize the seasonal soil moisture behavior. The VIC model used physically-based formulations for the calculation of sensible and latent heat fluxes along with the conceptual Arno baseflow model (Todini, 1996; Franchini and Pacciani, 1991) to simulate runoff generation from the deepest soil layer. To better represent rapid bare soil evaporation following small summer rainfall events, a thin soil layer was included in the VIC-2L model (Liang *et al.,* 1996) and the VIC-2L model became the VIC-3L model. Also, in the VIC-3L model, soil moisture diffusion processes between the three soil layers were considered. Afterward, Cherkauer and Lettenmaier (1999) improved the representation of processes for cold climates within the VIC model. Then, Liang and Xie (2001) and Xie *et al.* (2003) developed a new parameterization in the VIC-3L model to represent the infiltration excess runoff mechanism and combined it effectively with the original representation of the saturation excess runoff mechanism (Zhao, 1992). Thus, in this study, the VIC-3L model with the runoff parameterization was applied to simulate runoff within the Haihe River Basin.

Data sets

The VIC-3L model required three types of data information, namely vegetation, soil and forcing data, with vegetation data sets derived from remote sensing data sources (Hansen *et al.,* 2000; Wu *et al.,* 2004). In this study, vegetation, soil and forcing data needed to apply the VIC-3L model within the Haihe River Basin were prepared at a resolution of $0.25° \times 0.25°$.

The vegetation data set was derived based on the advanced very high resolution radiometer (AVHRR) and the land data assimilation systems (LDAS) information. AVHRR provided information on global land classification at the 30-second resolution (Hansen *et al.,* 2000). For each type of vegetation, the vegetation parameters, such as architectural resistance r_a, albedo α, minimum stomata resistance r_{smin}, leaf-area index LAI, roughness length z_0 and zero-plane displacement d_0, were derived based on the vegetation parameter information from LDAS, as described by Su and Xie (2003).

The classification of soil texture was based on global 5-min soil data provided by the National Oceanic and Atmospheric Administration (NOAA) Hydrology Office and the data were regridded to the $0.25° \times 0.25°$ resolution. As described by Su and Xie (2003), the individual soil parameters used in the VIC-3L model, such as porosity θ_s, saturated soil potential ψ_s, saturated hydraulic conductivity K_s and bulk density were then derived based on the work of Cosby *et al.* (1984) and Rawls *et al.* (1993).

The forcing data were obtained through interpolation methods based on 49 meteorological stations, which contained 11 years of daily precipitation and air temperature data from 1980 to 1990. Combining two interpolation methods: 1) the minimum distance method in which the value observed at the nearest rain gauge station was taken as the mean value of a grid cell, and 2) the linear interpolation weighted by the distance between the rain gauge and the grid cell of interest, the station information was mapped to a resolution of $0.25° \times 0.25°$ grids. For these interpolation methods the influence of topography was not considered. In future studies, a suitable method should be chosen to make up for this defect, for example by considering elevation in the interpolation.

Model calibration and modification

Since some parameters could not be determined adequately based on the available soil information, 6 parameters of the VIC-3L model, *i.e.* the infiltration parameter, the thicknesses of the first and second soil layers and 3 Arno model parameters, were calibrated before conducting numerical simulations by minimizing the difference between the simulated and observed streamflow values.

In this study, the areas within the Xiahui and Xiabao streamflow stations were selected to calibrate the 6 parameters. For the VIC-3L model, simulated runoff at each grid was routed to the outlets of the two discharge stations using the unit hydrograph method for overland flow and the Muskingum method (Cunge, 1969) for channel flow. Calibration was performed manually and focused on matching the total annual flow volume and the shape of the monthly hydrograph. Fig. 1 shows the observed and simulated monthly streamflow hydrographs at the Xiahui Streamflow Station from 1980 to 1990 and the Xiabao Streamflow Station from 1980 to 1985. It could be seen that there was good agreement between the observed and simulated streamflow values and that the calibrated parameters were effective in runoff simulation over the studied watersheds.

