Application of SWAT model with CMADS data for hydrological simulation in western China

Yuejian Wang, Guang Yang, Xinchen Gu, Xinlin He, Yongli Gao, Lijun Tian and Na Liao

ABSTRACT

Precise simulations of hydrological processes under the influence of climate change and human activities have special significance in arid basins. During the past 60 years, the annual average temperature and precipitation at the northern foothills of the Tianshan Mountains have increased at the rates of 0.035 °C/year and 0.881 mm/year, respectively. Rising temperatures will change the temporal and spatial distributions and forms of precipitation, accelerate glacier retreat, melt snow on high mountains, cause the degeneration of frozen soil, and change the runoff composition in the Tianshan area. In this work, the CMADS (China Meteorological Assimilation Driving Dataset for the SWAT model) was combined with the SWAT (Soil and Water Assessment Tool) model to simulate runoff in the upper reaches of the Jing River and Bo River Basins in the Tianshan area. The results were as follows. (1) On the monthly scale, the average Nash–Sutcliffe efficiency (NSE) coefficients of the calibration period in the Wenquan and Jinghe–Shankou hydrological stations were 0.79 and 0.87, respectively, and the NSE coefficients of validation period were 0.71 and 0.82, respectively. On the daily scale, the NSE coefficients of the two hydrological stations were between 0.69 and 0.77. The simulation results were considered to be ideal on the monthly and daily scales. (2) Under different climate scenarios and land-use patterns, the cultivated land in the basin leads to the reduction of runoff, and the grassland and woodland stabilise the river flood season. Lakes and wetlands, which can reduce the flow in the flood season and provide water for rivers in the dry season, are very important for runoff regulation. Compared with the traditional meteorological stations, CMADS demonstrates good representativeness and reliability in the Jinghe River and Bohe River Basins under different climate and land-use scenarios, greatly improving the runoff simulation ability.

Key words | CMADS, hydrological processes, SWAT model

Yuejian Wang
Na Liao
Department of Geography, College of Science,
Shihezi University,
Shihezi, Xinjiang 832000,
China

Guang Yang (corresponding author)
Xinchen Gu
Xinlin He
College of Water and Architectural Engineering,
Shihezi University,
Shihezi, Xinjiang 832000,
China
and
Xinjiang Production and Construction Group Key Laboratory of Modern Water-Saving Irrigation,
Shihezi, Xinjiang 832000,
China
E-mail: *mikeyork@163.com*

Yongli Gao
Lijun Tian
Department of Geological Sciences, Center for Water Research,
University of Texas,
San Antonio, TX,
USA

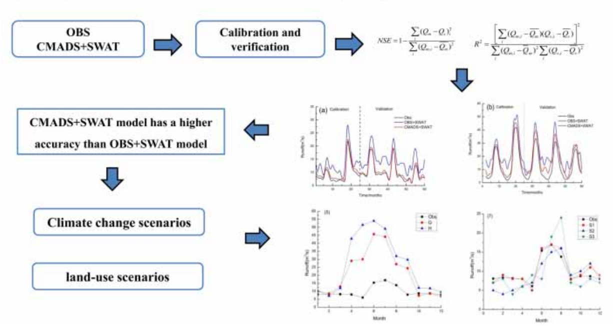
HIGHLIGHTS

- The hydrological simulation by the CMADS + SWAT model has a higher accuracy than the OBS + SWAT model.
- Increasing temperatures and precipitation significantly increased positive runoff. Increasing arable lands and decreasing the total water area will reduce the runoff.
- Reducing the grass, woodland, and shrub forest area will lead to the runoff in the flood season becoming more concentrated.

doi: 10.2166/wcc.2020.040

GRAPHICAL ABSTRACT

Hydrological Simulations and Scenario Analysis by the CMADS and SWAT Model



INTRODUCTION

According to the fifth assessment report issued by the Intergovernmental Panel on Climate Change in 2014, during the period 1880–2012, the global average surface temperature increased by 0.85 °C (0.65–1.06 °C) (Change 2007), the snow decreased by 10%, and the freezing season of rivers and lakes was reduced by 2 weeks (Minville *et al.* 2009). Small changes in precipitation and temperature are usually not statistically significant; however, they have a significant impact on river runoff. The rise in global temperatures has led to the acceleration of regional water cycles and increased precipitation, with seasonal droughts, floods, and other disasters occurring more frequently (Zhao & Cheng 2002; Ye *et al.* 2012). In addition, human activities, such as building reservoirs and reclaiming farmland, have changed land use, affecting the spatial and temporal distribution of local water resources, as well as local hydrological processes (Guang *et al.* 2017; Yang *et al.* 2017). The impact of human activities on water resources has radiated from many river basins to the atmosphere, soil circle, and other levels. Unreasonable land-use practices and extreme climate change threaten human life and the environment, and water resources are highly susceptible to these changes (Shi *et al.* 2002; Li *et al.* 2003; Ding *et al.* 2006; Wang *et al.* 2017; Yang *et al.* 2019a, 2019b).

Chiew *et al.* (1995) simulated the effects of climate change (temperature and precipitation) on runoff and soil moisture in the Australian basin. Singh & Bengtsson (2004) simulated three warming scenarios and four types of precipitation, and Lee & Chung (2007) studied the effects on a small watershed of 13.42 km^2 in the dry monsoon region of Korea, finding that the main meteorological factors that influence runoff in arid areas are temperature, rainfall, humidity, wind speed, and solar radiation. The impact of climate change or land use on runoff has also been evaluated through different hydrological models, and the factors and influences on runoff have been identified (Barlow *et al.* 2003; Ahlfeld 2004; Albek *et al.* 2004; Chuanji *et al.* 2004; Claessens *et al.* 2006).

Hydrological simulation research on climate change and land-use change in the Jing River and Bo River Basins has also been carried out. Climate change in the river basins during the years 1960–2015 has been analysed (Wang *et al.* 2017, 2018), revealing that the annual average temperature in the region was 0.33 °C, and the average temperature for the most recent 7 years has increased by 1 °C compared with the average temperature over the past 50 years. The annual precipitation increased at a rate of 7.97 mm/year. Compared with the average precipitation over the past 50 years, the average precipitation for the past 7 years has increased by 32.45 mm/year. The annual potential evapotranspiration in Ebinur Lake Basin over the past 57 years is 2.51 mm/year, which shows a downward trend, whereas the average potential evapotranspiration for the past 7 years was 77.36 mm less than that for the preceding 50 years. Xu *et al.* (2015) analysed the changes in the basin from 1961 to 2010 with results showing fluctuating temperature and precipitation, changing from warm and dry to warm and wet. Winter warming contributes significantly to the increase in temperature and precipitation in the basin, and the annual average temperature with discharge is positively correlated, in which the change in annual precipitation and runoff is significantly synchronous. Jing *et al.* (2016) predicted land use in the Ebinur Lake Basin with the Camokov model, showing that from 1998 to 2014, forests and grasslands, saline–alkali lands, dry lakebeds, and deserts in the basin increased in the research area, whereas water bodies and other land types prominently decreased by 34.8%. It was predicted that from 2014 to 2030, forests, grasslands, saline–alkali lands, and deserts in the Ebinur Lake wetland nature reserve would increase, whereas lakebeds, water bodies, and other land types would reduce. Meng *et al.* (2017b) fully verified the meteorological driving data by using CMADS meteorological reanalysis data to drive the SWAT model. According to its applicability in the watershed, the spatio-temporal evolution law of soil moisture and evapotranspiration was clarified.

