Response of runoff in the upper reaches of the Minjiang River to climate change

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ABSTRACT

Climate change affects the water cycle in different regions. The response of annual runoff and seasonal distribution to climate change in the upper reaches of the Minjiang River during 2021–2050 was studied by coupling the Statistical Downscaling Model (SDSM) and the Soil and Water Assessment Tool (SWAT). This model was driven by the second-generation Canadian Earth System Model (CanESM2) under RCP2.6, RCP4.5, and RCP8.5 scenarios. The results show that the runoff in the upper reaches of the Minjiang River has a unique response to climate change. The maximum and minimum temperatures will increase with the increase in emissions, especially in December–January. The daily precipitation shows an upward trend, especially in July–August in the RCP4.5 scenario. The annual runoff shows an upward trend with the increase in emissions. Compared with the current increase of 13–26%, the most prominent period is November–April. Because the study area covers high mountains and gorge landforms, the altitude difference is great, and the influence of evapotranspiration and snow melting processes is more prominent, causing the monthly runoff to decrease in June–July with an increase in precipitation. From April to May, precipitation decreased while runoff increased.

Key words: change of runoff, Minjiang river, soil and water assessment tool, statistical downscaling model, typical concentration paths

HIGHLIGHTS

• The first study on annual runoff, seasonal distribution, and primary tributaries of the upper Yangtze River response to climate change in the Minjiang River upper reaches.
• Analysis of differences among the Minjiang upper reaches and other upper reaches of the Yangtze River.
• Runoff variation causes about seasons and three typical concentration paths.
• Coupling SDSM and SWAT analyzes application.

INTRODUCTION

The fifth Intergovernmental Panel on Climate Change (IPCC) assessment report pointed out that the average temperature has risen by 0.65–1.06 °C in the past 120 years (Qin & Thomas 2014). The global climate has been gradually warming. Climate change alters the original water cycle and changes the distribution and the total number of water resources, thereby increasing extreme hydrological events. The prediction of the water cycle and water resource fluctuations is one of the primary components in alleviating the impact of climate change on water resources (Githui et al. 2009; Moss et al. 2010; Taylor et al. 2012; Shrestha et al. 2017). The response of water resources to future climate change usually follows the future climate scenario settings, such as hydrological simulation of future events (Chen et al. 2014; Yang et al. 2015). Researchers worldwide have carried out several studies on this issue. Wang et al. (2015) showed that under the IPCC scenarios A2 and B2, the precipitation and runoff would be reduced in the Yangtze River. Su et al. (2017) analyzed the runoff changes in the Yangtze River using CMIP5 climate models. The results show that the runoff will increase due to increased precipitation. Birkinshaw et al. (2017) showed that under the RCP8.5 typical concentration paths, the precipitation in the upper reaches of the Three Gorges reservoir would increase by 4.1% between 2041 and 2070. However, due to the apparent increase in evapotranspiration caused, the inflow of the Three Gorges reservoir...
will decrease by 11.1%. Yang et al. (2019a, 2019b) showed that the runoff in the upper reaches of the Yangtze River would increase by 11.33–64.08% in winter and 8.64–40.97% in summer by using CMIP5 climate models. Chen et al. (2017) showed that the summer, spring, and annual runoff in the upper reaches of the Yangtze River would show an upward trend under the climate scenario, whereas the autumn and winter runoff will show a downward trend. The increase in runoff will increase the frequency and intensity of flood disasters, especially in summer. Yang et al. (2019a, 2019b) showed that runoff in the upper reaches of the Yangtze River shows a noticeable increase in the CanESM2 model. However, a downward trend is observed in the NorESM1-M model.

