Evaluation of hydrological response to extreme climate variability using SWAT model: application to the Fuhe basin of Poyang Lake watershed, China

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ABSTRACT

Differences between simulated and observed data often occur when the watershed model is applied under extreme climate. It is necessary to assess the stability of hydrological models in a wide range of climate variation. A case study was conducted in Fuhe basin of Poyang Lake, China using the Soil and Water Assessment Tool (SWAT) model, which was calibrated under different climates in average years, dry and wet years, high and low temperature years, respectively. The model was first calibrated with dataset in average years, and the validation in the whole period showed results agreed well with the observed stream flow. The well-parameterized model calibrated under extreme climate was used to simulate hydrological responses in different climate years. All simulations generated results closely matching observed data with R^2 and E_{NS} greater than 0.88, although the model was likely to slightly overestimate stream flow in average and dry years, and underestimate in wet years and high temperature years. In addition, each simulation was independent to other simulations with different parameters calibrated in different climate periods tested by Student's T-test. Therefore, the model has the potential probability to accommodate a large range of climate variation to predict hydrological responses to climate change.

Key words | extreme climate, Fuhe basin, hydrological response, parameter calibration, Poyang Lake, SWAT model

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INTRODUCTION

In the fifth assessment report of climate change by the Inter-governmental Panel on Climate Change (IPCC), it is stated that each of the last three decades has been successively warmer at the earth surface than any preceding decade since 1850, and the decade of the 2000s was the warmest (IPCC 2013). According to its forecast, as the climate becomes warmer, high temperature and heat wave will become more frequent and last longer, rainfall intensity and density will rise on a global scale and parts of the world will experience more severe and frequent droughts.

It is indicated that the probability of extreme climate may further increase in the future. Thus, when we evaluate the effects of future climate change on hydrological processes with watershed models, extreme climate conditions such as climates in wet and dry years, high and low temperature years should be taken into account.

Hydrological models have been used widely and effectively to simulate impacts of climate change and land use cover change on hydrologic cycles in a variety of watersheds (Arnold et al. 1998; Xu 1999; Li et al. 2015; Singh et al. 2015;

Omer *et al.* 2016). When we calibrate a hydrological model, average climate condition or the best available data are often used (Leavesley *et al.* 2002; Eckhardt & Ulbrich 2003; Legesse *et al.* 2003; Dettinger *et al.* 2004; Gosain *et al.* 2006; Zhang *et al.* 2007; Awan *et al.* 2016). Considering climate variation, a model calibrated for such condition may not be stable under altered conditions (Singh *et al.* 2005; Tolson & Shoemaker 2007). An ideal hydrologic calibration and validation dataset should include combined climate conditions in extreme climate years and average years. In fact, we often calibrate and validate the model based on data easily available. Discrepancies between observed and simulated results by hydrological models during extreme years or seasons have been investigated in previous studies. Singh *et al.* (2005) used the calibrated model to validate the model in dry, average and wet climate conditions and found that two commonly hydrological models used underestimated stream flow during average years by 3.2% to 3.7%, and overestimated flow during the wet years by 16.4% to 13.7%. Govender & Everson (2005) found that the Soil and Water Assessment Tool (SWAT) model performed better in the average and dry years than in the wet years when the hydrological model obviously underestimated the catchment stream flow on the east coast of South Africa. Reasons for such discrepancies might come from different sources, such as the limitations of modelling snowmelt for flow volumes and simulating evapotranspiration (ET) of the SWAT model (Benaman *et al.* 2005). Another reason may be ignorance of the sensitivity of hydrologic parameters in different climate situations (Xu 2003). Such existence of disagreement further indicates it is necessary to calibrate hydrological models under extreme climate conditions. Therefore, hydrological models should be fully calibrated under different climate conditions prior to predicting hydrological processes.

Several studies have discussed model calibration under different climate conditions. Wu & Johnston (2007) used different climate datasets representing drought and average conditions to calibrate a watershed model and found that the drought-calibrated version of the model performed much better during the validation period. Another study was conducted to calibrate the model with dry, average and wet periods; the better results could be achieved if the model was calibrated under wet climate conditions (van

Liew & Garbrecht 2003). Although they both used different climate conditions to calibrate the model, high and low temperature years were not considered. In fact, hydrological components and model parameters were very sensitive to changes of temperature (Fontaine *et al.* 2001).

The hydrological processes and parameters vary in response to hydro-climate conditions and, in particular, climate variability can alter the ET, runoff accumulation and exchange of groundwater with surface water. In this study, we aim to investigate such hydrological processes in response to extreme climate, so as to reveal the changes of surface water runoff under different hydro-climate variabilities. The performance of the watershed model was hereby evaluated by testing its responses to a wide range of hydro-climate variations. Thus, taking the SWAT model established for the Fuhe basin of the Poyang Lake watershed as an example, the extreme climate periods were selected from the studied history years based on the annual average precipitation, runoff and temperature to calibrate established a SWAT model, which was parameterized considering ET, groundwater exchange, runoff accumulation and so on under extreme climate conditions. The parameters were then applied to simulate hydrology under the other climate conditions in order to investigate their accommodation for a wide range of climate variation. Finally, the parameterized hydrological model in the entire time period, including the average years, wet and dry years, low temperature years and high temperature years was run to assess the modelling capacity under different extreme climate conditions.

STUDY AREA AND DATA

Study area

The Fuhe basin is located in southeastern Jiangxi province, China. The Fuhe River, with a drainage area of 15,811 km^2 (above the hydrologic station of Lijiadu), is the second longest river discharging to Poyang Lake among the five tributaries. The area is located at latitude 26°30′–28°20′N and longitude 115°36′–117°10′E. The hydrologic station of Lijiadu was selected as the outlet to study the hydrological process of the basin. There are four weather stations close to the basin: Zhangshu, Guixi, Guangchang

and Nancheng (Figure 1). There is abundant rainfall with an annual mean rainfall of approximately 1,700 mm during 1962 to 1998. The temporal and spatial distributions of precipitation vary significantly. Precipitation during the period of May to July accounts for approximately 51% of total annual rainfall while there is little rain in winter and spring (October to March). The peak flow and maximum discharge often occur in June; the monthly average discharge amounted to greater than 2,900 m^3/s in June 1998 and the largest amount of precipitation was 189 mm on 22 June 1998 at Guixi station. According to temperature records, in the years 1961–1998, the lowest temperature of $-11\,^{\circ}$C was measured on 29 December 1991 while the highest temperature of 41 $^{\circ}$C was measured on 1 August 1971. The annual mean temperature is 17.2 $^{\circ}$C–18.9 $^{\circ}$C in the Fuhe basin.

Spatial data

The spatial database used to establish the SWAT model included digital elevation model (DEM), soil type and land use data. DEM data are important data describing the spatial distribution of regional topography and they play a fundamental role in the definition of the basin boundary, division of sub-basins, generation of river network, extraction of various hydrological parameters and division of the hydrological response unit (HRU). In this study, DEM data (Figure 1) were obtained through the ASTER GDEM with 30 m resolution.