The above-mentioned studies have revealed significant information regarding climate change, land-use change, and the adaptability of CMADS in the Jingbo River Basin. Most of the research has focused on the following topics: (1) impact of climate change and human activities on water resources in the Jingbo River Basin; (2) ecological environment assessment of the Jingbo River Basin; (3) landscape pattern and desertification of the basin; and (4) ecological restoration benefits and simulation of the Ebinur Lake's tail region. However, the viewpoints of the studies are scattered, and the studies have not been carried out from the perspective of the entire basin. In particular, there is a lack of simulation studies on upstream hydrological processes. In fact, changes in the upstream water resources have an extremely important impact on the middle and lower reaches, especially under the influence of climate change and human activities, whereas the uncertainty of the output and assessment of hydrological simulation in this region is significantly enhanced. Therefore, to fully understand the essence of the Jingbo River Basin under climate change and hydrological responses to land-use change, particularly in the expected extreme scenarios of the future, this study uses the distributed hydrological model SWAT and data from CMADS to analyse different climate change and land-use change scenarios. In this manner, the northwest arid areas are given priority, with the ice and snow melt water supply mechanism from runoff assigned an important reference value.

To fully understand the hydrological response of the Jingbo River Basin under climate change and land-use changes, especially any changes in the hydrological elements under extreme future scenarios, we applied a distributed hydrological model and existing meteorological and reanalysis data as drivers to simulate the effect of different climates and land uses in this study. First, the SWAT model was driven by different meteorological data (measured meteorological data and CMADS reanalysis data) to obtain simulated results that can better reflect the basin's meteorological conditions. Second, we considered changes in land use to explore the processes of runoff response in different scenarios.

Study area

The Jing River and Bo River Basins are located in the hinterlands of the Asia–Europe continental region, in the northern foothills of the western Tianshan Mountains and in the southwest area of Junggar Basin, with a range of 81.77°–83.85° E and 44.03°–45.16° N and an area of 11.275 km^2 (Figure 1; Li *et al.* 2019). Owing to the high mountains in the west, north, and south, moisture from the Arctic Ocean and the Atlantic Ocean is blocked, resulting in drought and a low amount of rainfall in the basin. Meanwhile, the sunlight is sufficient, and the evaporation is intense. Alpine precipitation and snowmelt water are the main sources of river runoff in the basin. According to the second glacier inventory data set (Liu *et al.* 2015), in the Jinghe and Bohe regions, the glacier area is 206.5 km^2, and glacier recharge accounts for 20.6 and 21.4% of the annual river runoff, respectively.

DATA AND METHODS

Digital elevation model

In this study, we used the SRTM 90 m digital elevation model (DEM) data (http://srtm.csi.cgiar.org/selection/inputCoord.asp). We considered the surface of the study area and height of the river basin in the region 160–4,600 m

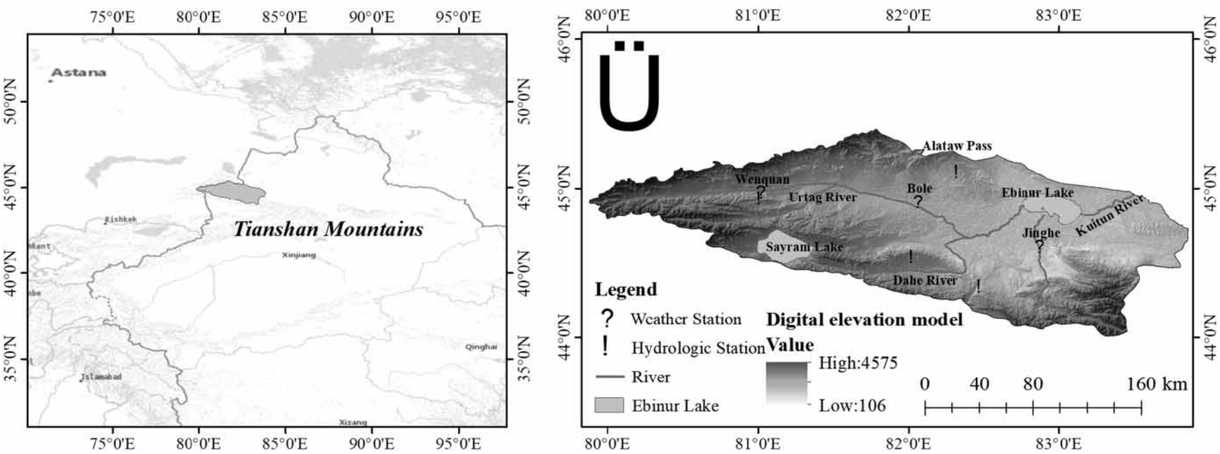


Figure 1 | Location of the Jing River and Bo River Basins.

above sea level, which accounts for a total area of 11,275 km^2. The west, south, and north of the basin have continuous mountains, whereas the east has a relatively flat plain.

Soil data

The SWAT model for calculating the field water-holding capacity and hydraulic conductivity coefficients needs soil attribute parameters (Fischer *et al.* 2000; Meng *et al.* 2017d). The soil data used in our study are based on the World Soil Data Set, which has a resolution of 1 km, provided by the Cold and Arid Regions Scientific Data Center (http://westdc.westgis.ac.cn) and the Chinese soil data set of HWSD (v1.1). In our model, we reclassified the soil types with the same soil properties, utilising the soil water characteristics from the software.

Land-use data

The LUCC land-use data were obtained from remote-sensing observations of the Ebinur Lake Basin. Glaciers are indicators of climate change and important water resources in northwest China. Thus, research on hydrological response to climate change is necessary. In this research, changes in glaciers need to be considered. Therefore, the second glacier inventory data set was superimposed on the original land-use data (Meng *et al.* 2017b).

Meteorological driving data

The CMADS used in the SWAT model form part of the public data set developed by Prof. Xianyong Meng at the China Agriculture University (http://www.cmads.org). CMADS was established using the CMA Land Data Assimilation System, which combines data loop nesting, model estimation, and other technical means. The data set includes seven types of meteorological elements: daily accumulated precipitation, maximum temperature, minimum temperature, daily average relative humidity, daily average wind speed, daily average solar radiation, and daily average air pressure. The amount of precipitation according to the background field from the CPC morphing technique and the observational data of China precipitation automatic station were also integrated. Temperature, pressure, relative humidity, and wind speed were based on data from the National Centers for Environmental Prediction–Global Forecast System, which used the Space and Time Mesoscale Analysis System algorithm to fuse the observational data. Radiation fluxes were based on the International Satellite Cloud Climatology Project data as background data, and the fourth and fifth series of FengYun-2 nominal map data were obtained using the Discrete Ordinate Radiative Transfer atmospheric model. Inversion was carried out to calculate the total radiation irradiance of the ground-incident solar radiation at each grid point.

