Impacts of Climate Change on Streamflow in the Guijiang River Basin, China

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Abstract. We estimate streamflow in the Gui River Basin (GRB) in this work by calibrated SWAT model whose accuracy for depicting hydrological processes features at monthly scale is verified beforehand. Then we further make a prediction for streamflow in the GRB in the future based on data of climate change scenarios from HadCM3 under three Representative Concentration Pathways (RCPs). The simulations reveal the growth trend of streamflow in the GRB under every RCP and the increasing frequency of the runoff over 20000m^3/s between June and August in most RCPs relative to the baseline period. The results indicate that changes in streamflow are relatively slight in both RCP2.6 and RCP4.5 scenarios, but fairly dramatic under RCP8.5 in the future.

1. Introduction

Climate change is one of the biggest challenges to humanity in the 21st century. Mean annual surface temperature has increased 0.85°C from 1860 to 2012 [1], which was mentioned in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. As the growing influence of climate change and human activities on the hydrology and water resources, the potential impact has been gaining considerable attention [2]. In general, the researchers examined the effect of climate change on the hydrological system by using meteorological and hydrological model, especially at the basin scale.

The general circulation model (GCM) is a type of climate model which employs a mathematical model of the general circulation of a planetary atmosphere or ocean [3]. Considering the same atmospheric circulation predictors and period lengths among different GCMs, Xu et al. examined 22 GCMs' simulation capability in East Asia, which showed HadCM3 (Hadley Centre Coupled Model, version 3) had better performance on East Asia [4]. Liu et al. also showed that HadCM3 had better simulation effect in the Yellow river [5]. Thus, we finally select data simulated by HadCM3 to assess the effects of climate change on streamflow in this work.

The Gui River Basin (GRB) is a typical river basin in southern China and one of the major tributaries to the Xi River in the Pearl River Basin. Located in the subtropical region, the climate condition of GRB is clearly affected by monsoons. The annual average precipitation in the basin is around 1900 ~ 2700 mm. To our knowledge, there is no research focusing on predicting the impact of climate change on streamflow of the GRB in the future.

In this study, we attempt to project and analyse the future impact of climate change on runoff under different scenarios. First, we calibrate and validate the SWAT (Soil and Water Assessment Tool) hydrological model by observational data. Second, we derive the future meteorological data including temperature and precipitation by bilinear-interpolation method. Third, we get future streamflow by inputting future meteorological data into the calibrated SWAT model. Finally, we compare streamflow characteristics in three future periods (2020s, 2050s, 2080s) under RCP2.6, 4.5 and 8.5 scenarios. The results obtained from this study are valuable to local water management authorities for controlling disaster events and managing water resources. Besides, it can also contribute for assessing impacts of climate change on humanity in the future.

2. Method

2.1. SWAT hydrological model

The SWAT model is a comprehensive, time-continuous, semi-distributed, process-based model [6]. The land phase of the hydrologic cycle can be represented by the water balance equation [7]:

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \quad (1)$$

Where SW_t is the final soil water content at the time t, t is the time (days), SW_0 is the initial soil water content. R_{day} is the amount of precipitation on day i; Q_{surf} is the amount of surface runoff on day i; E_a is the amount of evapotranspiration on day i; W_{seep} is the amount of percolation on day i; and Q_{gw} is the amount of return flow on day i.

Calibration and validation of the model is the most important step in applying process. The determination coefficient (R^2) and Nash–Sutcliffe Efficiency (E_{ns}) were applied to evaluate the SWAT model performance, which are calculated as follows:

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(Q_{m,i} - Q_{m,avg}\right)\left(Q_{s,i} - Q_{s,avg}\right)\right]^2}{\sum_{i=1}^{n}\left(Q_{m,i} - Q_{m,avg}\right)^2 \sum_{i=1}^{n}\left(Q_{s,i} - Q_{s,avg}\right)^2} \quad (2)$$

$$E_{ns} = 1 - \frac{\sum_{i=1}^{n}\left(Q_{m,i} - Q_{s,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{m,i} - Q_{m,avg}\right)^2} \quad (3)$$

Where $Q_{m,i}$ and $Q_{s,i}$ are measured and simulated streamflow at each time step i; $Q_{m,avg}$ and $Q_{s,avg}$ are the mean measured and simulated streamflow; and n is the number of time steps. When R^2 greater than 0.6 and E_{ns} greater than 0.5, the model simulation can be considered acceptable and satisfactory [8].