Soil data are another major input parameter of the SWAT model, which include soil type map, index table of soil type and parameters of soil database (soil physical properties). The soils in Fuhe basin are classified into 14 unique
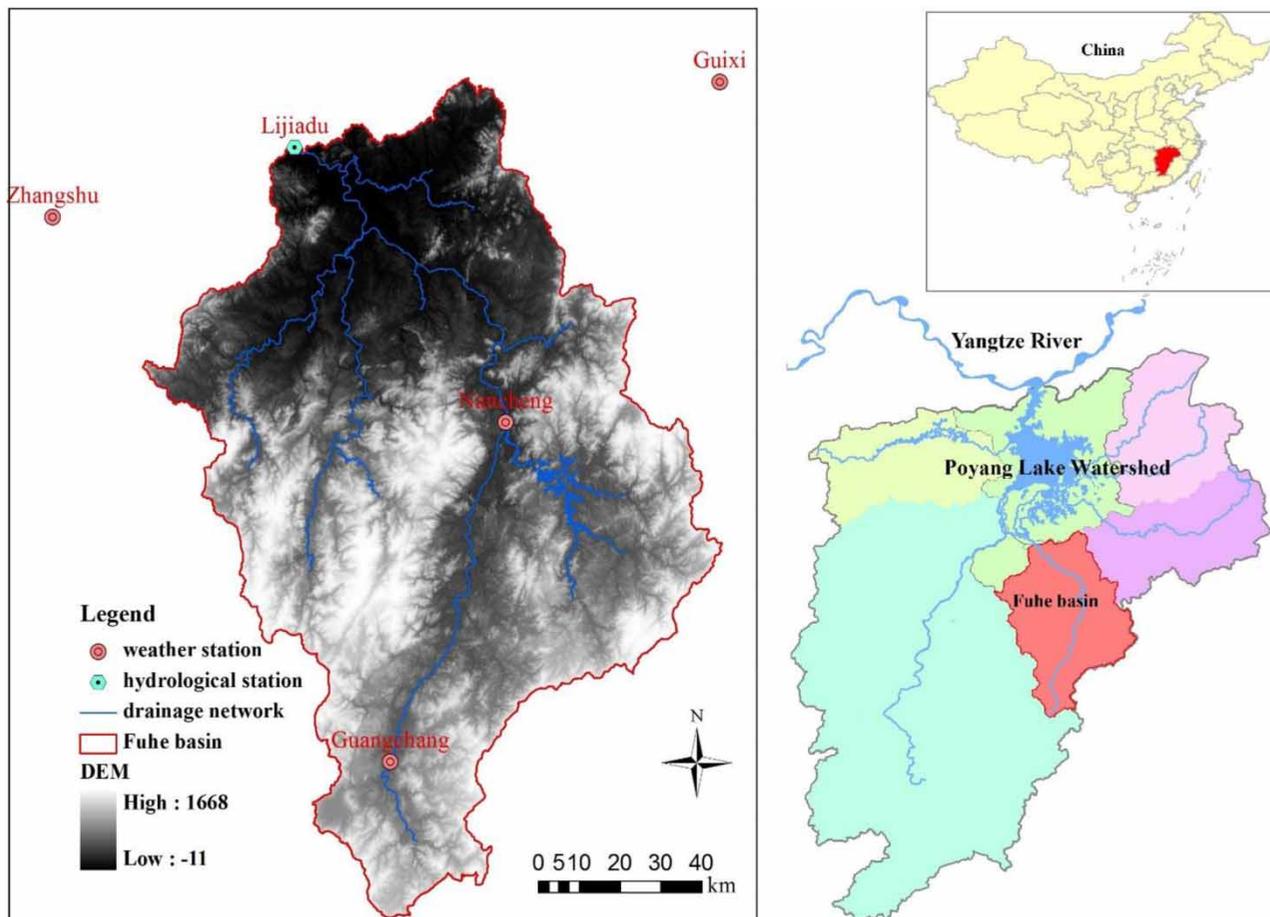

Figure 1 | Location of the Fuhe basin with a DEM of 30 m resolution (ASTER GDEM), drainage network, and hydrological and weather stations.

soil series by 1:1,000,000 Harmonized World Soil Database (HWSD, version 1.1), assembled by the Food and Agriculture Organization of the United Nations and International Institute for Applied Systems Analysis. The main soil types in Fuhe basin are haplic acrisols (63.73%), cumulic anthrosols (21.56%) and humic acrisols (2.30%) (Figure 2(a)). Soil physical properties mainly include soil saturated hydraulic conductivity (SOL_K), soil available water capacity (SOL_AWC) and soil moist bulk density (SOL_BD); these parameters were partially calculated by the software of soil water characteristics (SPAW, website: http://hrsl.arsusda.gov/SPAW/SPAWDownload.html).

Land use affects the runoff process in the land surface and has an important influence on the results of simulation. The land use map (Figure 2(b)) used in this study was produced by unsupervised classification using the Landsat TM images with 30 m resolution acquired in 1990s, in which land use types included forest, paddy, agricultural land, pasture, urban, water, bare land and wetland (Chen et al. 2007). Mountains and hills are the dominant topography in the Fuhe basin, whereas the forest coverage rate reaches 55.06%. The Fuhe basin is a major rice production area in China and rice paddies account for 19.74% in the Fuhe basin; thus, rice paddies were separated from crops and simulated specifically as rice and rice crop parameters were provided for the SWAT model (Tao et al. 2015). In addition, all crops were classified as agricultural land except for paddies.

