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Response of hydrological processes to climate change in the middle reaches of the Yellow River, China

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Abstract According to the IPCC Fourth Assessment, the temperature and evapotranspiration will increase in the future. As a sensitive region to climate change, hydrological process in the middle reaches of the Yellow River will be significantly affected by climate change. In this study, water resources change in the future for a typical basin there: Lushi basin is assessed using the Soil and Water Assessment Tool (SWAT) hydrological model. Downscaled ensemble output from sixteen General Circulation Models (GCMs) for the A1B emission scenario in the 2050s was input to SWAT as the regional climate change scenario. The prediction shows that ET of this basin increases in winter and spring, and decreases in summer and autumn, and the streamflow increases throughout the year. The increased streamflow will probably improve the water demand guarantee and be conducive to crop growth in winter and spring, and may improve the flood risk in summer.
Key words climate change; water resource; SWAT; the Yellow River

INTRODUCTION

Climate change has affected the social economic policymaking, and has focused more and more attention to environmental protection (Crossman *et al.*, 2013). Xu *et al.* (2005) and Jiang *et al.* (2007) argued that the impact of climate change on water resources and corresponding countermeasures against climate change have been the focus of scientific investigation over the past two decades. Due to the socio-economic importance of water resources, future hydrological processes need to be assessed as soon as possible. In some previous studies, the future climate scenario is extrapolated from the historical data and their trends (Araujo and New, 2007), which ignores the uncertainty in climate change and the prediction error (Shi *et al.*, 2013). In order to reduce the uncertainty, modelling has become an effective tool to predict future climate (Christensen and Christensen, 2007). Future climate scenarios predicted by General Circulation Models (GCMs) have been adopted as the available tool for obtaining the future climate information (Bates *et al.*, 2008; Whitehead *et al.*, 2009), and have been widely applied in much research (Mo *et al.*, 2013; Zhang *et al.*, 2011). The arid and semi-arid region is sensitive to climate change (Liu *et al.*, 2011). Hydrological processes, the soil water content and vegetation evapotranspiration in arid and semi-arid regions will be obviously affected by future climate change (Brown and Rosenberg, 1994).

The middle reaches of the Yellow River is an arid and semi-arid region with high intensity of human activities, where water resources play an important role in regional development. Therefore, the influence of future climate change on hydrological process research in this region must be explored intensively. The purpose of this study is to evaluate the impact of climate change on hydrology and water resources in Lushi basin, a typical basin in the middle reaches of the Yellow River. The rainfall−runoff processes will be simulated using a semi-distributed hydrological model: Soil and Water Assessment Tool (SWAT). Ensemble prediction of downscaled output from sixteen GCMs for the A1B emissions scenario in 2050s will be used to make the future climate scenario, which will be utilized as forcing data in SWAT to predict the changes of water cycle due to climate change.

STUDY AREA AND METHODOLOGY

Study area

Lushi River is the upstream of a tributary in the middle reaches of the Yellow River in China (Fig. 1), which has a total land area of 3902 km². According to a 90-m elevation map, the basin