CMADS provides a variety of data utilisation formats, and watersheds can be selected that are directly used as input to the SWAT model. CMADS has a high spatial and temporal resolution, comprehensive meteorological elements, and strong reliability. It is widely used in research for hydrological simulations of many watersheds in China, such as the Hei River, Hun River, Manas River, Jingbo River, and Juntang Lake River (Wang *et al.* 2016; Meng *et al.* 2017a, 2017b, 2017c). The time range of the CMADS data is 2008–2016. Meanwhile, the SWAT website recommends using CMADS as the weather-driven data set for the model.

Climate change scenarios

The climate change process is relatively slow and has long-term characteristics in terms of water circulation in the basin. The process of river runoff in cold and dry regions has typical characteristics. Precipitation is the primary source of water in the basin. However, it participates in the water cycle of the basin in various forms. Air temperature is the main factor controlling the form of precipitation and its spatial and temporal distributions. An increase in temperature changes rain to snow, accelerates the melting of glaciers and snow, and increases runoff in the watershed in the short term.

Compared with that during the pre-industrial revolution period, the global average annual surface temperature has increased by 2 °C. According to relevant research (Chen & Sun 2009; Jiang *et al.* 2009; Xu *et al.* 2009; Lu & Fu 2010; Sun & Ding 2010; Sun *et al.* 2010), under this assumption, the average annual surface temperature in China has increased by 2.0–3.4 °C, with some areas experiencing an increase up to 3.7 °C. Therefore, in this study, 2 °C is selected as the benchmark temperature; and the extreme climate change scenarios of −2 and 4 °C are selected as the control temperatures. Similarly, under different emission scenarios, the variation amplitude of rainfall does not vary greatly from model to model and is mainly concentrated between −10 and 10% (Jiang & Fu 2012). However, in the central and eastern parts of Xinjiang, the increase in rainfall could be as much as 15% (Zhou *et al.* 2019). Accordingly, we set up a scenario in which the temperature increases by 2 °C, and the rainfall increases by 10% to simulate the scenario in which human activities are not changed and the scenario in which human activities are reduced by half (1 °C, 5%). Overall speaking, to discuss the runoff changes under different temperature and precipitation scenarios in the basin, we set up eight climate change scenarios (Table 1): temperature changes of −2 , 2, and 4 °C (assuming that precipitation does not change), precipitation changes of −10, 10, and 15% (assuming that the temperature does not change), and situations in which the temperature and precipitation both change simultaneously.

Table 1 | Climate change scenarios

Climate change scenario	A	B	C	D	E	F	G	H
Temperature (°C)	−2	2	4	0	0	0	1	2
Precipitation (%)	0	0	0	−10	10	15	5	10

Land-use change scenarios

The expansion of urban construction land and changes in cultivated land area and human activities, such as damming rivers, directly cause changes in the quantity of water in the river basin, which affect water circulation in the river basin, incurring both short-term and far-reaching consequences. Increases in the basin's population, improvements in the level of urbanisation, and the development of industrial and commercial sectors have led to an increase in water consumption. Moreover, surface changes will affect the processes of water interception, infiltration, and depression filling. Indeed, water conservation projects, such as reservoirs and fabricated ditches, directly change the runoff process.

In this study, three soil types were considered in the land-use scenarios: (1) on the basis of a consistent water area, with other lands including construction land, woodlands, grasslands, and shrubbery reduced by one-third and converted into arable land; (2) on the basis of consistent land-use, but with the total water area reduced by one-third and converted into grassland; (3) on the basis of consistent cultivated land and water areas, but with other lands including grasslands, woodlands, and shrubbery reduced by one-fifth to be used for urban construction (Table 2).

SWAT model

The SWAT model is based on the Simulator for Water Resources in Rural Basins model, a semi-distributed

Table 2 | Land-use change scenarios

Land-use type	Area (km^2)	S1 (km^2)	S2 (km^2)	S3 (km^2)
Cultivated land	1,156.2	3,836.2	1,156.2	1,156.2
Woodland	413.2	275.5	413.2	330.6
Grassland	7,121.0	4,747.3	7,245.4	5,696.8
Shrub woods	505.9	337.2	505.9	404.7
Water	373.3	373.3	248.9	373.3
Construction	120.1	120.1	120.1	1,728.3
Other lands	1,585.3	1,585.3	1,585.3	1,585.3

hydrological model developed by Dr Jeff Arnold of the Agricultural Research Center of the United States Department of Agriculture (Cheng *et al.* 2009; Meng *et al.* 2014; Fu *et al.* 2016). The model considers the comprehensive effects of multiple complex factors, such as weather, soil, topography, vegetation, human activities, and changes in water resources (Zhang 2005). The model creates divisions, known as hydrological response units, according to soil type, land-use type, and slope of the considered basin and calculates the hydrology. The water balance of a response unit can be used in watersheds with many types of soil, complicated land usage, meteorological elements with significant spatial heterogeneity, and complicated water resources management scenarios. The SWAT model can accurately describe the spatio-temporal changes of the hydrological cycle process on the watershed scale, determine the hydrological response under climate change, and model the impact of simulated human activities on the water cycle in terms of changes in the underlying watershed(s) (Wang *et al.* 2003).

The SWAT model uses the Soil Conservation Service (SCS) curves to simulate surface runoff, and various evapotranspiration calculation methods are available. In this work, the P-M method was used to calculate the evapotranspiration (Wang & Cui 2009). CMADS contains all the meteorological parameters needed by the model, although the measured meteorological data lacks solar radiation. The weather generator built into the SWAT model was used to calculate and simulate the climate conditions of the basin. The period of the CMADS data was 2008–2014, in which the corresponding runoff data and measured meteorological data for this period were used in the simulations. The preheating period of the model was 2008, 2009–2010 was the simulation period, and 2011–2013 was the validation period.

Although the SWAT model has many parameters, it uses the professional software SWAT-CUP, which stands for the Calibration/Uncertainty or sensitivity programme for SWAT, for parameter calibration and sensitivity analysis. This programme significantly simplifies the number of free parameters in the model (Zuo & Xu 2012; Yang *et al.* 2013). In the SWAT model, 25 parameters are related to runoff change; in this study, 12 parameters with a P-value $\leq$0.05 (95% confidence interval) are selected for calibration according to the P-value sensitivity ranking (Table 3). The relevant rates were set in the process, which ensured that the annual evaporation, precipitation, and runoff in the basin conformed to reality. Because the time range of meteorological data provided by CMADS is the years 2008–2016, the data are not sufficient for SWAT simulation at the annual scale. Therefore, this study only considers monthly scale and daily scale simulations. Initially, at the monthly scale, we simulated the runoff measured by the Jinghe and Wenquan hydrological stations. On this basis of these results, the remaining day-scale simulations were conducted, and eventually, the values of the 12 considered parameters of the two hydrological stations were obtained.