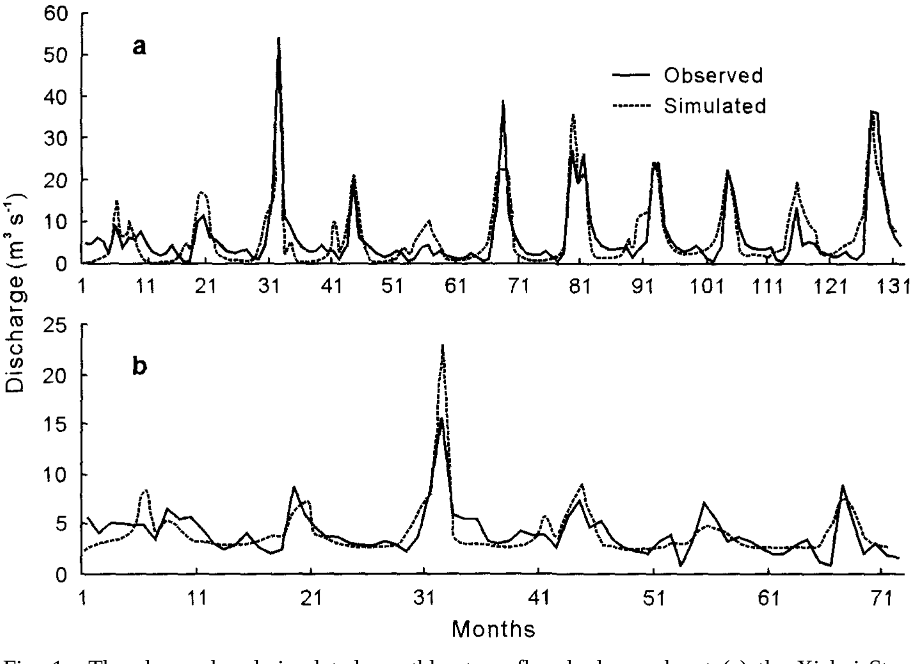

Fig. 1 The observed and simulated monthly streamflow hydrographs at (a) the Xiahui Streamflow Station from 1980 to 1990 and (b) the Xiabao Streamflow Station from 1980 to 1985.

Since no other suitable streamflow data could be obtained to calibrate these sensitive parameters over the remaining area in the Haihe River Basin and a semi-arid climate was characteristic of the whole river basin, the individual parameters for the Xiahui and Xiabao watersheds were averaged. Then under the premise that hydrologic processes and the parameters used to describe them were similar within similar climatic zones, these averaged parameters were designated for the entire region of the Haihe River Basin.

Predictions from the PRECIS model were employed as the inputs of the VIC-3L model. The Hadley Centre for Climate Prediction and Research developed the PRECIS regional climate model with a resolution of 50 × 50 km^2. An initial experiment performed with the PRECIS model for China over the period of 1979 to 1981 showed that the main patterns of simulated summer rainfall matched well with the observations. However, during this period, there was a tendency for the model to overestimate rainfall in southern and northeastern China.

Because of this overestimation in rainfall, it was necessary to adjust the PRECIS-predicted rainfall according to observations. In this study, the PRECIS-predicted rainfall data from 1980 to 1990 were compared with these forcing data that were based on data from 49 meteorological stations over the same period. For the 615 grid cells over the Haihe River Basin, the mean annual rainfall depths of the PRECIS prediction were 5% to 12% larger than those of the observed data. Therefore, a simple modification method was applied to reduce the systematic error: a modification coefficient equivalent to the ratio of the mean annual observed rainfall (1980-1990) and the PRECIS-predicted rainfall (1980-1990) of the corresponding grid was multiplied by the PRECIS-predicted daily rainfall of each grid for three climate scenarios.

Climate change scenarios

Four storylines (four kinds of possibilities) developed in the Intergovernmental Panel on Climate Change (IPCC) special report on emissions scenarios were utilized in PRECIS to describe how emissions of greenhouse gases could increase in the future. These storylines were labeled as A1F1, A2, B2 and B1, in the order of decreasing emissions. The Hadley centre predicted that between the present day and the end of the 21st century, there would be a warming of over 4 °C for A1F1, about 3.5 °C for A2, 2 °C for B2 and under 2 °C for B1. In this study, predictions from PRECIS on future climate A2 (1991-2100), future climate B2 (1991-2100) and recent climate (1961-1990) were used as climate change scenarios in the VIC-3L model for runoff simulations within the Haihe River Basin. All of these data sets, including daily rainfall and temperature, were at a 50×50 km^2 resolution; and assuming that the data values at the nearest 50×50 km^2 grid were equivalent with values of the $0.25° \times 0.25°$ grid.

Model application

The VIC-3L model was applied in the Haihe River Basin for runoff simulation, and the modified forcing data sets were used as the VIC-3L inputs. Three model runs were carried out to simulate the runoff distribution over the Haihe River Basin for recent climate (1961-1990), future climate A2 (1991-2100) and fature climate B2 (1991-2100), and daily runoff (in mm) series of each grid cell under these scenarios were generated. Mean annual and monthly statistics were also produced on the basis of the predictions from PRECIS and the simulated results from the VIC-3L model.