Hydro-meteorological data

As the meteorological data of four weather stations (Zhangshu, Guangchang, Nancheng and Guixi shown in Figure 1) generally cover the whole Fuhe basin, the datasets for 38 years from 1961 to 1998 were downloaded from the China Meteorological Data Sharing Service System
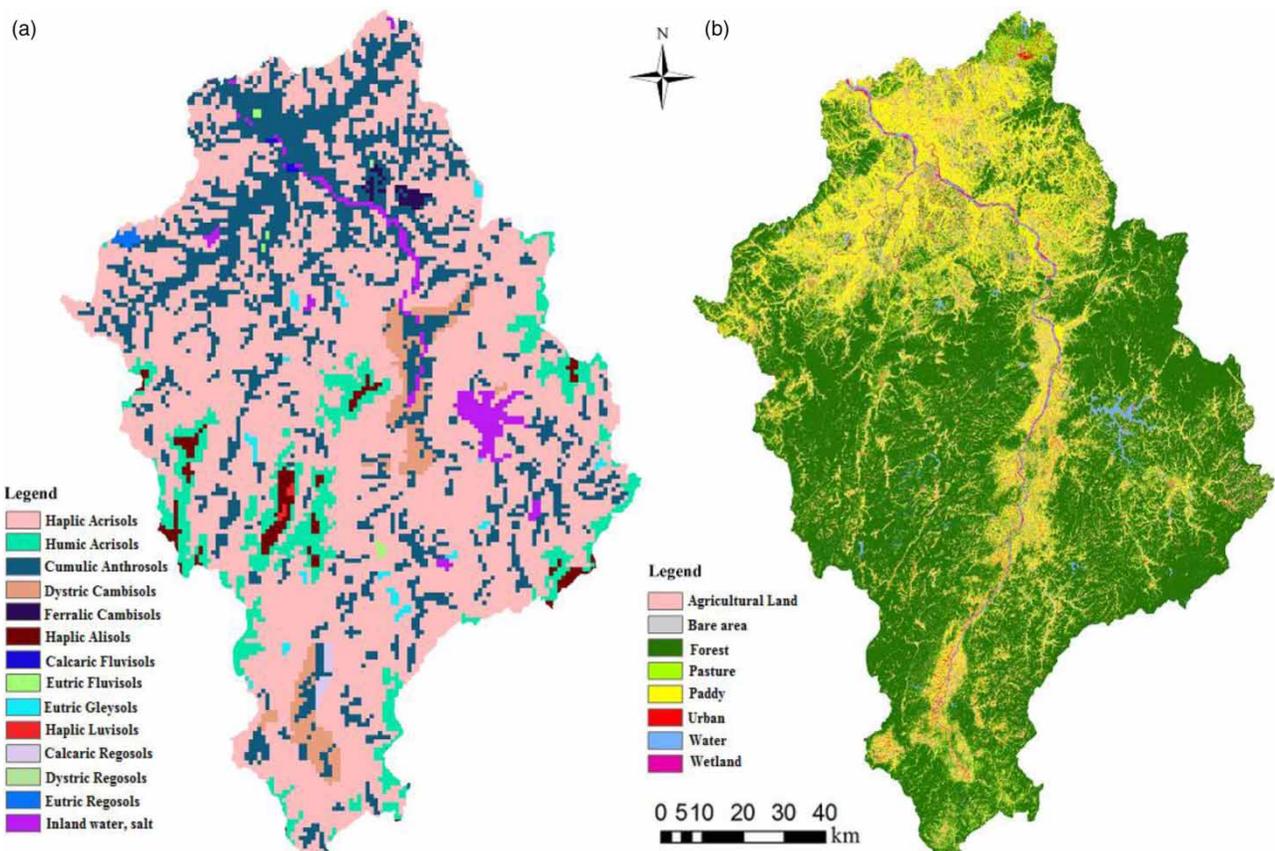

Figure 2 | Soil type and land use map of the Fuhe basin.

(http://cdc.nmic.cn). They include the daily maximum and minimum temperature, daily average temperature, precipitation, wind speed and direction, relative humidity, and monthly average solar radiation. The daily solar radiation data were generated by weather generator that was built with the parameters of temperature, precipitation, dew point temperature and monthly solar radiation, so that the weather generator makes up the deficiency of meteorological data for the hydrological model. As the watershed outlet, the hydrologic station Lijiadu monitored stream flows in the years 1961–1998 from all upstream portions of the Fuhe basin.

METHODOLOGY

SWAT model setup

The SWAT model (Arnold *et al.* 1993; Gassman *et al.* 2007, 2014), a river basin or watershed scale model, was developed by the United States Department of Agriculture Agricultural Research Service. The ArcSWAT Version 2009 interface integrated in ArcGIS 9.3 was used in this study. The Fuhe basin was divided into 31 sub-basins based on DEM data by river network analysis tool which is built in to the SWAT model. Combining with land use and soil data, the study area was further divided into 511 HRUs. Meteorological data were introduced into the model, and databases of soil and land use properties were edited to provide the required data for our study area. The Lijiadu hydrologic station was selected as a control point to evaluate the model with stream flow data.

A large number of parameters were involved in the SWAT model to describe the different hydrological processes. The purpose of sensitivity analysis is to analyse the sensitivity of the input parameters and then the most sensitive parameters were regarded as reference to select important factors from input parameters to adjust the model (Luo *et al.* 2008). In the period of sensitivity analysis, the automated sensitivity analysis tool integrated in ArcSWAT was used, and employed the Latin Hypercube Sampling-One at A Time analysis method (van Griensven *et al.* 2006).

Considering the complex hydrologic processes, natural characteristics of the study area and limitations of the model itself, the SWAT model usually must be calibrated to generate good results before being applied to study hydrology (Wu & Johnston 2007). Therefore, after sensitivity analysis, model calibration can be carried out and was executed manually and using SWAT Calibration Uncertainty Procedures (SWAT-CUP). Through the manual calibration, the range of each parameter can be confirmed by adjusting only one parameter while others were kept constant in each simulation. Special attention was given to SWAT-CUP in which the SUFI2 (Sequential Uncertainty FItting Ver. 2) (Abbaspour *et al.* 2007) procedure was used to further determine the values based on the ranges of parameters. Then, a few manual calibrations were conducted to calibrate the model until the best results were simulated. In order to reduce uncertainty, the automatic tool SWAT-CUP was used for most calibrations in average, wet and dry, high and low temperature years with the same parameter ranges and iteration numbers, while manual calibration was not conducted very often. The performance of the SWAT model was evaluated using three indexes: the correlation coefficient (R^2), Nash–Sutcliffe efficiency coefficient (E_{NS}) and percent bias (PBias) (Moriasi *et al.* 2007).

Criterion definition of selecting extreme hydro-climate and average years

In order to ensure the SWAT model reflects the hydrologic cycle better under fluctuating climate, it is necessary to demonstrate that the model can generate good results in comparison with observed discharge under different hydro-climate conditions. Therefore, an ideal hydrologic validation set should include combined hydro-climate conditions of dry and wet years, high and low temperature years as well as average years. Thus, the selection criteria of different climate conditions should be defined based on the hydrological regime and meteorological regulations. The extreme climate periods were selected based on annual patterns of stream flow and precipitation, and data availability of daily precipitation and air temperature.

The selection criteria of wet and dry years were defined as follows: (1) selecting wet and dry years from the years 1962–1998; (2) obtaining annual average runoff depth and precipitation data of the basin in the years 1962–1998 and choosing several successive years with much higher or lower runoff depth and annual precipitation of the basin.

The selection criteria of high and low temperature years were defined as follows: (1) selecting high and low temperature years from the years 1962–1998; (2) obtaining annual average temperature from the monthly average temperature of the meteorological stations of Zhangshu, Guangchang, Nancheng and Guixi, then selecting several successive years with much higher or lower temperature of the four weather stations. In addition, in order to fully calibrate the SWAT model, each period with extreme hydro-meteorological conditions should span at least three successive years.

RESULTS AND DISCUSSION

Selection results of years with different hydro-meteorological conditions

In order to select periods with different hydro-meteorological conditions, the runoff depth and precipitation data as well as temperature (Figures 3 and 4) in the Fuhe basin during 1962 to 1998 were used to select average years and extreme climate periods. With regard to average years' selection, precipitation, runoff depth and temperature were taken into account at the same time. The average precipitation and runoff for the period of 1962–1998 were 1,707 mm and 797 mm, respectively, and the average temperature was 17.95 °C. The three successive years (1993–1995) with values of these three parameters fluctuating around the average value were picked as the average years. This period was chosen with an average annual precipitation of 1,784.0 mm, annual runoff of 833.4 mm and annual temperature of 18.00 °C compared with the 37-year average values.