In this study, the NSE coefficient and local qualitative coefficient R^2 are selected as the evaluation criteria of the model simulation results. The NSE coefficient is a commonly used reference standard to measure the quality of model simulation results in hydrology. The coefficient reflects the fitting degree of the simulated and observed values. The calculation formula is as follows:

$$\mathrm{NSE} = 1 - \frac{\sum_i (Q_m - Q_s)_i^2}{\sum_i (Q_{m,i} - \overline{Q_m})^2} \quad (1)$$

where Q is the runoff value variable; Q_m and Q_s represent the observed and model values, respectively; and $\overline{Q_m}$ indicates the mean observed runoff. The NSE is in the range of $-\infty$ to 1. When the NSE calculation result is 1, the observed value and modal value can be regarded as consistent; when the value is between 0.5 and 1, the model results are acceptable; and when the NSE is less than 0, the model

Table 3 | The final values of the SWAT model parameters

Parameter names	Parameter definitions	Parameters final values	Parameters sensitivity ranking
CN2.mgt	SCS runoff curve values	34	1
ALPHA_BF.gw	Baseflow α factor	0.453	2
GW_DELAY.gw	Aquiclude replenish delay time (days)	42	3
GWQMN.gw	Water level threshold for shallow aquifers when groundwater is imported into the main river course	8.5	4
GW_REVAP.gw	Groundwater re-evaporation coefficient	0.03	5
ESCO.hru	Soil evaporation replenish coefficient	1.008	6
ALPHA_BNK.rte	Baseflow water recession coefficient	0.45	7
SFTMP	Average temperature on snowmelt day (°C)	4.8	8
PLAPS	Lapse rate of precipitation day (mm/km)	44.5	9
SMFMN	Snowmelt factor on 21 December (mm/day °C)	9.407	10
SMFMX	Snowmelt factor on 21 June	0.1302	11
TLAPS	Temperature lapse rate (°C/km)	−4.3039	12

Table 4 | Simulated runoff for different driving models

		Wenquan station				Jinghe station			
		Calibration period		Validation period		Calibration period		Validation period	
Driving model	Time scale	NSE	R^2	NSE	R^2	NSE	R^2	NSE	R^2
OBS + SWAT	Month	0.43	0.64	0.38	0.62	0.53	0.77	0.47	0.63
	Day	0.17	0.69	0.21	0.51	0.39	0.71	0.35	0.59
CMADS + SWAT	Month	0.79	0.88	0.71	0.93	0.87	0.94	0.82	0.91
	Day	0.72	0.84	0.69	0.91	0.77	0.86	0.71	0.89

results can be considered as poor. The deterministic coefficient R^2 determines the degree of correlation between the variables, and it was calculated using the following equation:

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

where Q_m and Q_s are the same as in Equation (1) and i indicates the ith observed or simulated value. Many researchers have used $R^2 \geq 0.5$ and NSE ≥ 0.5 as satisfactory criteria for the SWAT model. In this study, we used the criteria set by Moriasi et al. (2007); that is, when the model was in its calibration stage, if the monthly scale simulation results were NSE ≥ 0.65 or if the daily scale simulation results were NSE ≥ 0.5, then the model simulation results were deemed as acceptable.

Considering the large elevation difference in the basin, the basin was divided into 10 elevation zones, and the precipitation decline rate (PLAPS) and temperature decline rate (TLAPS) in the activation model were determined. At the same time, the runoff at the Wenquan station and Jinghe station were calibrated by the model, and ultimately, the calibration values of the 12 selected parameters were obtained. The PLAPS value at the Jinghe station was 51.3 mm/km, and the TLAPS value was 4.21 °C/km. The results of the CMADS-driven SWAT model (CMADS + SWAT) are relative to the measured meteorological data. Meanwhile, the driven SWAT hydrological model (OBS + SWAT) was significantly improved (Table 4).

RESULTS AND DISCUSSION

Runoff simulation

At the monthly scale, the NSE coefficients of OBS + SWAT in the Wenquan station from 2009 to 2013 are 0.43 and 0.38 in the calibration and validation periods, respectively, whereas the results of CMADS + SWAT were 0.79 and 0.71, respectively. CMADS significantly improved the accuracy of the runoff simulation, and indeed, the rates determined for the Jinghe hydrological station are satisfactory. The NSE coefficients of CMADS + SWAT were 0.87 and 0.82 for the calibration period and the verification period, respectively, which were deemed satisfactory (Figure 2).

In terms of daily values, the NSE coefficients of CMADS + SWAT for the same aforementioned periods were 0.72 and 0.69 for the Wenquan station and 0.77 and 0.71, respectively, at the Jinghe station. Compared with CMADS + SWAT, OBS + SWAT yielded smaller values. Owing to the poor simulation results of OBS + SWAT, only the results of CMADS + SWAT at the Wenquan station and Jinghe station at the daily scale are shown in Figure 3. The CMADS-simulated results were larger at the daily scale; however, the fitting degree with the measured runoff hydrograph was still considered as acceptable.

Hydrological response under different climate scenarios

Temperature changes

The simulated results arising from different temperatures are shown in Figure 4. Upstream from the Wenquan hydrological station, the river flow was less in winter, and any increase or decrease in the air temperature had only a small impact on the runoff. The effects of temperature change on runoff during the snowmelt period in spring were the following: when the temperature dropped by 2 °C, the annual runoff at the Wenquan hydrological station increased by 32%. When the temperature rose by 2 °C, the annual runoff increased by 44%, of which the spring runoff increased from 7.4 to 17.3 m^3/s. When the temperature increased by 4 °C, the annual runoff increased by 59%, and the spring runoff increased to 26.4 m^3/s. The leading reason behind these values was that the river basin is supplied primarily by ice and snow. When the temperature rises, the ice and snow melt rapidly, and the runoff significantly increases. When the temperature rises by 4 °C, significant runoff occurs during spring. The amount of runoff in all seasons increases but not significantly, with a slight increase in summer and in other seasons. The direct effect of the rise in temperature on the ice and snow runoff area is to advance the flood season, which results in the significant increase in the spring runoff. The Jinghe

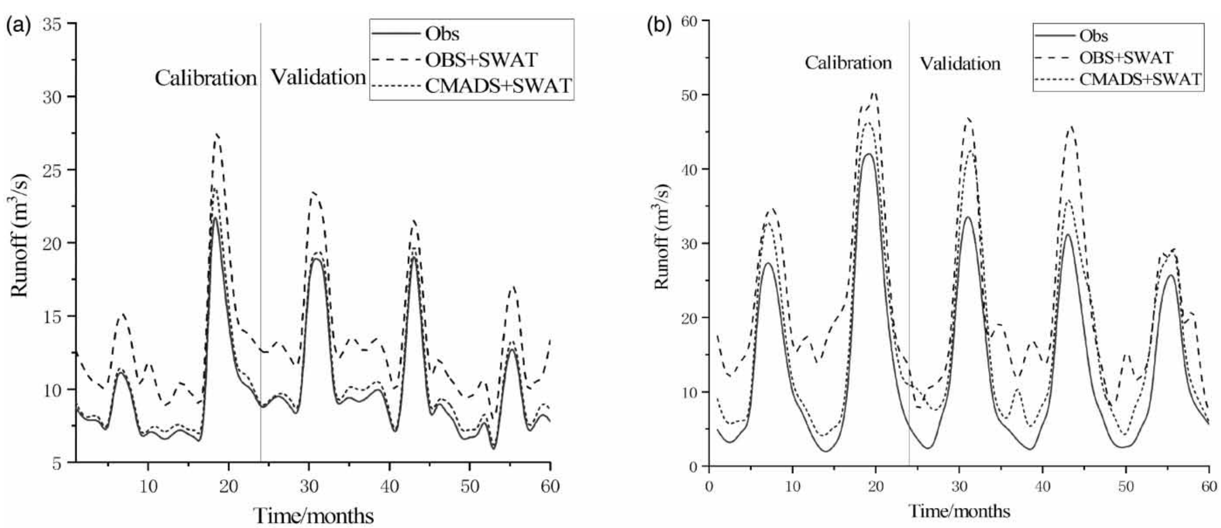


Figure 2 | Monthly scale simulations at (a) Wenquan station and (b) and Jinghe station, with different weather data driving the SWAT model for the period 2009–2013.

