



# Effect of climate change on water resources in the Yuanshui River Basin: a SWAT model assessment

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## Abstract

The Yuanshui River Basin is one of the most important river basins ensuring food production and livelihoods in the Hunan and Guizhou Provinces of China. Based on digital elevation model, land use, soil, and meteorological data, the soil and water assessment tool was used to analyze the response of water resources in the basin to climate change. Specifically, the monthly runoff from the Yuanshui River Basin was simulated. Runoff measurements from the 1961–1990 series were used to calibrate model parameters, and measurements from the 1991–2010 series were used for model validation. The Nash–Sutcliffe efficiency coefficient, correlation coefficient, and water balance error were used to evaluate the simulation results; the values obtained for these parameters were 0.925, 0.929, and 2.0%, respectively, indicating that the established model can be applied successfully to runoff simulations. To evaluate the effects of climate change and human activities on runoff, 24 different climate scenarios were modeled. By comparing the model simulation results with the baseline scenario, the effects of climate change were analyzed by year, during the dry season, and during extremely dry conditions. The results showed that runoff decreased with increasing air temperature and decreasing precipitation, and that the effects of rainfall on runoff were greater than those of air temperature. Under the same baseline conditions, the effects of climate change on runoff were most pronounced during extremely dry months.

**Keywords** Climate change · Water resources · SWAT model · Yuanshui River basin

## Introduction

Runoff simulations play an important role in the study of the water cycle. Simulation data can serve as the foundation for solving many hydrological problems. In recent years, a representative hydrological model—the soil and water assessment tool (SWAT)—has been applied to different watersheds globally. Due to its successful implementation, the SWAT has been regarded as an effective tool for evaluating the impact of climate change on the water cycle. For example, Bajracharya et al. (Bajracharya et al. 2018) assessed the impact of climate change on the

hydrological regime in the Kaligandaki Basin using the SWAT model. The results from their study showed that climate change will cause a significant hydrological regime change in this basin, and that discharge at the outline of this basin may increase by 50% by the end of the twenty-first century. Navarro et al. (Navarro et al. 2018) quantified the effects of climate change on the Odense Fjord catchment in Denmark. Their research revealed that local river discharge will likely increase under high-emission scenarios, while runoff will likely remain stable under moderate-emission scenarios. Ficklin et al. (Ficklin et al. 2009) assessed the sensitivity of the San Joaquin watershed in the USA to climate change, specifically with regard to climate change effects on meteorological factors and river discharge in the watershed. Their results indicated that this watershed is quite sensitive to climate change. Chaplot et al. (Chaplot, 2007) utilized the SWAT to analyze the effect of climate change on water and soil resources in two agriculture watersheds. Their results revealed that precipitation has a greater effect on water resources than temperature and CO<sub>2</sub> emissions. Moreover,

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many other studies for water resource assessment have been conducted using the SWAT model (Maite Meaurio et al. 2015; Hojat et al. 2016; Kim et al. 2012; Josh et al. 2009; Tuan & Hatim, 2015; Darren et al. 2012).

In China, extensive research has been conducted using the SWAT model to assess the response of water resources in many typical watersheds to climate change. Lin et al. (Lin et al. 2015) analyzed the impacts of land use change on catchment runoff in the JinJiang catchment. Their results demonstrated that changes in the quantity of runoff varied among different time scales; annual runoff had the smallest amount of variability, while daily runoff had the largest amount of variability. Lotz et al. (Lotez et al. 2017) detected factors that may affect river runoff in the Dongting Lake Basin. The results of their study revealed that, under the same rainfall conditions, surface runoff is primarily affected by land cover, and groundwater flow is closely related to the slope angle of the site. Song et al. (Lirong & Jianyun, 2012) assessed the impact of climate change on runoff in the Beijiang River Basin using the SWAT model and noted that precipitation and temperature have the opposite effect on river discharge in this watershed. Chen et al. (Chen et al. 2009) analyzed the impacts of land use change on Xitiao Basin; their results demonstrated that changes in land use may increase total runoff and peak discharge in this watershed. Similar research using the SWAT model has been conducted in many other areas with diverse types of climate, topography, and land cover (Junying & Baolin, 2010; Xuan et al., 2010; Zhang & Chen, 2007; Zhu & Wanchang, 2005; Xiaofeng, 2009). These studies justified the applicability of the SWAT model to watersheds in China of different types and scales. Furthermore, some researchers analyzed the effect of climate change on water resources in the Yuanjiang River Basin. Chen et al. indicated that the regional runoff is very sensitive to changes in rainfall and temperature in the Yuanjiang River (Xi et al. 2003). Cheng et al. analyzed the contribution of climate change and human activities on the variation in runoff in the Yuanjiang River Basin and showed that climate change was the main contributor to runoff variation (Junxiang et al. 2016).