elevation ranges between 600 and 2300 m and falls from the northwest to the southeast. The north is a mountainous area, whose area is about 33% of this basin. The central and western parts of the basin is hilly area, covering the loess terrace and hills, whose area account for 59% of the basin. The eastern downstream part is valley plains, with terraces and flood plains. The main land-use/land cover types are forest, grassland and farmland. The main soil types are brown native soil and brown loam. According to statistical analysis of data of 20 precipitation stations for many years in this basin, the average annual precipitation is 642 mm, of which approximately 60% happens in the wet season from June to September.
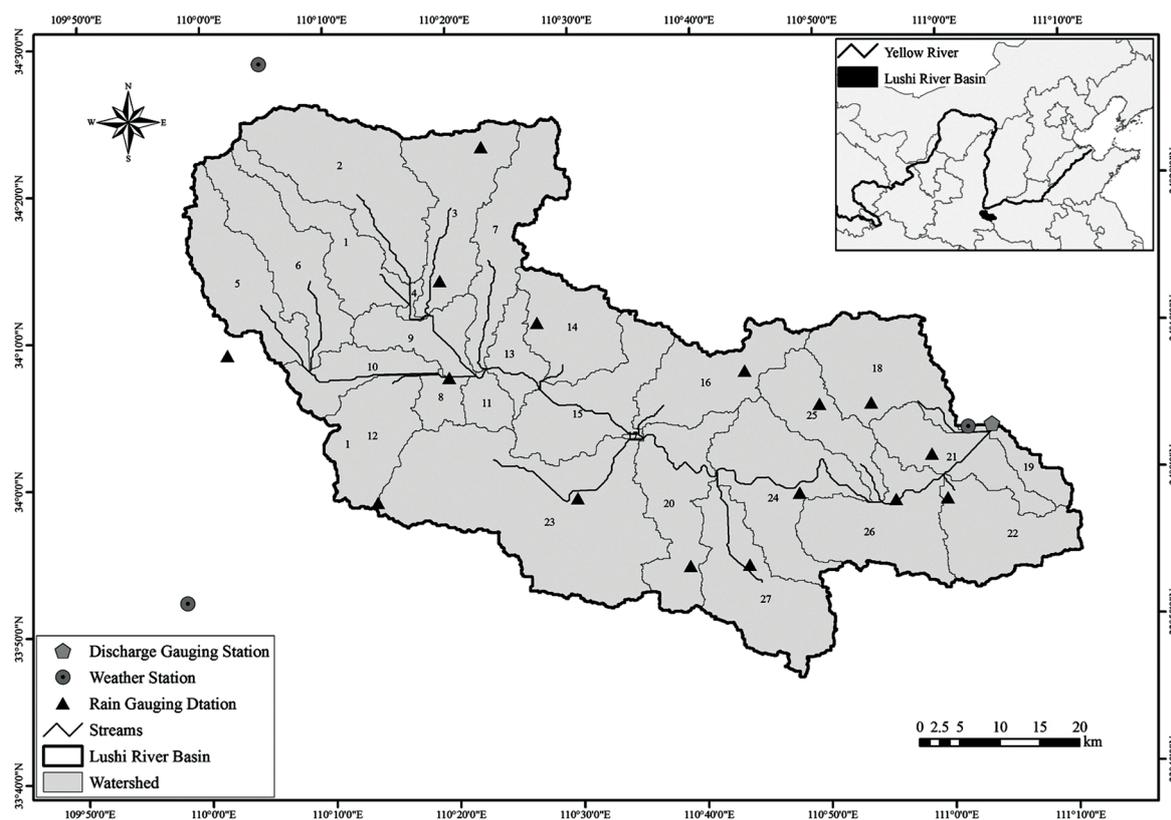

Fig. 1 Lushi Basin and sub-basin distribution.

SWAT model

It is difficult to analyse the hydrological processes in large basins such as the study basin, without a hydrological model. Hydrological models are a useful tool in management planning. From a theoretical viewpoint, a physical model represents the underlying hydrological and land surface processes in greater detail than conceptual or statistical models (Beven, 2001). The SWAT model is a conceptual physically-based model developed by the United States Department of Agriculture (USDA) for evaluating watershed hydrology and water quality that operates on a daily time step (Neitsch, 2011). In this model, the simulated watershed can be divided into explicit parameterized smaller sub-basins and distinct hydrological response units (HRUs). The HRUs are delineated by overlaying topography, soil maps and land-use maps, and are assumed to be homogeneous with respect to their hydrological properties. The modelling process of SWAT can simultaneously consider hydrological, environmental and biological processes as well as land management based on available data (Jayakrishnan, 2005; Wu, 2007; Douglas-Mankin, 2010; Lam, 2010).