During 1962 to 1998, the annual precipitation ranged from 1,035.8 to 2,332.8 mm, while the runoff depth of the basin varied from 230.9 to 1,431.7 mm (Figure 3). According to the defined selecting criteria, the dry period (1963–1965) and wet period (1975–1977) were selected, in which both the average precipitation and runoff depth were much
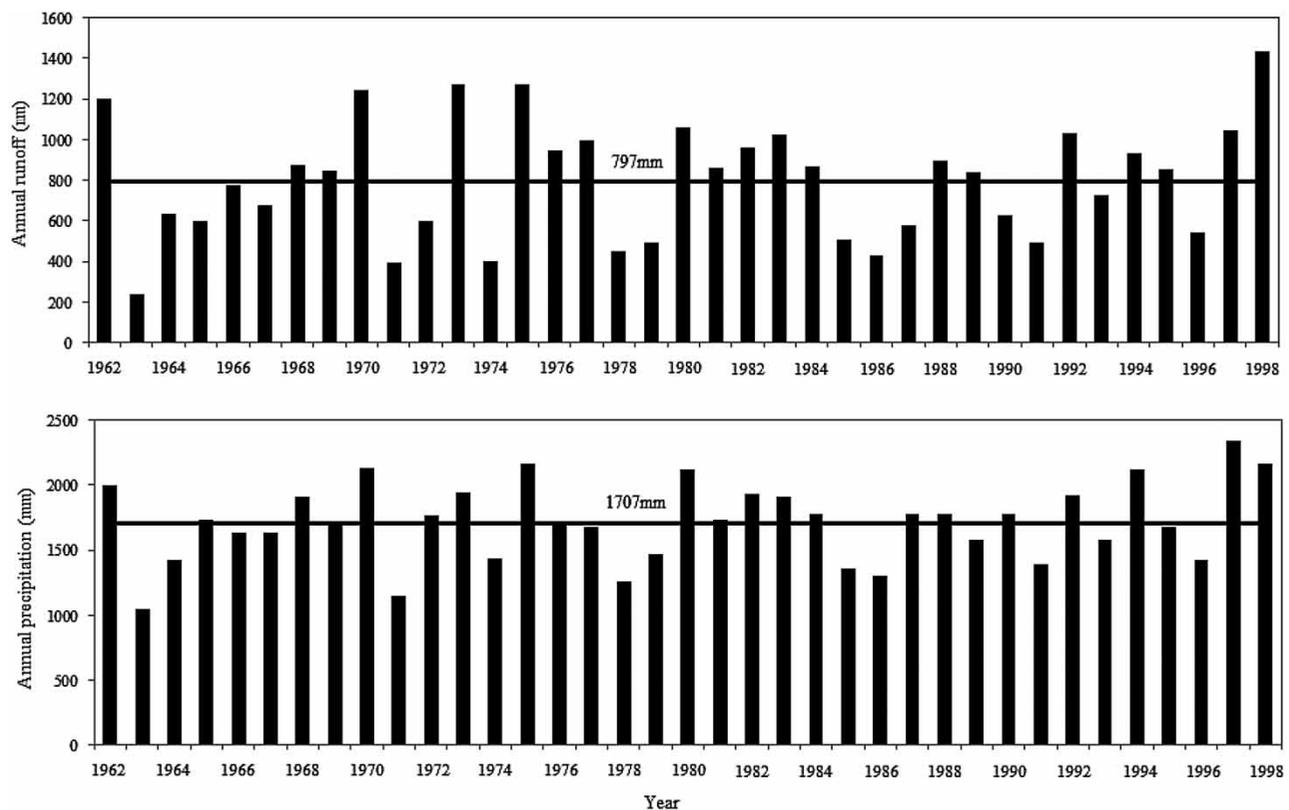

Figure 3 │ Long-term patterns of annual runoff depth and annual average precipitation in the Fuhe basin. Horizontal line describes the long-term average values of these years (1962–1998).
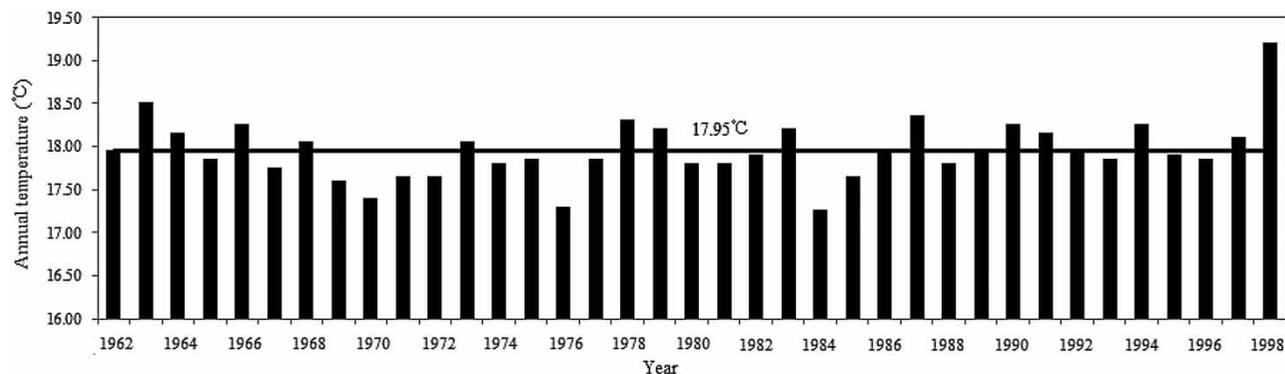
Figure 4 | Annual average temperature of the Fuhe basin. Horizontal line represents the long-term average values of these years (1962–1998).

drier and wetter, respectively. The annual average precipitation for these two periods, based on the records at Zhangshu, Guangchang, Nancheng and Guixi meteorological stations, were 1,393.8 mm and 1,842.8 mm, respectively, which have relative differences of −21.87% and 3% compared with the average precipitation in the selected average years. The annual average runoff for dry and wet periods, based on Lijiadu hydrologic station, were 484.8 mm and 1,068.0 mm, respectively, which have relative differences of −41.83% and 28.15% compared with the average runoff in the selected average years.

For the high and low temperature period selection, Figure 4 shows the annual average temperature of the Fuhe basin in the years 1962–1998. The annual average temperatures during 1962 to 1998 varied from 17.25 °C to 19.20 °C with an average of 17.95 °C. According to the defined selecting criteria, several successive years in which annual average temperature was relatively highest or lowest than the average value should be selected. Thus, the high temperature period (1996–1998) was chosen where the temperature ranged from 17.85 to 19.20 °C and an average of 18.38 °C compared with the average temperature of 18.00 °C in average years. Meanwhile, the low temperature period (1975–1977) was chosen with the temperature ranging from 17.30 to 17.85 °C and the average for these three years being 17.67 °C, which was 0.33 °C lower than that in the average years. According to selection results of high and low temperature periods, and dry and wet periods based on previous criteria, the low temperature years (1975–1977) and wet years (1975–1977) were selected in the same period.

Parameters calibrated under different hydro-climate conditions

For each simulation in different climate conditions, parameter sensitivity analysis and parameter calibration were conducted respectively. After sensitivity analysis was carried out, the most sensitive parameters were obtained to be calibrated in the model for all the simulations. As a result, the most sensitive parameters were initial SCS runoff curve number for moisture condition II (CN2), soil evaporation compensation factor (ESCO), baseflow alpha factor (ALPHA_BF), and threshold depth of water in the shallow aquifer for return flow to occur (GWQMIN, unit: mm). According to the parameter calibration by the combination of SWAT-CUP and manual calibration, the values of the most sensitive parameters were determined under different climate conditions. The most sensitive parameters in each simulation and their values are listed in Table 1.