2.2. Bilinear-interpolation

Bilinear-interpolation is a conventional method, in which monthly average temperature and precipitation from CGCMs are interpolated into station points by bilinear-interpolation. Then, daily precipitation is calculated by scaling ratio of daily precipitation and monthly value over the baseline time-series. Daily temperature is calculated by adding or reducing the difference between daily and monthly values [9].

Suppose that the value of the unknown function f at the point (x, y) is the value to be evaluated. It is assumed that the values of f at the four points $Q_{11} = (x_1, y_1)$, $Q_{12} = (x_1, y_2)$, $Q_{21} = (x_2, y_1)$, and $Q_{22} = (x_2, y_2)$ are already known.

We can first do linear interpolation in the x-direction:

$$f(x, y_1) \approx \frac{x_2 - x}{x_2 - x_1} f\left(Q_{11}\right) + \frac{x - x_1}{x_2 - x_1} f\left(Q_{21}\right) \tag{4}$$

$$f(x, y_2) \approx \frac{x_2 - x}{x_2 - x_1} f\left(Q_{12}\right) + \frac{x - x_1}{x_2 - x_1} f\left(Q_{22}\right) \tag{5}$$

Then in the y-direction to obtain the desired estimate:

$$f(x, y) \approx \frac{y_2 - y}{y_2 - y_1} f\left(x, y_1\right) + \frac{y - y_1}{y_2 - y_1} f\left(x, y_2\right) \tag{6}$$

3. Results and discussion

3.1. SWAT model setup

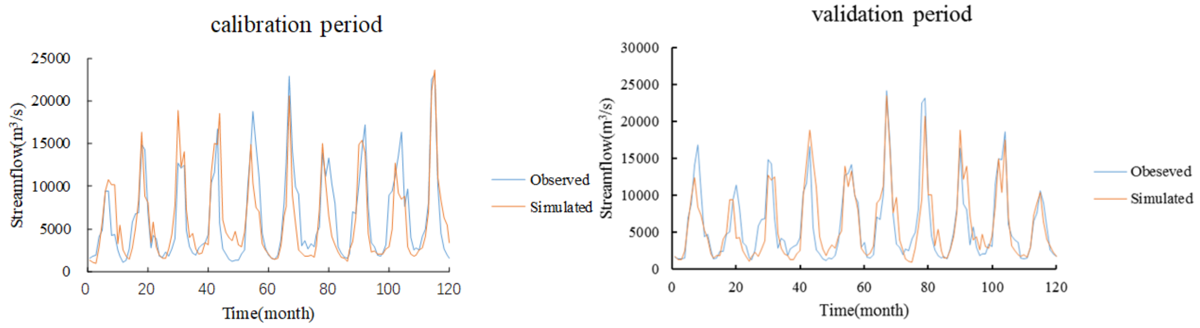
Based on the DEM, the GRB is divided into 22 sub-watersheds in this work. And then based on land use, soil type and slope, using a threshold of 10% for land use over the subbasin area, 15% for soil class over the land use area, and 10% for slope class over the soil area, the sub-watersheds are further divided into a total of 345 HRUs.