In general, annual and seasonal variations in the runoff in the same watershed are different. The uncertainty in research results is affected by the climate model, the hydrological model, the analysis period, and the station data. In addition, previous studies mainly focused on the total amount of water resources in the Yangtze River where the study area is located. The responses of different sub-basins in the upper reaches to regional climate change are different (Wang et al. 2015), but there are only a few studies on different sub-basins. Previous studies show that runoff changes are mainly affected by temperature and rainfall, and the changes in temperature and precipitation have strong spatial differences (Gu et al. 2015; Yang et al. 2019a, 2019b). For example, Luo et al. (2019) showed that precipitation and temperature in the western source of the Yangtze River were the most important climatic factors affecting the runoff during 1961–2016. In summer, the increases in precipitation, the annual average minimum temperature, and the amount of glacier and snowmelt affect the runoff. The apparent increase in spring runoff was related to the increase of the snow melting and the increase in the amount of snow melted due to temperature rise. In summary, the temporal and spatial differences in temperature and precipitation give the runoff unique characteristics. Previous studies mainly focused on analyzing annual runoff using multiple modes and multiple scenarios, and the studies that focus on the response of seasonal distribution of runoff to climate change are relatively scarce.

The Minjiang River Basin is the largest tributary of the upper reaches of the Yangtze River. The upper reaches of the Minjiang River are above Dujiangyan, which is the source of domestic and production water in the Chengdu Plain. The upper reaches of the Minjiang River have a large elevation difference, fragile geological conditions, and complex climate conditions. Climate change makes the difference between water demand and supply more obvious. Second, the Minjiang River is the ecological barrier of the Yangtze River. Further study of its future ecological environmental changes can provide a theoretical reference for constructing an ecological barrier. Furthermore, some changes in the Minjiang River Basin in recent years are prominent (Chen et al. 2019a, 2019b). Research on the change under the influence of climate change can provide useful data for hydropower energy development and flood control planning under climate change. In this study, the Statistical Downscaling Model (SDSM) is used to analyze the daily series of temperature and precipitation of the second-generation Canadian Earth System Model (CanESM2) in the future climate scenarios (RCP2.6, RCP4.5, and RCP8.5), and the possible changes under future climate scenarios in CMIP5 were analyzed. The Soil and Water Assessment Tool (SWAT) was used to simulate the runoff, and the sensitivity parameters were calibrated using SWAT-CUP. Finally, the SWAT derived by the temperature and precipitation series was used to analyze runoff changes in future climate scenarios. The possible trends of drought and flood events in the study area are analyzed by comparing the historical runoff data.

MATERIALS AND METHODOLOGY

Study area

The Minjiang River Basin is 790 km long, with a fall of 3,560 m and a drainage area of 135,881 km². The Minjiang River Basin originates from the Aba Prefecture of Sichuan Province and is rich in hydropower resources. According to the geographical characteristics of the mainstream, Dujiangyan City is upstream from the source of the basin, and hydropower generation is mostly concentrated upstream.

The upper reaches of the Minjiang River are located between 102°59’ E and 104°14’ E, and 26°33’ N and 33°16’ N, covering an area of 23,000 km² (as shown in Figure 1). The average annual precipitation in the upper reaches of the Minjiang River is 476 m³/s. The ecological environment has been gradually degrading in recent decades,
seriously threatening infrastructure security in the valley. The forest coverage is reduced, the ecological function is degraded, the soil and water loss is severe, and natural disasters occur frequently.

**Data sources**

The daily temperature and precipitation data from different national weather stations were obtained from [http://data.cma.cn/](http://data.cma.cn/) (Table 1). The data period is 1961–2016, which has passed strict quality control. The daily average discharge of the Zipingpu hydrological station at the outlet section of the study area from 1961 to 2016 and the daily rainfall (Table 2) was selected for the study, and data were obtained from the hydrological yearbook.