From the parameter values listed in Table 1, the ESCO describes the adjustment of water compensation between different soil layers. A larger value of ESCO indicates reducing the evaporation of deep layers and increasing runoff. Among the calibrated ESCO parameters in different climate conditions, the ESCO calibrated in dry and average years was the largest and it was smallest calibrated in wet years. The results show that the model tended to increase the evaporation in wet years and increase runoff in dry years. The GWQMIN and CN2 was larger in wet years than that in dry years, which complied with more runoff being produced in wet years. After the model was parameterized using completed climate conditions, including wet and dry years, high

Table 1 │ Values of parameters calibrated under different climate conditions

Parameters	Average years 1993–1995	Wet years 1975–1977	Dry years 1963–1965	High temperature years 1996–1998
CN2	Multiply original values by 1.09	Multiply original values by 1.20	Multiply original values by 1.15	Multiply original values by 1.18
ESCO	0.98	0.47	0.98	0.84
ALPHA_BF	0.039	0.019	0.015	0.014
GWQMIN	20.63	197.58	4.38	17.26

and low temperature years, and hydrologic average years, it can provide comprehensive awareness of hydrologic models under different climate variations.

Model validation for the Fuhe basin

In order to evaluate the SWAT model's applicability under different climate conditions, hydrological average years (1993–1995) were also selected as the ideal hydrologic condition. Consequently, a simulation has been done under hydrological average climate condition to compare with extreme climate years. Calibration and validation were performed by comparing the simulated data with the observed monthly discharge at hydrologic station Lijiadu. Therefore, the SWAT model was first calibrated by observed data in the average years, and validated in the entire study period of 1962–1998. Figure 5 shows the comparison between simulated results and observed discharge at Lijiadu station.

In the whole study time period, evaluation indices such as R^2, E_{NS} and PBias were likely to represent the main trend of the simulated results compared with observed data. As a result, the SWAT model should be calibrated and validated under different climate conditions separately.
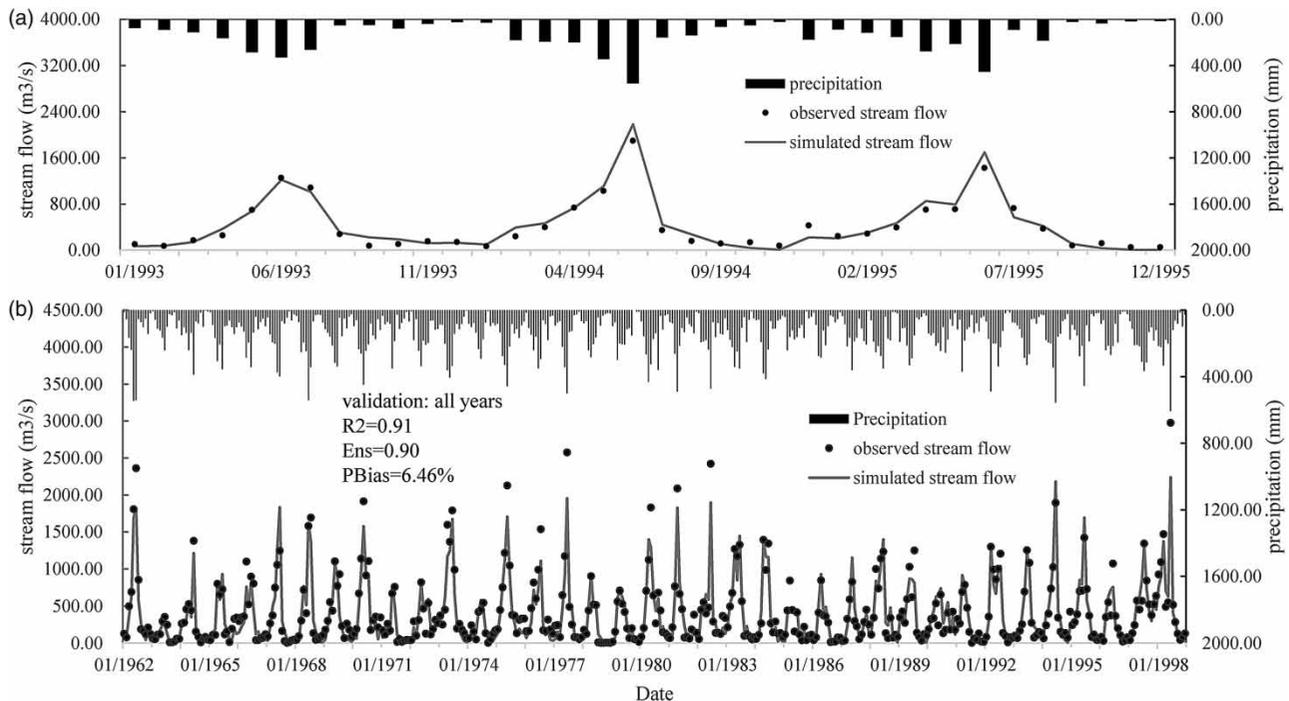

Figure 5 │ Comparison between monthly simulated and observed stream flow: (a) calibration in average years; (b) validation for the whole period (1962–1998) under calibrated parameters by data in average years.

According to the model calibration, the simulated stream flow was satisfactory through the whole simulation period (Figure 5(a)). The simulations generated good results with the R^2 and E_{NS} greater than 0.90 and the absolute values of PBias less than 7%. During the validation period, the SWAT model underestimated the discharge indicated by 6.46%. The discrepancies between simulated results and measured stream flow mainly occurred in flow peaks and usually in May and June. Based on the total hydrological process analysis, SWAT produced good results of monthly stream flow with both R^2 and E_{NS} larger than 0.90 in the validation. Furthermore, compared with the PBias in the average years, the predicted results for wet and dry years were overestimated by 21.12% and 8.37%, respectively, while prediction accuracy was much better in high temperature years, illustrated by the PBias of 7.46%. However, predicted results under extreme climate conditions fitted the observed data well as indicated by both R^2 and E_{NS} larger than 0.89 (Figure 6). Overall, the SWAT model calibrated by data in average years was suitable for the Fuhe basin.

Hydrological responses to extreme climate variability

High performance of the model means the model has more stability in a certain condition, and simulation efficiency with both R^2 and E_{NS} above 0.8 can be acceptable for stably predicting daily stream flow. Special attention was drawn to the validation of the model under extreme climate conditions, because the model performance determines whether the model can generate reliable and credible results. In practice, the model calibration and validation were often conducted based on average climate conditions, and studies on the model performance under extreme climate conditions were often neglected. However, the lack of calibration under the extreme conditions for the hydrological model may result in larger differences between simulated results and observed data, which often leads to the errors of experimental results (Bouraoui *et al.* 2002). In this study, as well as the model validation in average years, the extreme conditions were used to further calibrate and validate the model. By choosing different climate conditions to calibrate and validate this model, we can prove the established model was comprehensively stable.