The Nash–Sutcliffe (E_{NS}) coefficient of efficiency (Nash and Sutcliffe, 1970) and deterministic coefficient (R^2) are used as the objective function for optimizing the model performance. They are defined as:

$$E_{NS} = 1 - \frac{\sum\limits_{i=1}^{n}(Q_{m,i} - Q_{s,i})^2}{\sum\limits_{i=1}^{n}(Q_{m,i} - \overline{Q_m})^2}$$

(1)

$$R^2 = \frac{\left[\sum\limits_{i=1}^{n}\left(Q_{m,i} - \overline{Q_m}\right)\left(Q_{s,i} - \overline{Q_s}\right)\right]^2}{\sum\limits_{i=1}^{n}\left(Q_{m,i} - \overline{Q_m}\right)^2 \sum\limits_{i=1}^{n}\left(Q_{s,i} - \overline{Q_s}\right)^2}$$

(2)

where Q_m (m³ s⁻¹) and Q_s (m³ s⁻¹) are the observed and simulated streamflow at time step i, $\overline{Q_m}$ (m³ s⁻¹) is the average observed streamflow, and $\overline{Q_s}$ (m³ s⁻¹) is the average simulated streamflow for the whole period.

Data preparation

A digital elevation map (DEM) was used for extracting the flow direction needed for the hydrological modelling. The land-use map was derived by the Chinese Academy of Sciences, and shows the dominant land-use types. Approximately 52% of the total area was covered by forest, whereas grassland covered 26%, and the remaining 22% was farmland. Regional land-use/land cover classification and definitions was showed in Table 1. The soil map in the basin was compiled from the Chinese national 1:1 000 000 scale soil map. The physical properties of these soils were taken from the China Soil Scientific Database (http://www.soil.csdb.cn/). The DEM, land use, soil and observed rainfall of 20 local rainfall stations and meteorological data of three national weather stations were the input to SWAT. Observed discharge (from 1990−1997) at the basin outlet was used to calibrate the parameters.

Table 1 The land use/land cover classification and definition.

	Abbreviation	Definition
1	RICE	paddy land, natural vegetation mosaic
2	AGRL	farmlands
3	FRST	forest-mixed
4	MESQ	shrub wood
5	ORCD	orchard
6	PAST	grasslands
7	WATR	stream, river
8	URBN	urban build-up, rural settlements

FUTURE SCENARIOS OF CLIMATE CHANGE

In this study, the future regional precipitation and temperature projected by the ensemble of 16 GCMs under the A1B emissions scenario were derived from the Climate Wizard dataset (available at: http://www.climatewizard.org/index.html) for the 2050s (2040–2069). The seasonal precipitation relative change and mean temperature absolute change were downscaled to the resolution of 50 km using an empirical statistical method (Fu *et al.*, 2007). Both the daily temperature and precipitation data for scenario were the input to SWAT to simulate the future hydrological regime in the 2050s. The simulation for the period of 1990–1997 is considered as the baseline period. The difference of hydrological process between these two period's simulations is considered as the impact of climate change.

Figure 2 shows averaged relative change of seasonal mean precipitation and absolute change of mean temperature between reference period and future climate scenario in 2050s respectively. The precipitation increases all the year. For winter, significant increase of precipitation is observed