Through literature research, it was understood that the CanESM2 model has a high spatial correlation coefficient in Southwest China, where the upper reaches of the Minjiang River are located \((r = 0.76)\) (Sun et al. 2015; Zhan et al. 2017). Because the CanESM2 model can output more accurate large-scale variables, such as the upper atmospheric field and atmospheric circulation (Zhan et al. 2017), the spatial resolution of output products is 2.5° × 2.5° and lacks regional climate information. We need to downscale the large-scale variables to obtain the information of the regional scale. The SDSM is a more accurate and widely used statistical downscaling model (Huang et al. 2008). NCEP reanalysis data were used in the downscaling analysis with SDSM. The NCEP data resolution is 2.5° × 2.5°, and each grid has 26 meteorological factors, including temperature, humidity, wind speed, and divergence. CanESM2 simulation results and NCEP reanalysis data were obtained from [http://climate-scenarios.canada.ca/?page=pred-canem2](http://climate-scenarios.canada.ca/?page=pred-canem2). Nine grids corresponding to the study area are selected, including the grid where the basin is located and eight adjacent grids.

**Figure 1** | Water system in the upper reaches of the Minjiang River.

**Table 1 | Basic information regarding meteorological stations**

| Station  | Longitude (°E) | Latitude (°N) | Altitude (m) |
|----------|----------------|---------------|--------------|
| Songpan  | 103.57         | 32.65         | 2,850        |
| Heishui  | 102.98         | 32.08         | 2,400        |
| Maoxian  | 103.85         | 31.68         | 1,591        |
| Wenchuan | 103.38         | 31.47         | 1,326        |
| Lixian   | 103.17         | 31.43         | 1,885        |
The SWAT model's hydrological data calibrated and verified show the daily runoff at the Zipingpu hydrological station in the study area from 1967 to 1987. The sensitivity parameters were calibrated using SWAT-CUP (Abbaspour 2007), an official parameter calibration tool recommended by SWAT. Table 3 indicates the input data of the SWAT. It mainly includes spatial and attribute data. Spatial data mainly include the digital elevation model (DEM), land-use type distribution, and soil spatial distribution. Spatial data are uniformly projected with WGS coordinate_1984_UTM_Zone_49N. The DEM was developed from geospatial data. Land-use data were obtained from the International Geosphere-Biosphere Programme (IGBP) and correspond to land-use types in SWAT. Land-use types are divided into five categories. Soil data are provided by the Food and Agriculture Organization of the United Nations (FAO). Soil types are divided into 27 categories.

**Methodology**

In this study, SDSM (Wilby 2002; Wilby et al. 2003) was used to analyze the daily series of temperature and precipitation of the CanESM2 in the future scenario. SDSM is one of the more accurate and widely used statistical downscaling models, which combines multiple linear regression and random weather generator. Precipitation and temperature are the primary influencing factors of flood season in the upper reaches of the Minjiang.

**Table 2 | Basic information regarding hydrological stations and rainfall stations**

| Station          | Latitude (°N) | Longitude (°E) |
|------------------|---------------|----------------|
| Hydrological station | Zipingpu     | 31°02'         | 103°34'         |
| Rainfall station | Songpan       | 32°38'         | 103°36'         |
|                  | Maladun       | 32°23'         | 103°28'         |
|                  | Shuzhuhua     | 32°31'         | 103°37'         |
|                  | Zhenjiangguan | 32°18'         | 103°44'         |
|                  | Jiaochangba   | 32°03'         | 103°40'         |
|                  | Zhimalin      | 32°11'         | 103°11'         |
|                  | Sandagou      | 32°15'         | 102°55'         |
|                  | Heishui       | 32°04'         | 103°00'         |
|                  | Cibushu       | 31°54'         | 103°24'         |
|                  | Shaba         | 31°50'         | 103°40'         |
|                  | Weimen        | 31°46'         | 103°50'         |
|                  | Milyalo       | 31°39'         | 102°49'         |
|                  | Zhagunao      | 31°26'         | 103°08'         |
|                  | Shangmeng     | 31°40'         | 103°08'         |
|                  | Sangping      | 31°29'         | 103°35'         |
|                  | Mianchi       | 31°22'         | 103°30'         |
|                  | Huahongshu    | 31°02'         | 103°11'         |
|                  | Yuzixi        | 32°04'         | 103°29'         |
|                  | Sanjiangkou   | 30°55'         | 103°21'         |
|                  | Shouxu        | 30°59'         | 103°29'         |
|                  | Guamenshi     | 31°08'         | 103°34'         |
|                  | Zipingpu      | 31°02'         | 103°34'         |