3.2. SWAT model calibration and validation

The SWAT flow simulations are calibrated against monthly flow from 1989 to 1998 and validated from 1999 to 2008 at the Wuzhou hydrological station. The results of the statistical evaluation performed on monthly observed and simulated streamflow are presented in Table 1. During the calibration periods, E_{ns} is 0.67, greater than 0.5, and R^2 is 0.66, greater than 0.6, indicating a close relationship between simulated streamflow and the observed values. During the validation period, E_{ns} is 0.72, and R^2 is 0.72, indicating good agreement between the simulated and observed values apparently.

Table 1. Performance assessment of SWAT model during calibration and validation periods using Nash-Sutcliffe efficiency (E_{ns}) and correlation coefficient (R^2).

Period	E_{ns}	R^2
Calibration (1989~1998)	0.67	0.66
Validation (1999~2008)	0.72	0.72



(a) (b)

Figure 1. Comparison of observed and simulated streamflow data at monthly timescales during (a) calibration periods and (b) validation periods

Considering the statistical evaluations discussed above, it is generally reasonable to conclude that hydrologic processes are modelled realistically by SWAT at monthly time step for the GRB using the given set of parameters.

3.3. Streamflow analysis under RCP scenarios

The future precipitation and temperature for the HadCM3 under three RCPs are input into the calibrated SWAT. For the three models' ensemble mean, the projected future changes in annual streamflow range between 3.9 and 9.4% under RCP2.6, between 7.8 and 16.6% under RCP4.5, and between 6.1 and 21.9% under RCP8.5. Compared with RCP8.5 scenario, future streamflow under RCP2.6 and RCP4.5 scenarios appears closer to the current streamflow volume.

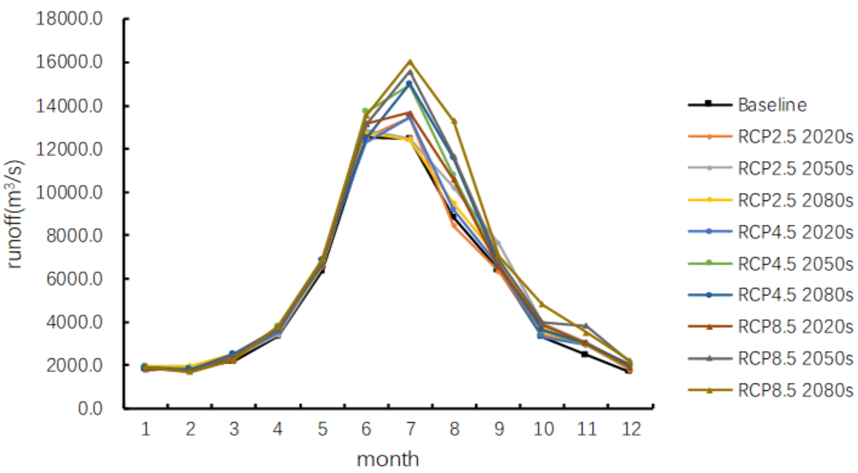


Figure 2. Comparison of monthly mean runoff between observed (1986–2008) and projected climate in three future periods.

3.4. Future extreme runoff analysis

Projected future low (10th percentile) and high (90th percentile) values of monthly streamflow changes in the GRB are shown in Fig. 3. The maxima of high and low streamflow (and the maximum difference between them) in the baseline period both occur between June and August. Each future period presents the similar low streamflow phenomena as the baseline period, however, there is a little lag in time for some maxima, which means different scenarios lead to disparate processes in high streamflow in the future, the curves for RCP8.5 in the 2050s and the 2080s even have two peaks between June and August. In Table 2, we count the frequency of the runoff over 20000m^3/s between June and August under

RCP2.6, RCP4.5 and RCP8.5 scenarios in three future periods and the baseline period, respectively. The statistics reflect that the likelihood of flooding in these three months is predicted to be increased under every scenario compared with the baseline period, and the anti-flood pressure will be particularly prominent under RCP8.5 scenario.