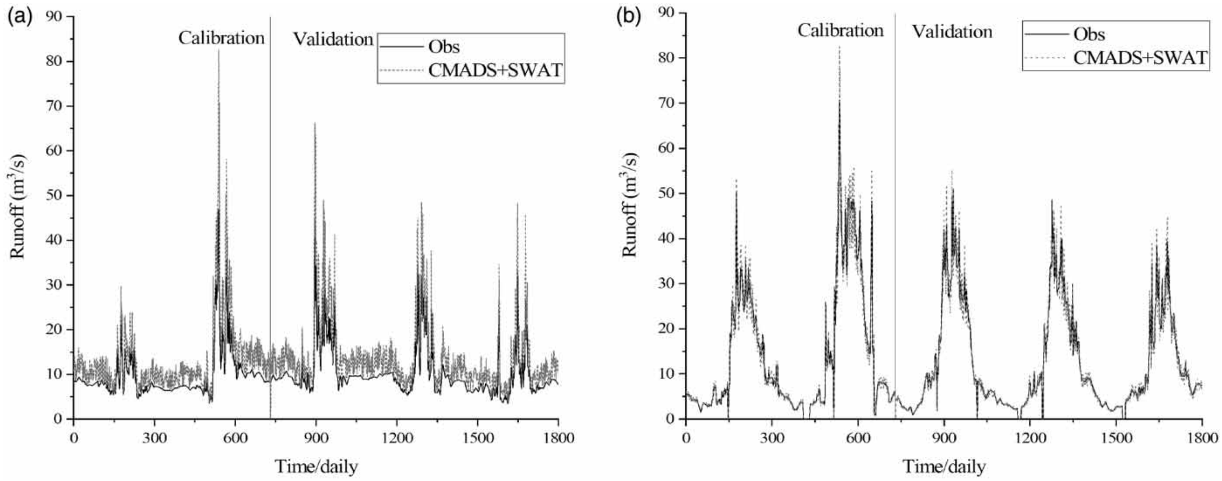


Figure 3 | The result of daily scale simulation at (a) Wenquan station and (b) Jinghe–Shankou station, with different weather data driving the SWAT model for the period 2009–2013.

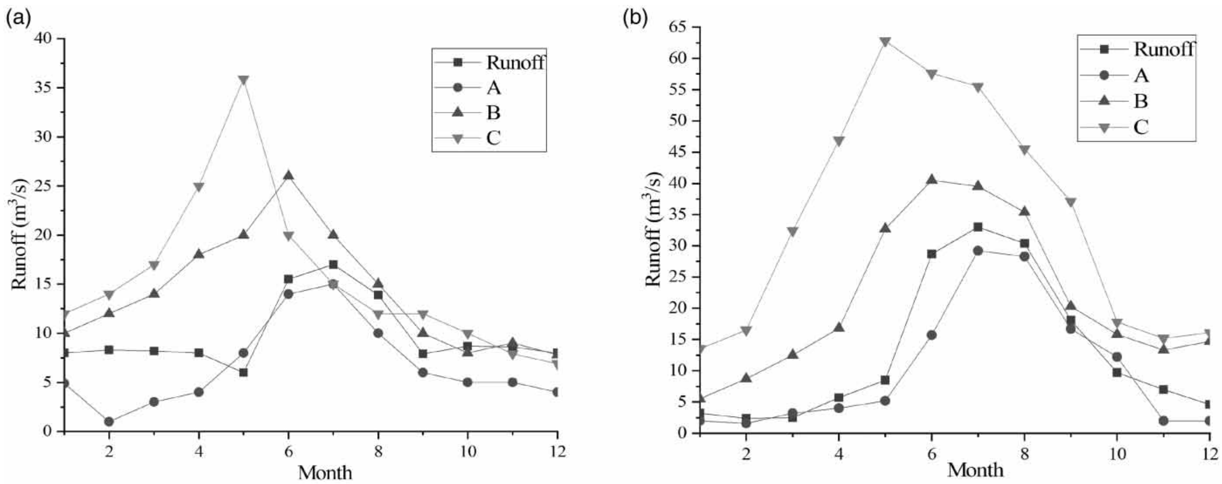


Figure 4 | Runoff at Wenquan station and Jinghe station for different temperatures.

hydrological station in the lower reaches of the river also shows this characteristic apparently. When the temperature drops by 2 °C, the runoff decreases by 21%. When the air temperature increases by 2 °C, the annual average runoff increases from 12.9 to 21.3 m^3/s, and the monsoon significantly advances, in which the spring runoff increases to 5.7 m^3/s.

Precipitation changes

The simulated results for different precipitation conditions are shown in Figure 5, whereby the temperature remained unchanged. Runoff mainly shows an increase in inflow during the flood season. In spring, owing to a relative increase in snowmelt, runoff also increases. The upstream from the Wenquan station was located at the mountain exit of the river basin. The melting water of ice and snow in spring and mountain precipitation in summer were the primary supply sources of the river basin. While the precipitation increased by 10% during the year, the annual average runoff increased from 9.4 to 26.8 m^3/s, and the runoff in spring and summer increased from 7.4 and 15.4 m^3/s to 25.4 and 40.5 m^3/s, respectively. Similar changes were seen at the Jinghe hydrological station, which is located in