**Table 3 | Model input data list**

| Data name          | Data description                                      | Data source                  |
|--------------------|-------------------------------------------------------|------------------------------|
| DEM data           | DEM 30 m dataset (elevation, slope)                   | [www.gscloud.cn/search](http://www.gscloud.cn/search) |
| Land-use data      | 1 km resolution (spatial distribution of land-use types) released by IGBP | [http://www.igbp.net/](http://www.igbp.net/) |
| Soil data          | 1 km resolution (spatial distribution and soil properties) | [http://www.crensen.ac.cn/portal/](http://www.crensen.ac.cn/portal/) |
| Meteorological data| Daily meteorological data provided by CMA. The future meteorological data are from the highest, lowest temperature, and daily precipitation data from CanESM2 simulated by SDSM | [http://data.cma.cn/](http://data.cma.cn/) |
| Hydrological data  | Daily runoff data of the Zipingpu hydrological station from 1967 to 1987 | Hydrological yearbook |
River, so SDSM is used to study the downscaling of precipitation and temperature in the upper reaches of the Minjiang River.

The relationship between SDSM generated predictor ($R$) and predictor ($L$) is as follows:

$$R = F(L)$$

where $F$ is a deterministic or stochastic function. The prediction factor $L$ is mainly selected according to the station data and research purposes.

SWAT was used to simulate the runoff, and the sensitivity parameters were calibrated using SWAT-CUP (Arnold et al. 1998; Olivera et al. 2006). The SWAT model is mainly composed of terrain sub-model, runoff sub-model, confluence sub-model, and water proton model. The model uses a grid to discretize the watershed, which can better reflect the uneven distribution of terrain, soil, land use, vegetation cover, and other time and space, and can reflect the response of water quantity and water quality brought by natural changes and human activities. The model parameters can reflect the physical characteristics of the underlying surface of the watershed. The SWAT model uses the hydrological response unit as the minimum calculation unit, which simplifies much calculation compared with other models, giving the SWAT model significant advantages in a long-term simulation of the large-scale watershed.

## RESULTS

### The prediction of future climate scenarios in the study area

The steps for constructing a downscaling model using SDSM in the study area are as follows. First, the optimal grid is selected using the correlation between NCEP and measured data. The optimal predictor is selected using the partial phase relation number of each prediction factor to the prediction variables, and the statistical relationship is established. Second, the independent observation data were used to test the statistical relationship, and the statistical relationship was used to predict the future daily meteorological information.

### Prediction factor selection

The grid of meteorological stations in the study area and eight adjacent grids were selected. Based on the large-scale temperature, the grid with the highest correlation with temperature is selected. The grid with the highest correlation with precipitation is selected based on the surface absolute humidity. Referring to Wilby’s research results (Wilby 2002; Wilby et al. 2003), the prediction factors of temperature and precipitation (Table 4), and rainfall station forecast factors are selected.