According to the calibration in wet years, the simulated stream flow was satisfactory although a larger peak deviation appeared in June 1977, which may be caused by overestimating ET in summer (Figure 7(a)). Overall, the simulation generated good results with the R^2 and E_{NS} greater than 0.90 and the absolute value of PBias less than 15%. During the validation period (Figure 7(b)–7(d)), the SWAT model tended to overestimate the stream flow. In the average years, the stream flow was underestimated. On the contrary, simulated results in wet years were overestimated, while prediction accuracy was much better in dry and high temperature years. In flow peaks, discrepancies more often occurred between predicted and observed stream flow. Larger discrepancies appeared in June of 1994 and 1995 in average years (Figure 7(c)). The possible reason was that the model which calibrated in dry years may underestimate infiltration when it rained in the rainy month of June. However, based on the total hydrological process analysis, the R^2 and E_{NS} in the validation were both larger than 0.89. In other words, the SWAT model also provided satisfactory stream flow prediction in average years, dry and high temperature years. From the analysis above, we can conclude that the model built for the Fuhe basin is suitable for predicting hydrological response when the model is calibrated in wet years.

From model calibration under dry climate condition, we can see that the SWAT model tended to overestimate the stream flow by 1.17% (Figure 8(a)). From an overall perspective, the simulation results were satisfactory when the model was calibrated in dry years. In the validation period (Figure 8(b)–8(d)), although there were four larger deviations occurring in flow peaks in May of 1975, July of 1976 and June of 1977 in wet years, and June of 1998 in high temperature years, the simulation generated acceptable results in the comparison with observed discharge under wet years, average years and high temperature years. There were a few deviations occurring in June of 1994 and June of 1995 in average years (Figure 8(c)), which may be caused by underestimating ET with the model calibrated in dry years. Considering the main trend of the simulated results in the validation period, the stream flows in average years were overestimated by 11.29% and 1.17% in dry years. Meanwhile, the stream
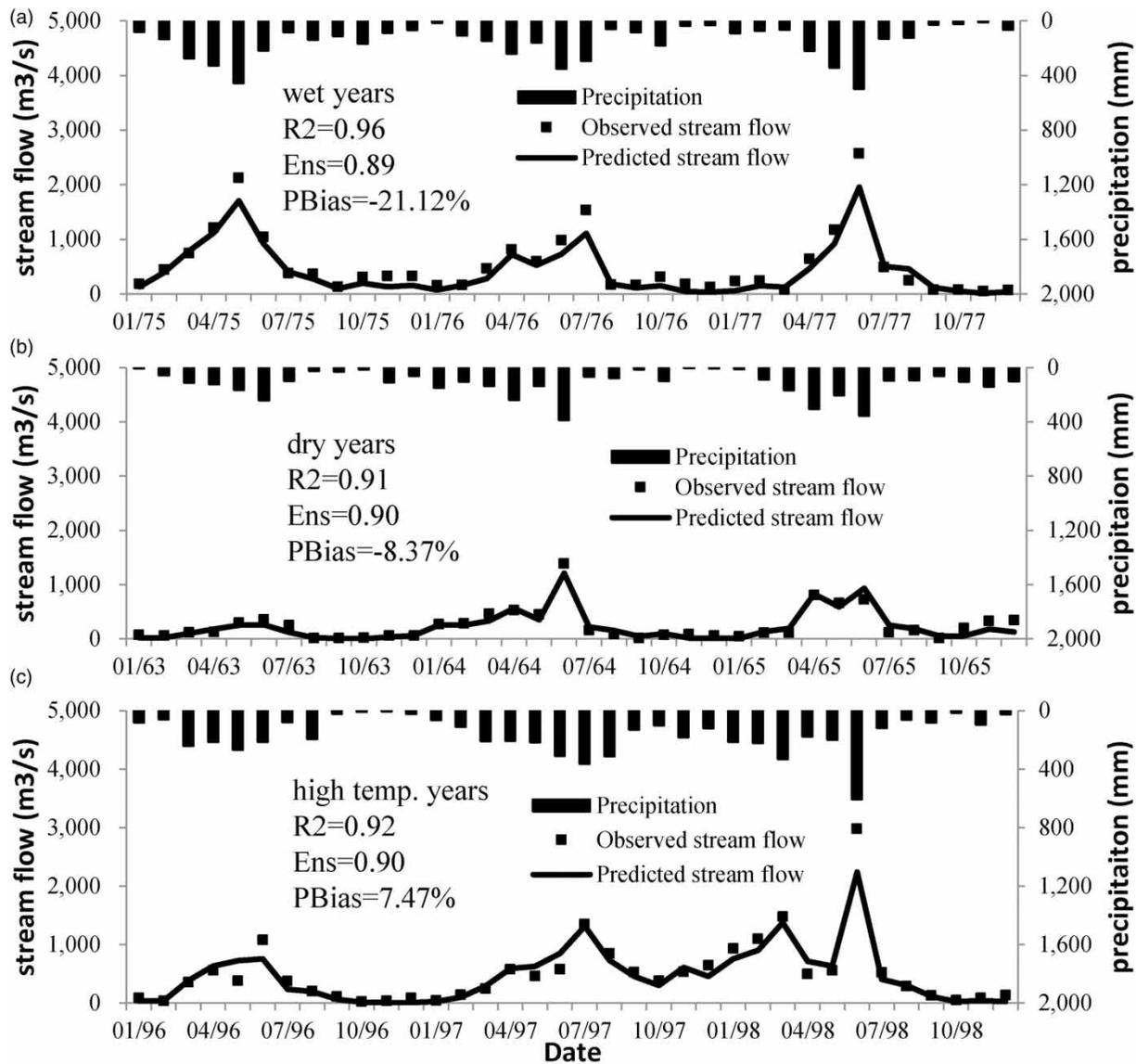
Figure 6 | Validation of stream flow from SWAT model calibrated in the average years: (a) validation in wet years; (b) validation in dry years; (c) validation in high temperature years.

flow in both the wet (low temperature) and high temperature years were underestimated by 17.51% and 2.95%, respectively. Generally, the SWAT model was calibrated well enough to simulate stream flow, which can be proved by the correlation coefficient with more than 0.90. As a result, the model was also stable for evaluating the hydrologic process with potential climate change when it was calibrated in dry years.

As for the high and low temperature years, only high temperature years were used to calibrate the model