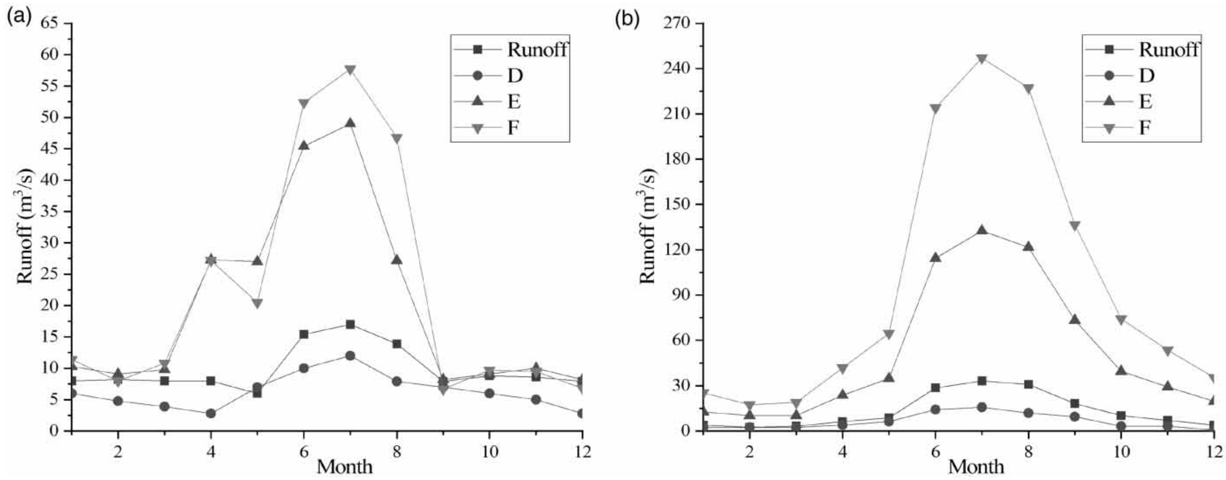


Figure 5 | Runoff at Wenquan station and Jinghe station for different levels of precipitation.

the lower reaches of the basin and has a larger catchment area. Simulated increases of 10 and 15%, respectively, representing the amount of runoff in summer, were found with a slight increase in runoff in spring as well.

Comprehensive changes

For scenarios where the temperature and precipitation changed simultaneously (i.e., scenarios G and H), the simulation results are shown in Figure 6. In these cases, the runoff significantly increased. On the one hand, the water produced by melting ice and snow increased considerably and the mountains dropped increased amounts of water, all of which directly led to a substantial increase in the runoff and the advancement of the flood season. At the Wenquan hydrological station, the temperature increased by 1 °C, the precipitation increased by 5%, and the annual runoff increased from 9.8 to 25.3 m^3/s. When the temperature rose by 2 °C, the precipitation increased by 10%, and the annual runoff increased to 32.4 m^3/s. Runoff at the Jinghe hydrological station was similar to that of the hot spring station but less severe. When the temperature

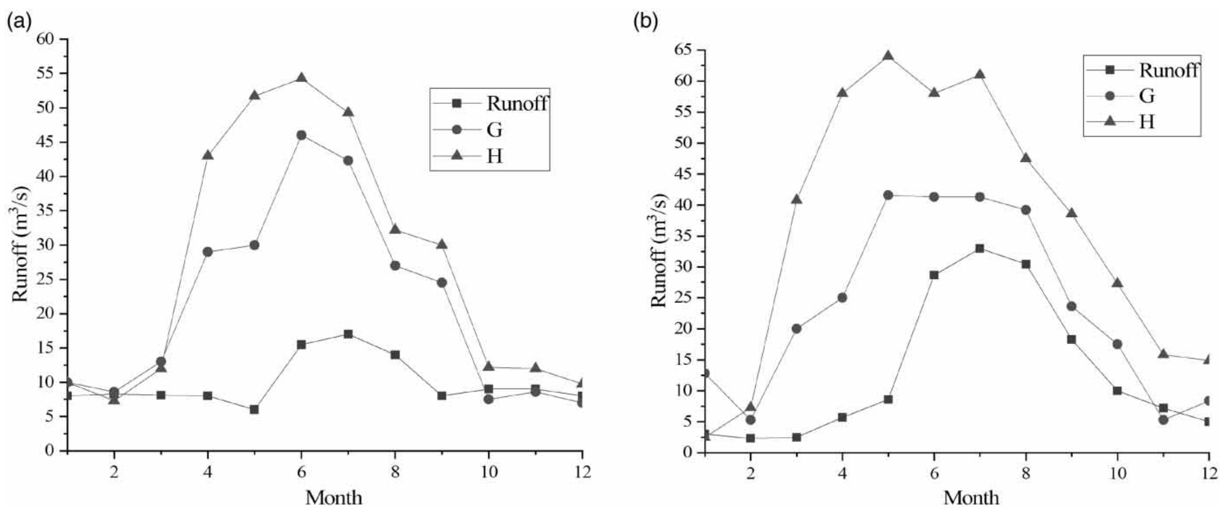


Figure 6 | Runoff at Wenquan station and Jinghe station as the temperature and precipitation simultaneously changed.

increased by 1 °C, the precipitation increased by 5%, and the annual average runoff increased by 13.4% to 27.3 m^3/s. For an increase in temperature of 2 °C, the precipitation increased by 10%, and the annual runoff increased to 40.3 m^3/s.

Hydrological response under different land-use scenarios

The simulated results for the three chosen land-use scenarios are shown in Figure 7. The annual average runoff at the Jinghe station for scenarios S1, S2, and S3 were 10.35, 11.6, and 12.75 m^3/s, respectively, which corresponded to relative increases of 21, 12, and 11.6%. The annual average runoff at the Wenquan station for these three scenarios was 10.3, 9.1, and 11.2 m^3/s, respectively. Under the scenario of increased cultivated land area (S1), irrigation water consumption increased, which also led to evapotranspiration. The amount of runoff also increased, resulting in a significant decrease in the runoff, especially in summer. Water areas have certain replenishment and regulation functions for runoff: in the S2 scenario, the reduction of the water area has little effect on runoff. Reduced summer runoff was seen at the Jinghe station and Wenquan station when the water area was reduced. Finally, in the S3 scenario where the amount of grass in the basin decreased, the area of construction land increased significantly. As woodlands, grasslands, and shrub forests have a certain degree of water-holding capacity, when large-scale degradation of these lands occur or the land is developed into cities, the basin's ability to retain water correspondingly changes. Indeed, the simulated water-holding capacity of the basin decreased, resulting in more concentrated runoff during the summer flood season. During July and August, runoff at the Wenquan station increased significantly due to grassland degradation.

CONCLUSIONS

In this study, the SWAT model was driven by data from CMADS, and the representativeness and feasibility of these data to different climate and land-use change scenarios in the Jing River and Bo River Basins were analysed. The simulation results were analysed to characterise the hydrological processes of the basin. The main conclusions of this study are as follows:

(1) CMADS has good representativeness and reliability in the Jing River and Bo River Basins, which greatly improves the runoff simulation ability. However, the simulation ability of the SWAT model driven only by the measured meteorological data is poor, with an NSE coefficient of less than 0.5.
(2) According to the simulation of different climate change scenarios, we found that an increase in temperature will lead to the advance of the snow melting period, mainly