While previous studies mainly focused on one or two factors influencing runoff quantity, this study conducted a more comprehensive assessment of factors affecting runoff using the SWAT model to simulate monthly runoff in the Yuanshui River Basin. Additionally, the study evaluated the potential responses of runoff to climate change, specifically the response of runoff to 24 different climate scenarios following changes in simulated temperature and precipitation. The findings of this study will be informative and useful for climate change adaptation efforts in the Yuanshui River Basin and for understanding the general impacts of climate change on water resources in similar watersheds.

## SWAT model

### Development and characteristics of the SWAT model

In the early 1990s, the US Department of Agriculture's Agriculture Research Service integrated two models—the simulator for water resources in rural basins and routing outputs to the outlet models—to obtain the SWAT model. This model is very powerful and has been mainly used to evaluate the long-term effects of human activities and land use management policies on the river basin water cycle. The SWAT model has also been applied to work aimed at assessing the transport of sediments and agricultural pollution within river basins.

The SWAT model has the following characteristics. (1) It is a versatile, physical concept-based, combination model that has a strong physical foundation and considers the effects of weather, topography, soil properties, vegetation, and human land management on the target area's hydrology. The model is flexible in that it can handle a variety of complex application conditions. (2) The SWAT model is well suited for long temporal-scale hydrological cycle and material cycle research, and while it can also be used to generate short-term hydrological forecasts, the model tends to perform better in long-term applications (Kliment et al. 2008). (3) The SWAT model is suitable for macro-scale simulations. (4) In addition to water cycle simulations, the model can be used to simulate the dynamics of soil erosion, nutrient transport, pesticides, pathogens, and other substances in river basins; such a feat can be achieved by modeling water as the carrier. (5) The SWAT model is capable of dealing with missing data; it has a strong model database. (6) This model acts as a distributed computing machine wherein the research area is divided into sub-basins, and the sub-basins can be further divided into hydrological response units (HRUs), which are useful for detailed investigations. These units are discussed in more detail below.

### Principle of the SWAT model

The SWAT model is a watershed-scale model. It can predict the long-term effects of land management on water, sediments, and chemicals in large basins under complicated and variable soil types, land use modes, and management implementation measures. As mentioned above, when the SWAT model is run, the model divides the study basin into a plurality of sub-basins. Within each sub-basin, according to the land use mode, soil type, and management measures, the domain can be divided further into different HRUs (Pang, 2007); an HRU is the minimum perceptible calculation unit. The hydrologic process is simulated independently on each HRU, and then the hydrologic budget is summarized at the sub-basin scale (Feng et al. 2008; Tongzhao & Jinyu, 2009).