because low temperature years and wet years were in the same period. Figure 9(a) shows that comparing with observed data in the calibration period, the largest discrepancy (17%) occurred in June 1998, which was mainly caused by the floods in summer. Apart from that, the model generated good results in the simulation period which is indicated by E_{NS} and R^2 with greater than 0.90, PBias with 0.66%, respectively. In the validation period (Figure 9(b)–9(d)), the discrepancies between simulated and measured data mainly occurred in flow peaks,
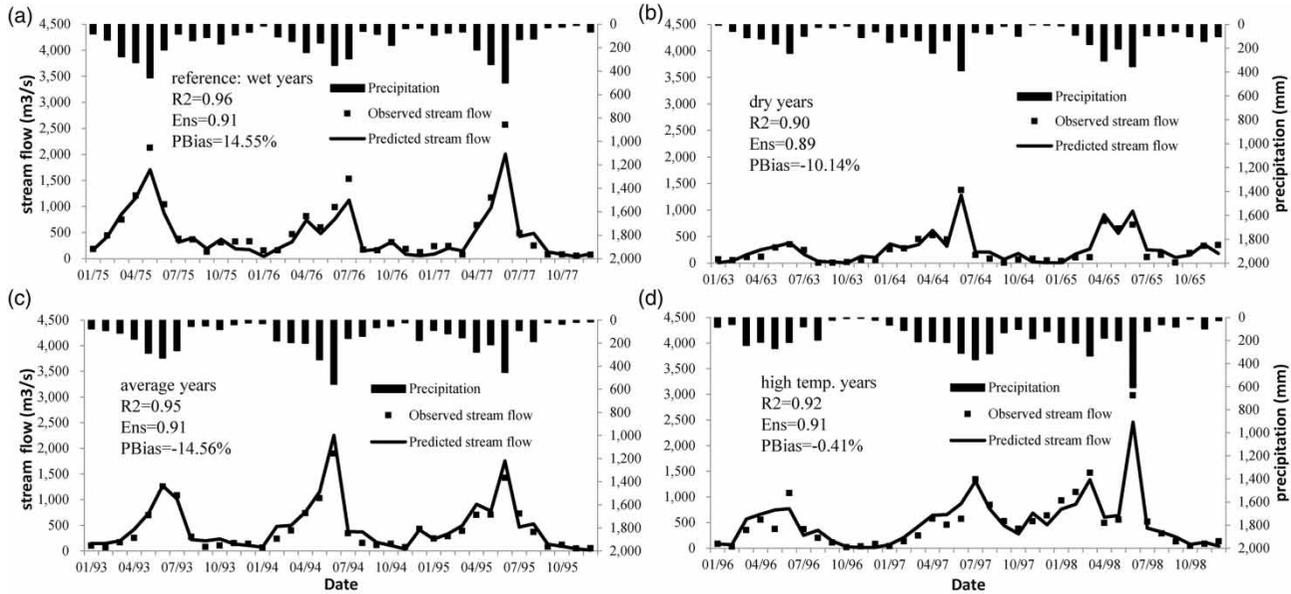
Figure 7 | Hydrological responses to the parameters calibrated in wet years in the Fuhe basin: (a) calibration period; (b) validation in dry years; (c) validation in average years; (d) validation in high temperature years.
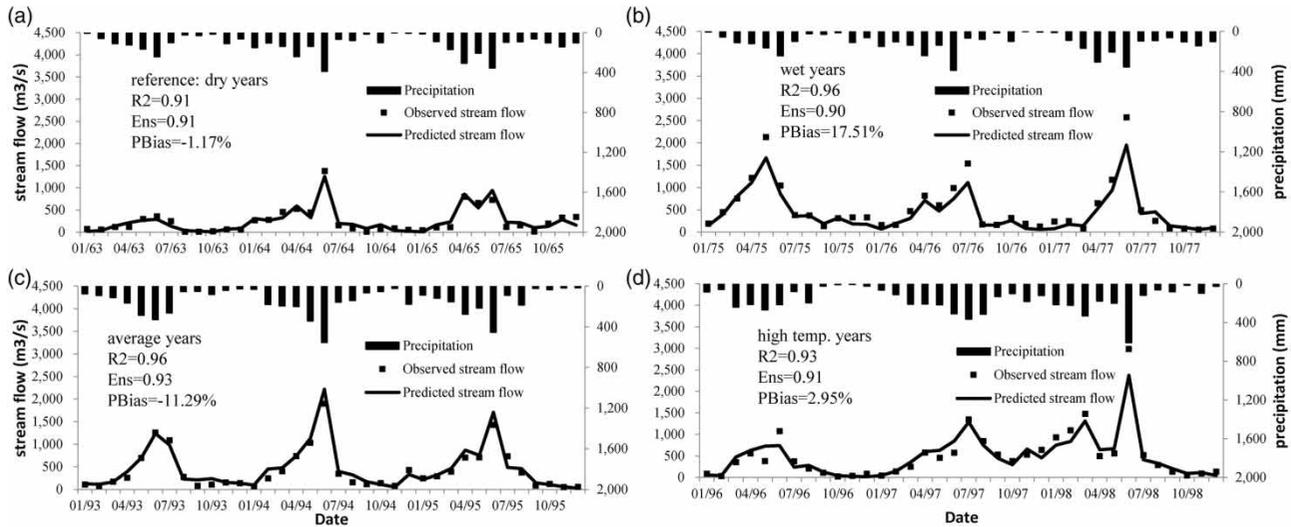

Figure 8 | Hydrological responses to the parameters calibrated in dry years in the Fuhe basin: (a) calibration period; (b) validation in wet years; (c) validation in average years; (d) validation in high temperature years.

especially in wet years, and the model often overestimated stream flow in flow peaks. In addition, the model overestimated the stream flows in average and dry years. Conversely, the predicted results were underestimated by 15.30% in wet years. However, the simulation generated good results under dry years, wet years and average years, in which both E_{NS} and R^2 were greater than 0.90,

which showed that the model was suitable for hydrology simulation when it was calibrated in wet years.

From the simulated results under different extreme conditions, it was indicated that the discrepancies between observed and simulated data mainly occurred when flow peaks happened. During the average years and dry years in either the calibration or validation period, the simulated
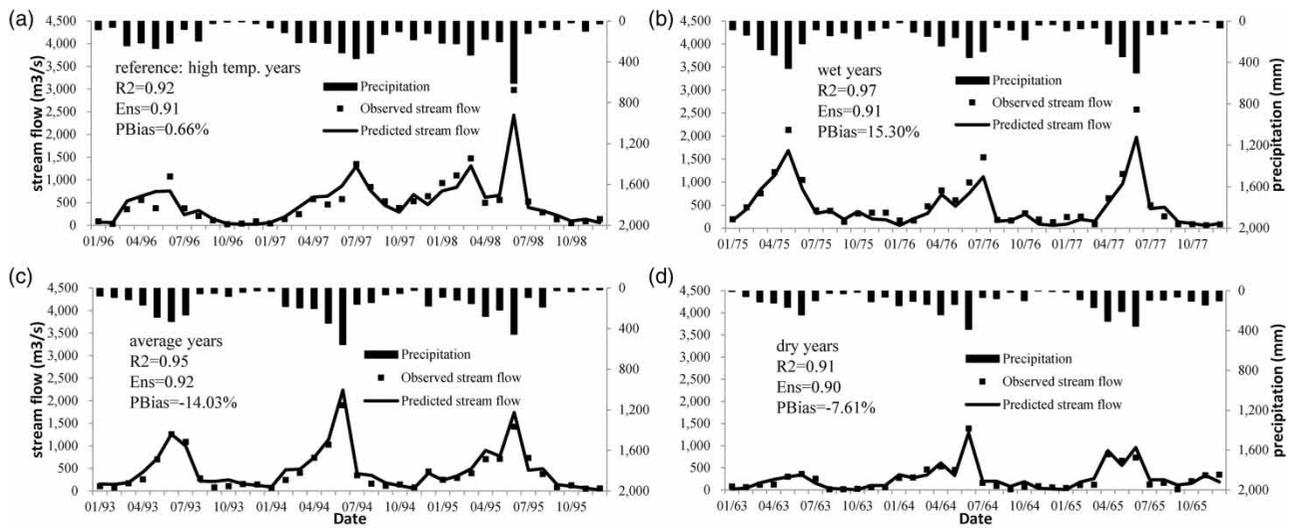
Figure 9 │ Hydrological responses to the parameters calibrated in high temperature years in the Fuhe basin: (a) calibration period; (b) validation in wet years; (c) validation in average years; (d) validation in dry years.

stream flows were often larger than observed data in May and June because the Fuhe basin is a major rice production area and rice is the main agricultural land use in this area. During the rice growing months, the rice paddy land was heavily irrigated (Xie & Cui 2011; Sakaguchi *et al.* 2014). The land impounded large amounts of water in this area, which led to less water yield. The built SWAT model did not especially consider the irrigation process in this study, which was why the model overestimated the stream flows in May and June in average years and dry years. However, considering the simulation efficiency at flow peaks, the SWAT model was also supposed to be adequate for simulating the effects of the climate change on hydrological response under extreme climate conditions.