(30%). For summer and autumn, the increased proportion of rainfall is less. For absolute change of seasonal mean temperature, it increases all the year with an average change of 3.5 degree Centigrade. The winter warming will probably improve the availability of the heat resource and prolong the season of crop growing. Meanwhile, rising temperature will also probably increase evapotranspiration and decrease the water resource on the Earth's surface.
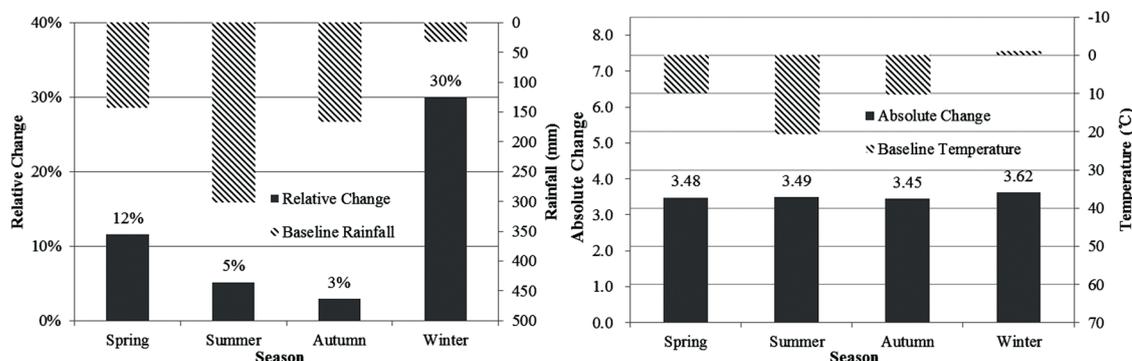

Fig. 2 Basin averaged changes of seasonal mean precipitation and temperature between baseline and future climate scenario in 2050s.

RESULTS AND DISCUSSION

The calibration and validation periods for streamflow are 1990–1995 and 1996–1997, respectively. Figure 3 shows the observed and simulated monthly streamflow in calibration and validation. The model performance for calibration and validation period for a monthly time-step is tabulated in Table 2. The performance, especially the result of E_{NS}, is not very satisfactory because a large amount of moisture returned to the atmosphere in the form of evapotranspiration (ET) in this basin. And the observed ET data for the whole basin are not available. The performance of discharge indicates that the simulation of streamflow by SWAT model is reasonable for this basin. The reasonable performance justifies the application of SWAT for the impact assessment planned.

The daily meteorological data of 2050s A1B scenario was used as input to SWAT for simulating hydrological processes in the future. The seasonal relative changes of ET and streamflow between the baseline period and the 2050s scenario are depicted in Fig. 4. The ET increases in the 2050s in winter and spring. As mean temperatures in whole year are higher in
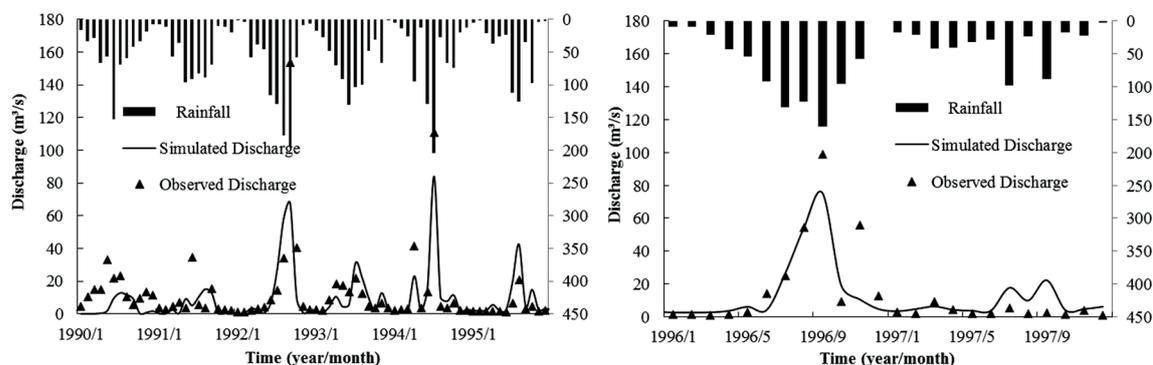

Fig. 3 Results of calibration and validation.

Table 2 Model performance for calibration and validation.