## Research area and data preparation

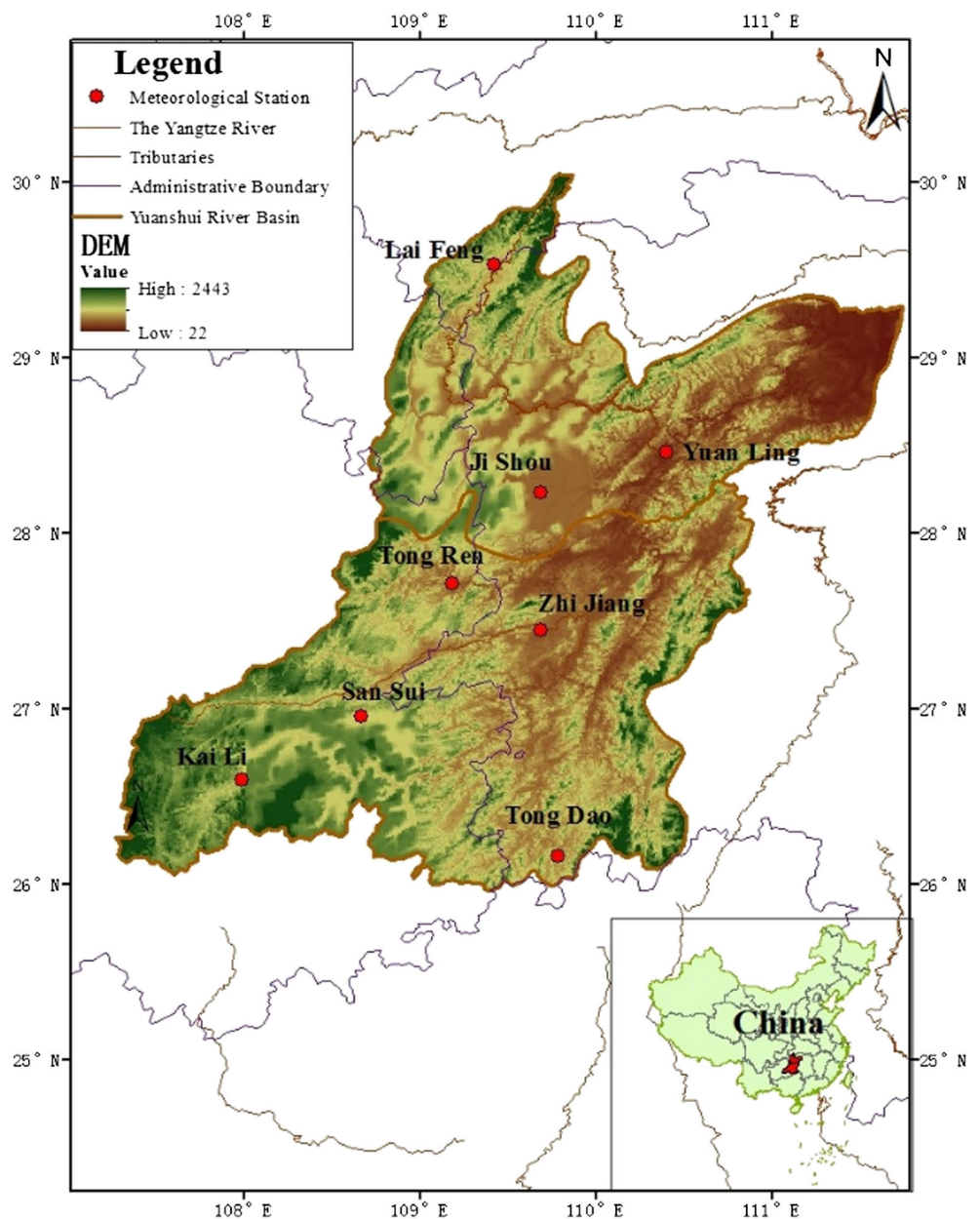
### Study area

The Yuanshui River is one of four major rivers that drain into the Dongting Lake, the second-largest freshwater lake in China. The length of the river is 1022 km; it flows through 21 counties and its watershed area is 89,000 km<sup>2</sup>. The river can be divided into two source areas—the north source area, located in the vicinity of Pingyue Mountain of Majiang County, Guizhou Province, and the south source area, containing the cloud mountains of Duyun County, Guizhou Province. After the confluence of the two source area tributaries at Yuanling,

the waters continue to flow east through the Hunan Province to Changde before emptying into Dongting Lake. Past Dongting Lake, the waters flow into the Yangtze River, the longest river in China.

The Yuanshui River Basin is in a sub-tropical monsoon climate region, where the weather is dry and cold in winter, and warm and rainy in summer. The annual average temperature ranges from 14.3 to 17.2 °C; while the temperature in the upper reaches is lower, that in the middle and lower reaches is higher. The local temperature shows an increasing trend from west to east. The average annual precipitation is between 1090 and 1506 mm. The distribution of precipitation is uneven during the year, with the amount of precipitation from April to October accounting