We summarized the evaluation indexes of model performance for hydrology simulation under different climate conditions from previous analysis, as shown in Table 2. The established SWAT model for the Fuhe basin generated results which closely matched the observed data with the rather higher R^2 in average years and wet years than that in dry and high temperature years. From the perspective of PBias values of different simulations, it seems that the established model was likely to overestimate the stream flow in average and dry years, and underestimate in wet years (except calibration period in average years) and high temperature years (except calibration in wet years). What is more, the stream flows in average years were overestimated the most among those in different climate conditions and the simulated results showed the least deviation to the observed data in high temperature years. The performances of the SWAT model for stream flow prediction in Fuhe basin can have high efficiency as illustrated in Table 2.

Table 2 │ Evaluation indexes of model performance for stream flow prediction under different climate conditions in the Fuhe basin

Reference	Average			Wet			Dry			High temp.		
	R^2	E_{NS}	PBias/%	R^2	E_{NS}	PBias/%	R^2	E_{NS}	PBias/%	R^2	E_{NS}	PBias/%
Average	0.96	0.94	−6.39	0.96	0.89	−21.12	0.91	0.90	−8.37	0.92	0.90	7.47
Wet	0.95	0.91	−14.56	0.96	0.91	14.55	0.90	0.89	−10.14	0.92	0.91	−0.41
Dry	0.96	0.93	−11.29	0.96	0.90	17.51	0.91	0.91	−1.17	0.93	0.91	2.95
High temp.	0.95	0.92	−14.03	0.97	0.91	15.30	0.91	0.90	−7.61	0.92	0.91	0.66

Performance of SWAT model under extreme climate conditions for Fuhe basin

In order to evaluate the performance of the established SWAT model for the Fuhe basin in a long-term period that includes the average years, wet years, dry years and high temperature years, the four groups of parameters, shown in Table 1, calibrated under different climate conditions were applied to the hydrological model from 1962 to 1998. The indexes, including R^2, E_{NS}, PBias, SD (Standard deviation), SE (Standard Error) and Student's T-test were used to assess the accuracy of simulated results and discrete degree in terms of the observed data (Table 3).

From Table 3, all simulations with different groups of parameters could generate good results with R^2 and E_{NS} greater than 0.88 and the absolute value of PBias less than 8%. The SWAT model slightly overestimates the stream flow by 3.55% and 2.32% in the simulation with parameters calibrated in wet years and high temperature years. The simulated results with the parameters calibrated in dry years have a small absolute value of PBias, which indicates that the simulated results have a small deviation from observed results. The simulated results with the parameters calibrated in dry years were slightly underestimated compared to the observed results. From the indices of R^2 and E_{NS}, the simulation with parameters calibrated in average years obtains higher R^2 and E_{NS} than other simulations, although it is difficult to reach the peak stream flow for the simulated results comparing to the observed stream flow (Figure 5(b)). The model calibrated in average years generated the stream flow with the largest absolute value

of PBias during the entire study period of 1962–1998, while the smallest absolute value of percent bias was with the model calibrated in dry years. Regarding Student's T-test, all the simulations with the parameters calibrated in average years, wet years, dry years and high temperature years were with at high significant level testing by the confidence interval of 0.001. The Student's T-test results showed that each simulation had was independent to other simulations with the different parameters calibrated in different climate periods. Therefore, the SWAT model presented a performance that provided satisfactory stream flows in average years, dry and high temperature years. From the analysis above, we can conclude that the well-parameterized model built in this study will be suitable for predicting hydrological response to climate change with extreme variations in the case of the Fuhe basin.

CONCLUSION

In order to assess the stability of the hydrological model in a large range of climate variation, the average years (1992–1995), dry (1963–1965) and wet years (1975–1977), high (1996–1998) and low temperature years (1975–1977) were selected during the period of 1962 to 1998 based on defined criteria for extreme climate period selection. The four groups of parameter were calibrated under these periods of different conditions after parameter sensitivity analysis. From the calibrated parameters under different climate conditions, the soil evaporation compensation factor (ESCO) calibrated in wet years was the largest while the smallest in dry years, which shows that the model tended to increase the evaporation in wet years and increase runoff in dry year. The threshold water depth in the shallow aquifer for return flow to occur (GWQMIN) and the runoff curve number for moisture condition II (CN2) were larger in wet years than that in dry years which complied with more runoff produced in wet years. The parameters calibrated in average years were applied to simulate hydrological responses in wet and dry, and high and low temperature years with the E_{NS} and R^2 all larger than 0.89, in which there were the largest estimation percent biases (PBias) in wet years among the extreme climate simulations. Although the

Table 3 | Performance of the SWAT model for the Fuhe basin in the years 1962–1998 with the four groups of parameters calibrated under average years, wet years, dry years and high temperature years

	Average years	Wet years	Dry years	High temp. years
R^2	0.91	0.89	0.90	0.89
E_{NS}	0.90	0.88	0.89	0.89
PBias/%	6.46	−3.55	1.00	−2.32
SD	419.42	420.10	408.38	412.99
SE	19.90	19.94	19.38	19.60
Student's T-test [1]	***	***	***	***

(1) Significance levels: *** denotes the significance with the confidence interval of 0.001.

stream flow was likely overestimated a little in average and dry years, and underestimated in wet years and high temperature years, the well-calibrated model can accommodate the large range of climate variations. Thus, we conclude that it was able to fit large variations of future climate change when it was used to predict the hydrological responses to the climate change in the Fuhe basin.

All the simulations, running in the entire study period (1962–1998) with different groups of parameters can generate good results with R^2 and E_{NS} greater than 0.88 and the absolute value of PBias less than 8%. Also, all the simulations for different climate variabilities were with high significant level tested by Student's T-test, which showed that each of the simulations was independent to other simulations with the different parameters calibrated in different climate periods. Thus, the SWAT model presented its capacity to provide satisfactory stream flow prediction under a wide range of climate variations as in our case. Therefore, it is significant to calibrate the SWAT model with data collected under extreme climate conditions rather than data in average conditions, so that the calibrated parameters have significant possibilities to accommodate a large range of future climate change. From the analysis of this study, parameterizing the model using complete climate conditions, including wet and dry years, high and low temperature years, and hydrologic average years, can provide comprehensive awareness of the performance of the hydrologic model under different climate variations.

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