RESULTS AND DISCUSSION

Table I shows the simulated mean annual temperature, precipitation, evaporation and runoff under recent climate and future climate scenarios A2 and B2 for the Haihe River Basin. As mean surface temperature increased, the saturation vapor pressure at continental surface increased, thereby enhancing both evaporation and precipitation. Compared with recent climate, PRECIS predicted an increase in mean annual temperature and precipitation of 2.3 °C and 10.2 % (from 520.5 mm to 574.1 mm) under future climate scenario A2 (1991-2100), respectively. As a result, the mean annual evaporation and runoff were predicted to increase by 8.5 % (from 400.4 mm to 434.3 mm) and 16.4 % (from 120.1 mm to 139.8 mm), respectively. However, the inter-decadal variability of water regime over the Haihe River Basin was remarkable as shown in Table I. Under A2, the mean annual runoff was 160.1 mm for the period 1991-2030; but in the years 2031-2070 it was reduced by 36.4 mm due to a significant decrease of 31.1 mm in mean annual precipitation and a smaller increase of 5.3 mm in mean annual evaporation; and subsequently the mean annual runoff increased up to 134.3 mm resulted from the increased mean annual precipitation in the years 2071-2100. Meanwhile, under future climate B2 the situation was similar to that of the A2 climate. Overall, under future climate scenarios A2 and B2, the Haihe River Basin would experience warmer climate with increased precipitation, evaporation and runoff production as compared with recent climate, but in the years 2031-2070 runoff depth was considerably lower than these of the other two periods (1991-2030 and 2071-2100) and close to that of recent climate, indicating water shortages in the Haihe River Basin.

TABLE I

Simulated mean annual temperature, precipitation, evaporation and runoff under recent climate and future climate scenarios A2 and B2 for the Haihe River Basin

Scenario	Range of years	Temperature	Precipitation	Evaporation	Runoff
		°C	mm		
Recent climate	1961–1990	9.0	520.5	400.4	120.1
Future climate A2	1991–2030	9.8	584.4	424.3	160.1
	2031–2070	11.3	553.3	429.6	123.7
	2071–2100	13.3	588.3	454.0	134.3
Future climate B2	1991–2030	9.9	557.8	417.4	140.4
	2031–2070	11.2	552.6	429.1	123.5
	2071–2100	12.2	575.2	443.2	132.2

In regions where total precipitation has increased, it is very likely that there have been more pronounced increase in heavy and extreme precipitation events (IPCC, 2001). July was a month with ample water within the Haihe River Basin and also a flood-prone period, with the mean monthly precipitation being over 1/4 of the annual total. As shown in Table II precipitation and runoff in July increased under future climate scenarios A2 and B2. This increase implied a greater possibility of flood occurrence.

TABLE II

Simulated mean precipitation and runoff in July under recent climate and future climate scenarios A2 and B2 over the Haihe River Basin

Scenario	Range of years	Precipitation	Runoff
		mm	
Recent climate	1961–1990	152.6	11.3
Future climate A2	1991–2030	160.9	15.5
	2031–2070	172.5	13.5
	2071–2100	169.3	14.1
Future climate B2	1991–2030	160.7	14.1
	2031–2070	172.5	13.5
	2071–2100	168.8	13.8

When assessing the impacts of climate change, it is important to use more than one climate scenario to cover the range of uncertainties. Greenhouse gas emissions in the future are one of the great uncertainties. Nevertheless, quite a few uncertainties are involved in climate change, which arise from three main causes: the magnitude of future emissions, the response of the climatic system and natural variability. These must be considered in the future work.

CONCLUSIONS

The VIC-3L model was used to evaluate future water resources within the Haihe River Basin in China at the spatial resolution of 0.25° × 0.25° under three climate change scenarios: recent climate (1961-1990), future climate A2 (1991-2100) and future climate B2 (1991-2100). Predictions from the regional climate modeling system of PRECIS with these climate scenarios were employed as the inputs for the VIC-3L model on the runoff simulation over the Haihe River Basin. Results showed that mean annual runoff under the A2 and B2 scenarios were predicted to increase in the years 1991-2100, but the Haihe River Basin would be still likely prone to water shortages in the period of 2031-2070. In addition, with future climate A2 and B2 an increase of runoff in the flood season was found, thereby increasing the possibility of flood occurrence.

In terms of the magnitude of future emissions, IPCC has provided four storylines. In this study, only two storylines (A2 and B2) were taken into account due to the unavailability of model predictions on the other two storylines. In further studies, all the emission scenarios must be considered in assessing climate change impacts.

In this study, predicted rainfall data from PRECIS was systematically overestimated as compared with the observed data. A simple modification was made to reduce the error, but this method itself increased the uncertainty of the predictions. Therefore, great efforts are needed to enhance a better understanding of the way that the earth's climate system works so as to improve climate change predictions. Furthermore, the natural variability can make climate change more complicated and abstruse, which to some extent influences the credibility of climate change impact assessments.

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