**Fig. 1** Location of the study area and meteorological stations selected for the study



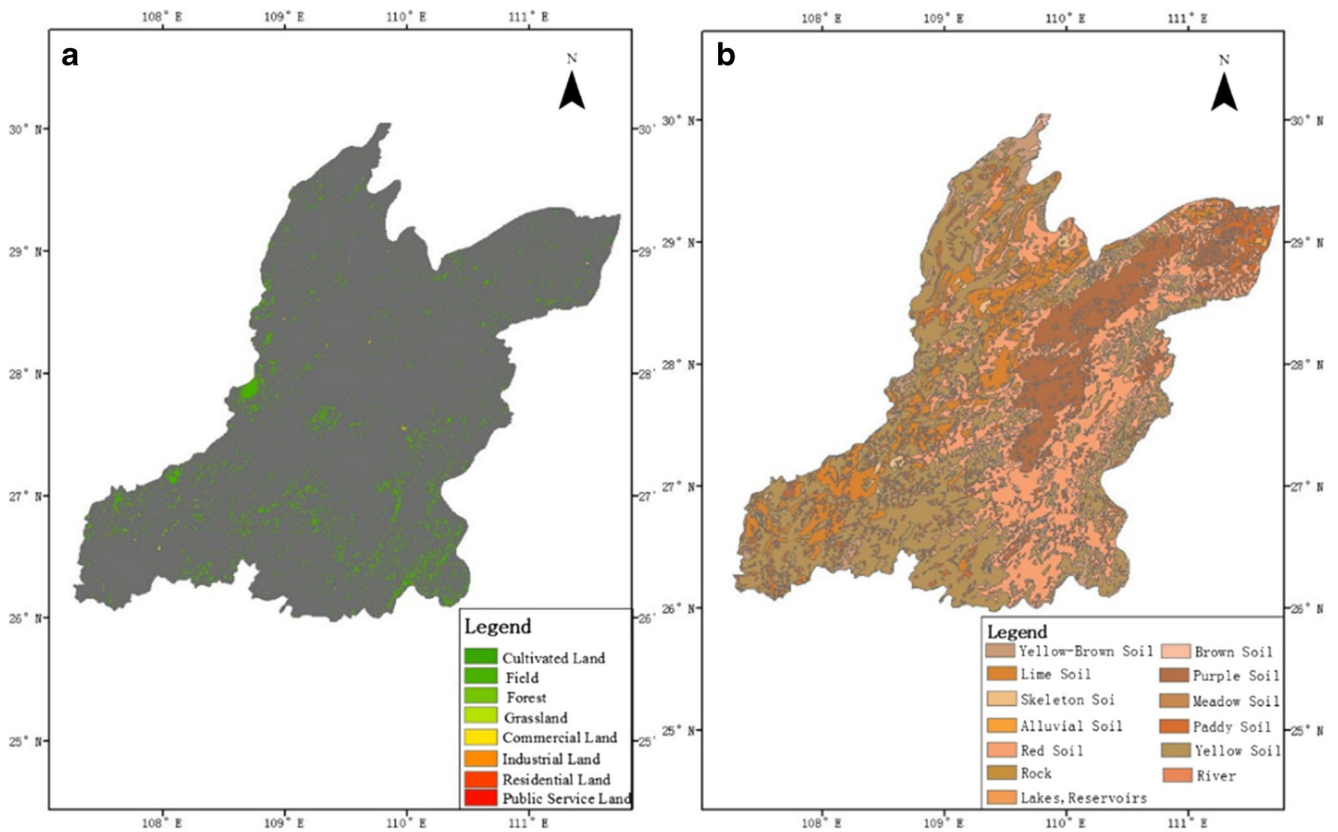


Fig. 2 Yuanshui River Basin a land use and b soil type classification maps

for 66% of the total precipitation amount for the entire year and that from December to February accounting for only 9%. The location of the Yuanshui watershed and selected meteorological stations are shown in Fig. 1.

**Data preparation**

The data and data sources used for establishing the SWAT model in this study were as follows: 30-m-resolution digital elevation model (DEM), land use map, 1:100,000 soil distribution map, distributed daily precipitation from 1961 to 2010, daily maximum/minimum temperatures, relative humidity, solar radiation amounts, and wind speeds. The meteorological data were collected from eight meteorological observation sites (Laifeng, Jishou, Yuanling, Tongren, Zhijiang, Kaili, Sansui, Tongdao).