### Table 4 | Predictor of temperature and precipitation at representative stations in the study area

| Stations | Maximum temperature Grid | Predictor | | Minimum temperature Grid | Predictor | | Precipitation Grid | Predictor |
|----------|---------------------------|-----------|---------------------------|-----------|---------------------------|-----------|---------------------------|-----------|
| Maoxian  | 8                         | mslp;p1_u;p8_u;p850;s500;shum;temp | | 3                         | mslp;p1_u;p1_z;p5_z; p500;p850;s850;shum;temp | | 2                         | mslp;p1_v;p5zh;p1zh;p5_v; p5_z;p5sh;p8_v;prcp;p500;shum;temp |
| Songpan  | 5                         | mslp;p1_v;p5_u;p500;p8_v; p850;prcp;s850;shum;temp | | 2                         | mslp;p1_up1_v;p1zh;p5_v; s500;s850;shum;temp | | 1                         | mslp;p1_v;p1zh;p5_v;p500; p8_z;p850;p8zh;prcp;temp |
| Wenchuan | 9                         | mslp;p1zh;p500;p8_z;s850;shum;temp | | 3                         | mslp;p1_z;p500;p8zh; s850;shum;temp | | 1                         | mslp;p1_u;p1zh;p5_u;p5_z; p500;p5zh;p8_u;p8zh;s500;shum |
| Lixian   | 8                         | mslp;p1_v;p850;s500;s850;shum;temp | | 3                         | mslp;p1_z;p500;s850;shum;temp | | 1                         | mslp;p1_f1_u;p1zh;p5_z;p500; p5zh;p8_u;p8zh;prcp;shum;temp |
| Heishui  | 5                         | mslp;p1_v;p5_u;p5_z;p500; p5zh;prcp;s850;p500;shum;temp | | 1                         | mslp;p1zh;p5_v;p500; s850;shum;temp | | 2                         | p1_v;p1zh; p5_u;p5_z; p500; p8_u;p8zh;shum;temp |

Note: p, p5, and p1 refer to near-surface, 500 and 850 hPa geopotential height; s500 and s850 refer to 500 and 850 hPa geopotential height. temp, f, z, u, v, zh, th, rhum, r, and p refer to average temperature, geostrophic wind speed, vorticity, zonal wind speed, meridional wind speed, divergence, wind speed, near-surface relative humidity, relative humidity, and potential height.
The effect of downscaling simulation

From the comparison of the monthly mean maximum and minimum temperatures observed and simulated in Figure 2, it was understood that the mean value and standard deviation of the observed and simulated values are similar. Figure 2 shows that the simulated monthly precipitation values are generally slightly higher than the measured values, which may be related to the complex physical mechanism of precipitation and the discontinuity of precipitation in time and space. However, the statistical relationship established by SDSM is relatively simple; thus, the precipitation at the simulated stations has a certain error (Zhao et al. 2008).

Generally, SDSM can simulate the monthly variation of temperature and precipitation in the study area. This variation may be related to the establishment of a downscaling model by month in SDSM so that the monthly variation characteristics can be reflected. The difference between the maximum and minimum temperature and precipitation prediction results may also be related to the strong spatial-temporal difference in precipitation. In contrast, temperature is the continuous distribution of space–time.

The average absolute error of variables in the validation period (Table 5) was calculated. According to Table 5, the average absolute errors of the highest and lowest temperatures have small seasonal variations, whereas the average absolute error of precipitation in summer is higher than that in other seasons. Generally speaking, it is feasible to use SDSM to analyze the variables in the study area.

Table 6 shows the difference in standard deviation and interannual trend of variables in the study area between the measured and simulated data. The results show that the standard deviation between the measured and

![Figure 2](http://iwaponline.com/jwcc/article-pdf/doi/10.2166/wcc.2021.038/906961/jwc2021038.pdf)

**Figure 2** | Simulation results of temperature and precipitation, and precision of the SDSM in the study area during the validation period (1989–2005).
simulated results is similar. The simulation effect of the maximum and minimum temperatures is better than that of the precipitation.

**Prediction of future climate scenarios**

Table 7 shows the interannual changes in variables in the future scenario. The maximum temperature increases by 12–14% compared with the historical period; the warming of the Songpan and Wenchuan stations shows the largest difference. The minimum temperature is 23–28% higher than the historical period, and the temperature at the Maoxian station shows the largest difference. The increase in temperature increases with an increase in emissions. Compared with the minimum and maximum temperature changes, the minimum temperature rise is more significant than the maximum temperature rise. In the future scenario, the annual precipitation will increase by 33–44%. The precipitation increment trends among the three scenarios do not increase with the increase in carbon dioxide emissions, indicating that precipitation is more complicated due to climate change.