	Simulation Period	R^2	E_{NS}
Calibration	1990–1995	0.65	0.56
Validation	1996–1997	0.74	0.59

the 2050s, more energy is available for water to evaporate or transpire. The increased rainfall and temperature make it the most probable reason of ET increasing in winter and spring. Meanwhile, the reduction of ET in summer and autumn is considered as a comprehensive outcome of many factors. These are mainly solar radiation, temperature, relative humidity and wind speed. With the increased rainfall in summer and autumn, the solar radiation may decrease and the relative humidity may increase, which will lead to the decreased EI (Cohen *et al.*, 2002; Qiu and Liu, 2003).

The streamflow in 2050s exhibits an increasing trend over the whole year, with degrees varying from 17% (spring) to 25% (autumn). This can be explained as a consequence of increasing rainfall and decreased ET in summer and autumn. And the effect of increased rainfall in winter and spring is larger than the effect of increased ET. In summer, the improved streamflow will enhance the flooding risk. In winter and spring, the increased streamflow will improve the guarantee of water demand and be conducive to the growth of crops.

From the viewpoint of water resource availability, the contradiction between supply and demand of water resources will be alleviated in the future. Especially in the spring and winter, the agricultural water will be guaranteed. ET and streamflow temporal change will probably lead to the variation of land use/cover.
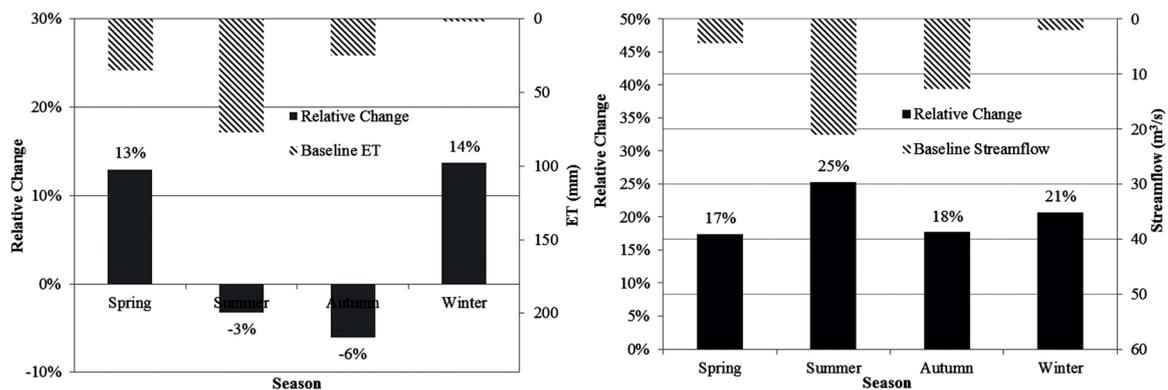

Fig. 4 Basin averaged changes of seasonal mean ET and streamflow between baseline and future climate scenario in 2050s.

CONCLUSION

Research about water resources availability change in future scenarios plays a major role in future agricultural production as well as in local social and economic development. To evaluate the influences of climate change on water resources in Lushi basin, GCMs and SWAT hydrological model were applied to predict the hydrological processes in this basin. By comparing the simulation data with baseline streamflow data, it was indicated that this method can make fairly reasonable hydrological predictions. After constructing a regional climate change scenario in this basin, the projected meteorological variables were input to the SWAT model for predicting hydrological processes in the 2050s.

This prediction shows that ET in this basin will increase in winter and spring and decrease in summer and autumn; the water resources will increase all through the year, which will lead to the seasonal migration of hydrological processes. In winter and spring, the increased streamflow will improve the guarantee of water supply and be conducive to the growth of crops. While in summer, the enhanced flood damage will bring serious soil erosion and cause huge social and economic losses. Therefore, the study of flood forecasting and warning and resource utilization should be paid more attention, and water supply and drainage facilities in cities should be strengthened. This result may benefit the making of reasonable water resource management policy in Lushi basin. To make the policy and decisions more targeted, an analysis of the water demand is necessary.

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