**Land use data processing**

Before the establishment of the SWAT model, the land use categories were converted to codes that the model could identify through land use reclassification (Lin & Xingwei, 2008). The results for this step are shown in Fig. 2a and Table 1.

**Soil type data processing**

In the SWAT model, soil data represent one of the main input parameters, and the quality of these data can have a serious impact on the simulation results (Huaibin et al. 2007). Therefore, in this paper, the soil types were reclassified first, after which the Soil-Plant-Air-Water model was used to calculate the soil properties and the soil database was established. The soil types were classified as shown in Fig. 2b and Table 2.

**Table 1** Yuanshui River Basin land use classification

Number	Land use type	SWAT code	Area (10,000 km <sup>2</sup> )	Area ratio (%)
1	Paddy field	RICE	0.887	10.163
2	Dry land	AGRL	0.843	9.657
3	Forest	FRSD	6.037	69.150
4	Grassland	PAST	0.858	9.828
5	Water	WATR	0.058	0.667
6	Others	URMD	0.047	0.535



**Table 2** Yuanshui River Basin soil classification

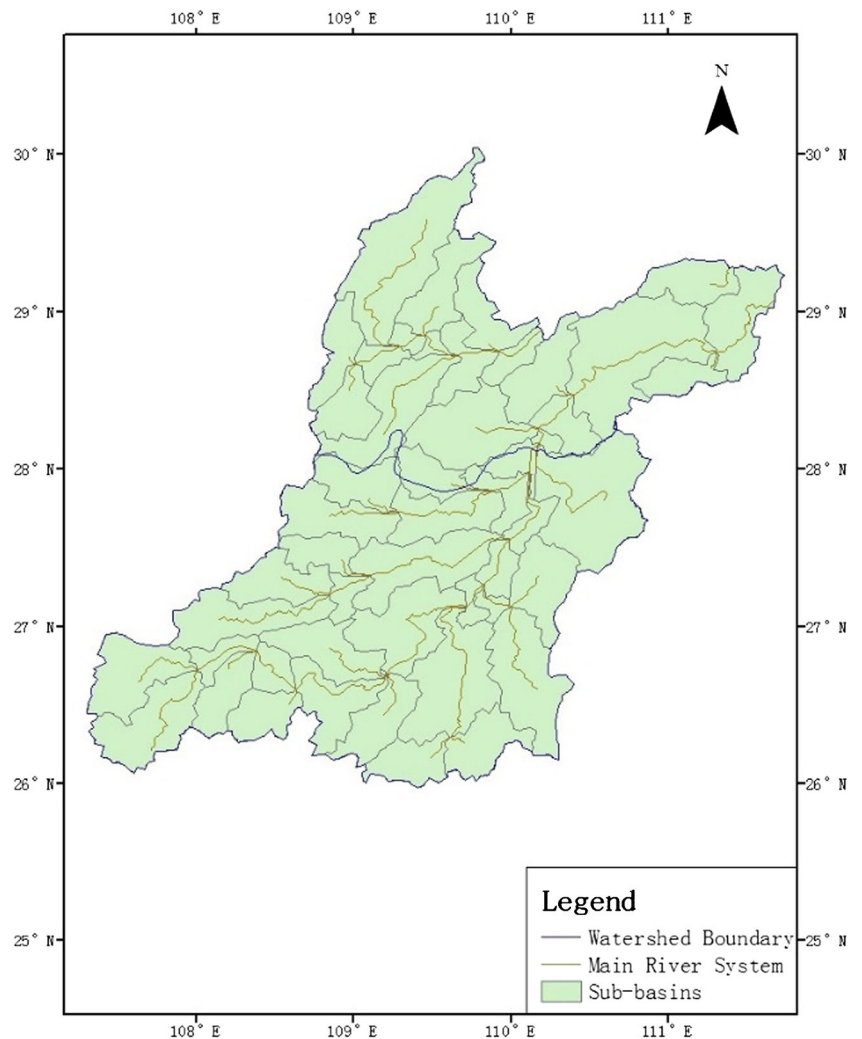
Number	Soil type	Area (10,000 km <sup>2</sup> )	Area ratio (%)	Number	Soil type	Area (10,000 km <sup>2</sup> )	Area ratio (%)
1	Yellow brown	0.295	3.379	9	Swamp soil	0.003	0.036
2	Brown	0.011	0.127	10	Paddy soil	0.896	10.264
3	Lime soil	1.105	12.662	11	Red soil	2.437	27.911
4	Purple soil	0.837	9.593	12	Yellow soil	3.059	35.036
5	Stony soil	0.006	0.072	13	Rock	0.004	0.048
6	Skeleton soil	0.047	0.537	14	Lakes and reservoirs	0.008	0.096
7	Mountain meadow soil	0.008	0.096	15	River	0.012	0.133
8	Alluvial soil	0.001	0.012				