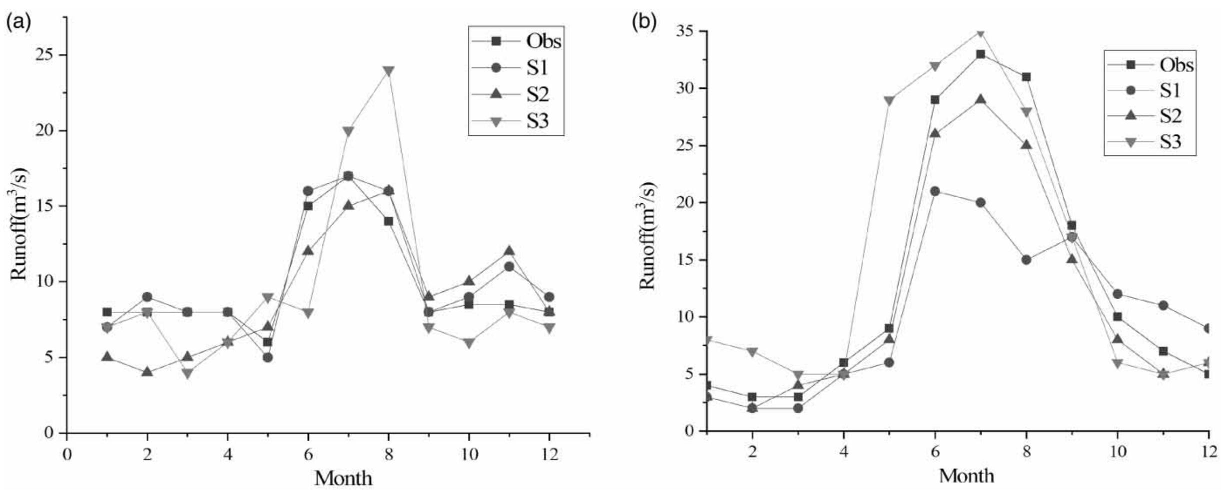


Figure 7 | Runoff at Wenquan station and Jinghe station under land change situations.

the increase in runoff during spring. An increase in rainfall will significantly increase the annual runoff.

(3) Meanwhile, the increase in cultivated land area in the Jing River and Bo River Basins is the key factor to reduce runoff. Grassland and forest land mainly provide the river flood season with more stability. Lakes and wetlands are very important for runoff regulation, which can reduce the flow in flood conditions and provide water for rivers in the dry season.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China [Grant Nos. 41661040 and U1803244]; Key Technologies Research and Development Program [Grant No. 2017YFC0404303]; Xinjiang Production and Construction Corps [Grant Nos. 2018CB023, CZ027204, 2018AB027, and 2018BC007]; and Shihezi University [Grant Nos. CXRC201801, RCZK2018C41, and RCZK2018C22].

REFERENCES

Ahlfeld, D. P. 2004 Nonlinear response of streamflow to groundwater pumping for a hydrologic streamflow model. *Advances in Water Resources* **27** (4), 349–360. doi:10.1016/j.advwatres.2004.02.006.

Albek, M., Öğütveren, Ü. B. & Albek, E. 2004 Hydrological modeling of Seydi Suyu watershed (Turkey) with HSPF. *Journal of Hydrology* **285** (1–4), 260–271. doi:10.1016/j.jhydrol.2003.09.002.

Barlow, P. M., Ahlfeld, D. P. & Dickerman, D. C. 2003 Conjunctive-management models for sustained yield of stream-aquifer systems. *Journal of Water Resources Planning and Management* **129** (1), 35–48. doi:10.1061/(asce)0733-9496(2003)129:1(35).

Change, I. C. 2007 The physical science basis. *Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change* 996. Cambridge University Press, Cambridge, UK.

Chen, H. P. & Sun, J. Q. 2009 How the 'Best' models project the future precipitation change in China. *Advances in Atmospheric Sciences* **26** (4), 773–782. doi:10.1007/s00376-009-8211-7.

Cheng, L., Xu, Z., Luo, R. & Mi, Y. 2009 SWAT application in arid and semi-arid region: a case study in the Kuye River Basin. *Geographical Research* **28** (1), 65–73. doi:10.11820/dlkxjz.2008.04.014.

Chiew, F., Whetton, P., McMahon, T. & Pittock, A. 1995 Simulation of the impacts of climate change on runoff and soil moisture in Australian catchments. *Journal of Hydrology* **167** (1–4), 121–147. doi:10.1016/0022-1694(94)02649-V.

Chuanji, C., Zhongming, H. & Zhonggui, W. 2004 Simulation methods of spring discharge variations in Karst area. In: *Proceedings of the 2nd Asia Pacific Association of Hydrology and Water Resources Conference* Vol. II, pp. 68–75. APHW, Kyoto.

Claessens, L., Hopkinson, C., Rastetter, E. & Vallino, J. 2006 Effect of historical changes in land use and climate on the water budget of an urbanizing watershed. *Water Resources Research* **42** (3). doi:10.1029/2005WR004131.

Ding, Y., Ren, G., Shi, G., Gong, P., Zheng, X., Zhai, P., Zhang, D., Zhao, Z., Wang, S. & Wang, H. 2006 National assessment report of climate change (I): climate change in China and its future trend. *Advances in Climate Change Research* **2** (1), 3–8. doi:10.1016/0360-1285(76)90008-3.

Fischer, G., van Velthuizen, H. T. & Nachtergaele, F. O. 2000 *Global Agro-Ecological Zones Assessment: Methodology and Results*. doi:10.1080/00063656609476139.

Fu, Y., Zang, W., Dong, F., Fu, M. & Zhang, J. 2016 Yield calculation of agricultural non-point source pollutants in Huntai River Basin based on SWAT model. *Transactions of the Chinese Society of Agricultural Engineering* **32** (8), 1–8. doi:10.11975/j.issn.1002-6819.2016.08.001.

Guang, Y., Dong, C., Xinlin, H., Aihua, L., Mingjie, Y. & Xiaolong, L. 2017 Land use change characteristics affected by water saving practices in Manas River Basin, China using Landsat satellite images. *International Journal of Agricultural and Biological Engineering* **10**, 123–133. doi:10.25165/j.ijabe.20171006.3435.

Jiang, D. B. & Fu, Y. H. 2012 Climate change over China with a 2°C global warming. *Chinese Journal of Atmospheric Sciences* **36** (2), 234–246.

Jiang, Z. H., Chen, W. L., Song, J. & Wang, J. 2009 Projection and evaluation of the precipitation extremes indices over China based on seven IPCC AR4 coupled climate models. *Chinese Journal of Atmospheric Sciences* **33**, 109–120.

Jing, Y. Q., Zhang, F. & Zhang, Y. 2016 Change and prediction of the land use/cover in Ebinur Lake Wetland Nature Reserve based on CA-Markov model. *Chinese Journal of Applied Ecology* **27** (11), 3649–3658. doi:10.13287/j.1001-9332.201611.027.

Lee, K. S. & Chung, E. S. 2007 Hydrological effects of climate change, groundwater withdrawal, and land use in a small Korean watershed. *Hydrological Processes* **21** (22), 3046–3056. doi:10.1002/hyp.6513.

Li, D. L., Wei, L. & Cai, Y. 2003 The facts and future trends of modern climate change in northwest China. *Journal of Glaciology and Geocryology. Advances in Climate Change Research* **25** (2), 135–142. doi:10.1007/BF02948883.

Li, Y., Wang, Y., Zheng, J. & Yang, M. 2019 Investigating spatial and temporal variation of hydrological processes in western

China driven by CMADS. *Water* **11** (3), 435. doi:10.3390/w11030435.

Liu, S., Yao, X., Guo, W., Junli, X. U., Shangguan, D., Wei, J., Bao, W. & Lizong, W. U. 2015 The contemporary glaciers in China based on the Second Chinese Glacier Inventory. *Acta Geographica Sinica* **70**, 3–16. doi:10.11821/dlxb201501001.