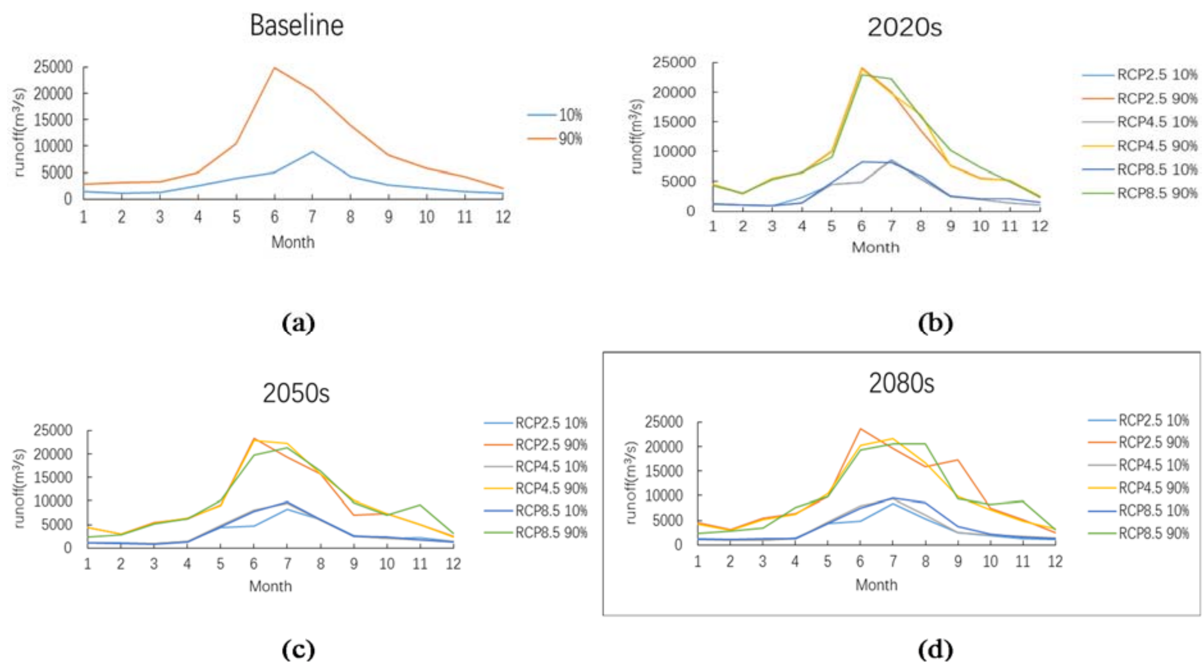


Figure 3. Low (10th percentile) and high (90th percentile) monthly streamflow in (a)baseline period, (b)2020s, (c)2080s, (d)2080s

Table 2. Frequency of the runoff over 20000m^3/s during June to August under RCP2.6, RCP4.5 and RCP8.5 scenarios in three future periods and the baseline period (1986–2008)

Periods	Baseline	RCP2.5			RCP4.5			RCP8.5		
		2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
Frequency	5.6%	8.9%	7.8%	6.7%	11.1%	18.9%	14.4%	13.3%	18.9%	27.8%

4. Conclusion

In this study, we investigate the future projection of climate change phenomena and their impacts on streamflow in the GRB over the course of the 21st century. The SWAT model is calibrated and applied to simulate future hydrological processes based on the outputs of the climate change scenarios. Then the effects of climate change on streamflow under different RCP scenarios are analysed. The most notable conclusions of this study can be summarized as follows:

1) Calibration and validation of the SWAT model indicate that all evaluation indices (E_{ns}, R^2) are satisfactory within monthly timescale. The calibrated SWAT model accurately reflects hydrological process characteristics and reasonably reveals the features of future streamflow in the GRB.

2) The streamflow in most RCPs increase between June and August relative to the baseline period. The results indicate relatively slight changes in streamflow in both RCP2.6 and RCP4.5, but fairly dramatic increase under RCP8.5 in the future.

3) The likelihood of flooding between June and August is predicted to be increased in the future, especially under the scenario of RCP8.5.

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