**Weather generator**

Meteorological data are of great importance in water cycle modeling. Because of various reasons, the meteorological observation data described above were not sufficient to model the entire basin, and thus, a weather generator was used to make up for the lack of meteorological data. The weather

generator (WXGEN) model can generate climatic data or fill in gaps in measured records. Therefore, it was necessary to set up weather database information before the SWAT model was established. The main input data included the daily average air pressure, daily average wind speed, daily average temperature, daily maximum/minimum temperature, daily average relative humidity, daily precipitation, and daily minimum/

**Fig. 3** Yuanshui watershed sub-divisions



**Table 3** The main parameters used in the Yuanshui River Basin analysis

Variable	Parameter description	Range	Units	Final parameter value
CN2	Runoff curve number	$\pm 0.2$	–	+ 0.16
SOL_AWC	Available water capacity of the soil layer	$\pm 0.1$	mm/mm	+ 0.04
ESCO	Soil evaporation compensation coefficient	0~1	–	0.94
GW_REVAP	Shallow groundwater re-evaporation coefficient	0.02~0.2	–	0.06
GW_DELAY	Groundwater delay days	0~500	Days	65
ALPHA_BF	Base flow regression coefficient	0~1	Days	0.18
SOL_K	Soil saturated hydraulic conductivity	$\pm 0.4$	mm/h	– 0.16
GWQMN	Shallow groundwater runoff coefficient	0~500	–	0.2

maximum evaporation. The necessary meteorological data for the SWAT model, such as the solar radiation and dew-point temperature, were then produced by the weather generator automatically. Details of weather generator equations can be seen in the theoretical documentation of SWAT (Arnold et al., 2009).

## Establishment and analysis of the SWAT model

### Establishment of the SWAT model

The SWAT model of the Yuanshui River Basin was established using DEM, land use map, soil type map, and meteorological data, which were input into the model; the river network was generated by the DEM data. Among the actual hydrological stations available, the Taoyuan station was selected to control the outlet of the river basin, and the area of the watershed that was modeled was 8.73 million km<sup>2</sup>. According to the distribution of the water system, the watershed was divided into sub-basins. Then, according to the land use, soil type, and

slope, each sub-basin was further divided into HRUs. In this paper, the threshold values of land use, soil type, and slope area were set as 5, 10, and 20%, respectively. This means that an area where the land use type was less than 5% would be ignored, and so forth. The area was allocated according to the area ratio of the rest. Following these steps, the Yuanshui River Basin was divided into 47 sub-basins (Fig. 3) and 275 HRUs. Finally, the model was run with the generated precipitation and air temperature data.

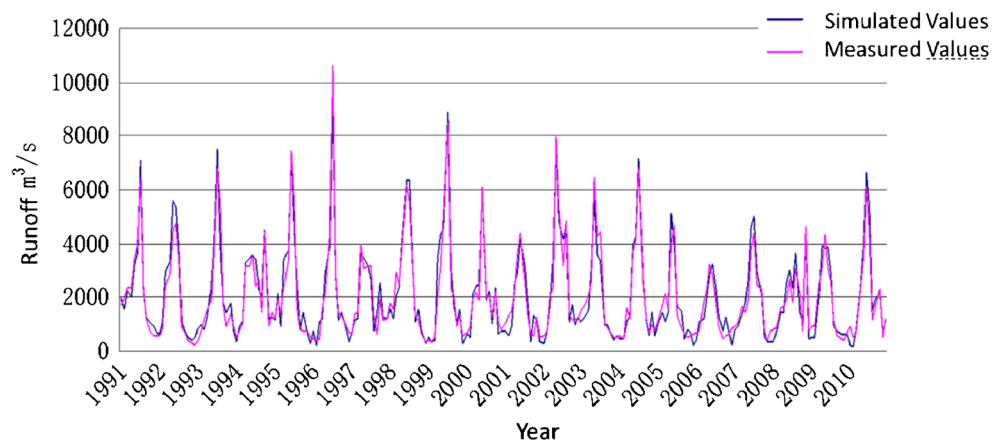
### Parameter calibration for the SWAT model