Lu, R. Y. & Fu, Y. H. 2010 Intensification of East Asian summer rain-fall interannual variability in the twenty-first century simulated by 12 CMIP3 coupled models. *Journal of Climate* **23** (12), 3316–3331. doi:10.1175/2009jcli3130.1.

Meng, X. Y., Xiao-Nan, J., Liu, Z. H., Xiao, J. C., Chen, X. & Wang, F. 2014 Research on improvement and application of snowmelt module in SWAT. *Journal of Natural Resources* **29** (3), 528–539. doi:10.11849/zrzyxb.2014.03.016.

Meng, X. Y., Wang, H., Cai, S. Y., Zhang, X. S., Leng, G. Y., Lei, X. H., Shi, C. X., Liu, S. Y. & Shang, Y. 2017a *The China Meteorological Assimilation Driving Datasets for the SWAT Model (CMADS) Application in China: A Case Study in Heihe River Basin*. doi:10.20944/preprints201612.0091.v2.

Meng, X., Wang, H. & Cai, S. 2017b Significance of the China meteorological assimilation driving datasets for the SWAT model (CMADS) of East Asia. *Water* **9** (10), 765. doi:10.3390/w9100765.

Meng, X., Wang, H., Lei, X., Cai, S., Wu, H., Ji, X. & Wang, J. 2017c Hydrological modeling in the Manas River Basin using soil and water assessment tool driven by CMADS. *Tehnički Vjesnik* **24** (2), 525–534. doi:10.17559/TV-20170108133334.

Meng, X., Wang, H., Wu, Y., Long, A., Wang, J., Shi, C. & Ji, X. 2017d Investigating spatiotemporal changes of the land-surface processes in Xinjiang using high-resolution CLM3.5 and CLDAS: soil temperature. *Scientific Reports* **7** (1), 13286. doi:10.1038/s41598-017-10665-8.

Minville, M., Brissette, F. & Leconte, R. 2009 Impacts and uncertainty of climate change on water resource management of the Peribonka River System (Canada). *Journal of Water Resources Planning and Management* **136** (3), 376–385. doi:10.1061/(asce)wr.1943-5452.0000041.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D. & Veith, T. L. 2007 Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE* **50** (3), 885–900. doi:10.13031/2013.23153.

Shi, Y. F., Shen, Y. P. & Hu, W. 2002 Preliminary discussion on the signal, influence and prospect of the transition of warm climate to warm and wet in Northwest China. *Journal of Glaciology and Geocryology* **24** (3), 219–226.

Singh, P. & Bengtsson, L. 2004 Hydrological sensitivity of a large Himalayan basin to climate change. *Hydrological Processes* **18** (13), 2363–2385. doi:10.1002/hyp.1468.

Sun, Y. & Ding, Y. H. 2010 A projection of future changes in summer precipitation and monsoon in East Asia. *Science China Earth Sciences* **53**, 284–300. doi:10.1007/s11430-009-0123-y.

Sun, J. Q., Wang, H. J., Yuan, W. & Chen, H. P. 2010 Spatial-temporal features of intense snowfall events in China and their possible change. *Journal of Geophysical Research* **115** (D16), 110. doi:10.1029/2009jd013541.

Wang, J. & Cui, Y. 2009 Simulation of regional evapotranspiration in different irrigation methods based on adapted SWAT distributed hydrological model. *Engineering Journal of Wuhan University* **42** (5), 605.

Wang, Z. G., Liu, C. M. & Huang, Y. B. 2003 Principle, structure and application of SWAT model. *Advances in Geography* **01**, 79–86.

Wang, Y.-J., Meng, X.-Y. & Liu, Z.-H. 2016 Snowmelt runoff analysis under generated climate change scenarios for the Juntanghu River Basin, in Xinjiang, China. *Tecnología y Ciencias del Agua* **7** (4), 41–54.

Wang, Y., Liu, Z., Yao, J. & Bayin, C. 2017 Effect of climate and land use change in Ebinur Lake Basin during the past five decades on hydrology and water resources. *Water Resources* **44** (2), 204–215. doi:10.1134/S0097807817020166.

Wang, Y., Liu, Z., Yao, J., Bayin, C. & Zhu, Y. 2018 Hydrological response of runoff to climate change of typical tributaries in Ebinur Lake Basin of Xinjiang. *Water Resources* **45** (2), 160–168. doi:10.1134/S0097807818020173.

Xu, Y., Xu, C. H., Gao, X. J. & Luo, Y. 2009 Projected changes in temperature and precipitation extremes over the Yangtze River basin of China in the 21st century. *Quaternary International* **208**, 444–452. doi:10.1016/j.quaint.2008.12.020.

Xu, X. B., Wang, Y. H. & Yao, J. Q. 2015 Climate change in the Ebinur Lake Basin and its impact on surface water resources. *Water Resources* **03**, 121–126.

Yang, J. J., Gao, X. H., Li, Q. J., Chen, Q. & Feng, S. C. 2013 SWAT model construction and uncertainty analysis on its parameters for the Huangshui River Basin. *Research of Soil and Water Conservation* **1** (20), 82–93.

Yang, G., Xue, L., He, X., Wang, C. & Long, A. 2017 Change in land use and evapotranspiration in the Manas River Basin, China with long-term water-saving measures. *Scientific Reports* **7**. doi:10.1038/s41598-017-18030-5.

Yang, G., Li, F., Chen, D., He, X., Xue, L. & Long, A. 2019a Assessment of changes in oasis scale and water management in the arid Manas River Basin, north western China. *Science of The Total Environment* **691**, 506–515. doi:10.1016/j.scitotenv.2019.07.143.

Yang, G., Tian, L., Li, X., He, X., Gao, Y., Li, F., Xue, L. & Li, P. 2019b Numerical assessment of the effect of water-saving irrigation on the water cycle at the Manas River Basin oasis, China. *Science of The Total Environment* **707**, 135587. doi:10.1016/j.scitotenv.2019.135587.

Ye, M., Xu, H. L. & Ren, M. 2012 Preliminary study on reasonable time of ecological water transport in the lower reaches of Tarim River. *Arid Zone Research* **29** (5), 907–912.

Zhang, Y. H. 2005 Research progress of SWAT model and its application. *Advances in Geography* **05**, 123–132.

Zhao, W. & Cheng, G. 2002 Review of several problems on the study of eco-hydrological processes in arid zones. *Chinese Science Bulletin* **47** (5), 353–360. doi:10.1360/02tb9084.

Zhou, M. Z., Zhou, G. S., Lu, X. M., Zhou, L. & Ji, Y. H. 2019 Projection of temperature and precipitation changes over China under global warming of 1.5 and 2°C. *Acta Meteorologica Sinica* **77** (4), 728–744.

Zuo, D. P. & Xu, Z. X. 2012 Distributed simulation of monthly runoff in Weihe River Basin based on SWAT model and SUFI-2 algorithm. *Journal of Beijing Normal University (Natural Science)* **5**, 490–496.

First received 21 February 2020; accepted in revised form 18 May 2020. Available online 26 June 2020