Many parameters can affect the runoff yield simulations. In this paper, the runoff curve number, soil layer available water capacity, and other key parameters were selected for the analysis. Additionally, the monthly runoff at Taoyuan station from 1961 to 1990 was selected for model calibration. The main parameters used are listed in Table 3.

### Validation of the SWAT model

To assess the validity of the model for the study area, this study used the Nash–Sutcliffe efficiency coefficient,

**Fig. 4** Yuanshui River Basin monthly runoff simulation results and verification with measured data



**Table 4** The simulation results verify the monthly runoff rate and regularity

Simulation period	Year	Nash–Sutcliffe coefficient	Correlation coefficient	Water balance error (%)
Calibration period	1961~1990	0.923	0.933	6.9
Validation period	1991~2010	0.925	0.929	2.0

correlation coefficient, and water balance error to evaluate the simulation results.

The Nash–Sutcliffe coefficient was computed as follows:

$$E_{ns} = 1 - \frac{\sum_{i=1}^n (Q_{o,i} - Q_{m,i})^2}{\sum_{i=1}^n (Q_{o,i} - \bar{Q}_o)^2} \tag{1}$$

The correlation coefficient was computed as follows:

$$r^2 = \frac{\left[ \sum_{i=1}^n (Q_{o,i} - \bar{Q}_o)(Q_{m,i} - \bar{Q}_m) \right]^2}{\sum_{i=1}^n (Q_{o,i} - \bar{Q}_o)^2 \sum_{i=1}^n (Q_{m,i} - \bar{Q}_m)^2} \tag{2}$$

Additionally, the water balance error was computed as follows:

$$RE = \frac{Q_m - Q_o}{Q_o} \times 100\% \tag{3}$$

In the above formulas,  $Q_{o,i}$  is the measured value;  $Q_{m,i}$  is the simulation value;  $\bar{Q}_o$  is the mean measured value; and  $\bar{Q}_m$  is the mean simulation value.

Higher values of the Nash–Sutcliffe efficiency coefficient and correlation coefficient indicate higher simulation efficiency, and water balance errors closer to 0 indicate better model performance. Usually,  $E_{ns} > 0.5$  is used as an evaluation standard for runoff simulation efficiency (Chunshu & Luo, 2006); similarly,  $r^2 > 0.6$  can be used as an evaluation standard to indicate agreement between simulation values and measured values (Zhihong et al. 2009).

**Table 5** Sensitivity analysis of monthly runoff to climate change (%)

$\Delta T$ (°C)	$\Delta P$				
	-20%	-10%	0	10%	20%
0	-29.17	-15.93	0	16.24	32.47
0.5	-33.80	-18.02	-2.15	12.14	31.98
1	-35.11	-19.42	-3.61	12.54	28.71
1.5	-36.15	-20.52	-4.74	11.40	27.68
2	-37.72	-22.23	-6.54	9.55	25.88

### Analysis of the SWAT model results

The comparison results for the measured and simulated monthly runoff data from 1991 to 2010 are shown in Fig. 4. Additionally, the Nash–Sutcliffe efficiency coefficient, correlation coefficient, and water balance error, which were used to evaluate the model, are presented in Table 4.

The simulated monthly runoff values were in good agreement with the experimental data from 1991 to 2010 (Fig. 4); therefore, we conclude that the simulation accuracy was good. Table 4 shows that  $E_{ns}$ ,  $r^2$ , and  $RE$  reached 0.923, 0.933, and 6.9%, respectively, during the calibration period, whereas these three factors reached 0.925, 0.929, and 2.0%, respectively, during the validation period. Overall, these findings indicate that the simulation results were consistent with the measured values, and that the SWAT model can be used successfully for water resource research and management in the basin.

### Impacts of climate change on water resources

In this study, using an arbitrary scene setting method, 24 future climate change scenarios were evaluated for the Yuanshui River Basin with the SWAT model; this involved assessing changes in the monthly runoff for temperature increases amounting to 0, 0.5, 1, 1.5, and 2 °C, and for variations in precipitation amounting to -20, -10, 0, 10, and 20% (the 0 °C, 0% case was not considered as a climate change scenario; instead, it was used as the baseline scenario for comparisons) (Tao et al. 2000). Simulation results for the runoff throughout the year, for the dry season (September to the following April), and for the extremely dry period (December–February) under the climate change scenarios

**Table 6** Sensitivity analysis of dry season runoff to climate change (%)

$\Delta T$ (°C)	$\Delta P$				
	-20%	-10%	0	10%	20%
0	-30.16	-16.96	0	17.73	35.67
0.5	-35.71	-19.54	-2.87	9.89	29.26
1	-36.72	-20.73	-4.23	13.15	30.78
1.5	-37.89	-21.96	-5.49	11.81	29.62
2	-39.68	-24.14	-8.02	9.00	26.72

**Table 7** Sensitivity analysis of the extremely dry period runoff to climate change (%)

$\Delta T$ ( $^{\circ}\text{C}$ )	$\Delta P$				
	-20%	-10%	0	10%	20%
0	-32.55	-18.02	0	18.97	38.78
0.5	-37.90	-21.14	-3.89	23.34	23.61
1	-38.79	-22.55	-5.52	13.01	32.05
1.5	-39.84	-23.62	-6.50	11.84	31.01
2	-41.58	-26.13	-10.06	7.87	26.61

relative to the baseline scenario, are listed in Tables 5, 6, and 7, respectively.

The results in Tables 5, 6, and 7 show that future changes in climate could have substantial effects on the monthly runoff in the Yuanshui River Basin. When the temperature remained unchanged and the precipitation increased by 20%, the predicted average monthly runoff was the highest. On the other hand, when the temperature increased by 2  $^{\circ}\text{C}$  and precipitation decreased by 20%, the predicted average monthly runoff was the lowest. In general, the influence of precipitation on runoff was higher than that of air temperature and increases in temperature or decreases in precipitation led to decreases in runoff. Under the same conditions, the effects of climate change on runoff during the extremely dry months were the most pronounced.

According to the outputs simulated by different climate models, the temperature in the Yuanshui River Basin will increase by 1.5  $^{\circ}\text{C}$  in the near future, leading to decreases in runoff. The outputs also indicate that, although the total precipitation will not change significantly, the precipitation in the wet season will increase and that in the dry season will decrease. Combining this finding with the results in this study, the frequency and intensity of droughts and floods will increase in the future, thus affecting the normal production and life of residents. Therefore, adaptive water resource management is urgently required in this basin.

## Conclusions

By incorporating DEM, land use, soil type, and meteorological data, the SWAT model was applied to the Yuanshui River Basin to simulate the monthly runoff in this region. Comparisons between the simulated and measured data for 1961–1990 showed that the SWAT model performance was good for this basin. Furthermore, the Nash–Sutcliffe efficiency coefficient, correlation coefficient, and water balance error values all showed that the model results were valid and that this model could be used for water resource research and management. The established SWAT model was used to

investigate the effects of future climate changes (i.e., temperature and precipitation changes) on runoff in the basin. The results showed that, in general, the influence of precipitation on runoff was higher than that of air temperature. Increases in temperature or decreases in precipitation will lead to decreases in runoff. The most pronounced effects of climate change on runoff were observed during the extremely dry months. The results also indicated that future changes in temperature, ranging from 0.5 to 2  $^{\circ}\text{C}$ , and in precipitation, ranging from 10 to 20%, could have substantial effects on the monthly runoff in the Yuanshui River Basin. Given this functionality of the SWAT model, many water resource issues in this basin can be addressed using this model. In the future, the frequency and intensity of droughts and floods in the Yuanshui River Basin will increase due to climate change, significantly affecting the basin's water resources. Therefore, the findings of this study will be valuable for climate change adaptation efforts in the Yuanshui River Basin and for understanding the general impacts of climate change on water resources in Asia. Furthermore, the research results could significantly contribute to the development of adaptive water resource management measures for this river basin.

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