The calculation of the changes in monthly reveals that the maximum temperature is higher than the historical maximum temperature (Figure 3). The temperature rises most obviously from December to January in winter by 2.6–3.2 °C, followed by June–August (summer) by 2.5–2.7 °C. The least rise is 0.5–1.5 °C in March–May in spring.
Under future climate change, the following annual distribution characteristics of the minimum temperature are observed. The temperature rises most obviously from December to January in winter by 2.7–2.9 °C, followed by June–August in summer by 2–2.6 °C. The least obvious increase is in March–May in spring, ranging from 0.5 to 1.5 °C.

Under future climate change, the daily precipitation will increase compared with that of the historical period except for April–May in spring. The most obvious increase is from July to August in summer, with an increase of 0.8–1.2 mm/day.

Runoff simulation model in the study area

Model parameters

According to the DEM, land use, and soil distribution, the study area is divided into 422 hydrological response units. The model was constructed in the study area based on historical daily runoff data from 1967 to 1987. The warm-up period was from 1967 to 1968. The model was calibrated from 1969 to 1979 and verified from 1980 to 1987.

The sensitive parameters area is calibrated. The final values of the parameters are shown in Table 8. The result indicates that the runoff is most sensitive to the groundwater’s base flow decline coefficient, followed by the base flow alpha factor and the minimum snow water equivalent under 100% snow cover. Under climate change, the exchange of surface water and groundwater changes significantly; the snow cover also changes, indicating that it is of great significance to study the response of the study area to climate change.

Calibration and validation of the SWAT model

The SWAT model was used to simulate the daily runoff in the study area. The simulation results showed that the determination coefficient of the regular rate was 0.87, the Naxi efficiency was 0.86, the determination coefficient in the validation period was 0.79, and the Naxi efficiency was 0.77. These results imply that the SWAT model is feasible for simulating the daily runoff in the study area. The runoff hydrograph of the period and validation periods is shown in Figures 4 and 5. Compared with the actual runoff and the simulated runoff, it was found that the SWAT model after parameter calibration can simulate the seasonal distribution characteristics of runoff. SWAT is more accurate in simulating runoff during the flood season. The runoff simulated by SWAT is
### Table 8 | The values of model parameters

| Parameter name       | Optimal value | T-stat | P-value |
|----------------------|---------------|--------|---------|
| v__GW_DELAY.gw       | 13.06         | 34.63  | 0       |
| v__ALPHA_BF.gw       | 0.63          | -7.46  | 0       |
| v__SNOCOVMX.bsn      | 358.99        | -1.82  | 0.07    |
| v__TLAPS.sub         | 18.31         | 1.53   | 0.15    |
| r__SOL_K(1).sol_1    | 0.72          | 1.23   | 0.22    |
| v__NPERCO.bsn        | 9.72          | 1.2    | 0.23    |
| v__CH_N2.rte         | -5.34         | -1.16  | 0.25    |
| v__SPEXP.bsn         | 1.45          | -0.96  | 0.34    |
| v__GW_REVAP.gw       | 0.02          | -1.04  | 0.3     |
| v__REVAPMN.gw_1      | 2.72          | 0.69   | 0.49    |
| v__EPCO.hru          | 1.27          | 0.66   | 0.51    |
| v__PHOSKD.bsn        | 147.57        | 0.44   | 0.66    |
| r__SOL_ALB(1).sol    | 0.22          | 0.42   | 0.68    |
| v__CH_K2.rte         | -489.23       | -0.42  | 0.68    |
| v__ESCO.hru          | 1.09          | -0.51  | 0.76    |
| a__GWQMN.gw          | 910.29        | -0.29  | 0.77    |
| v__SMFMN.bsn         | 11.66         | 0.25   | 0.8     |
| r__CN2.mgt           | -0.58         | -0.21  | 0.84    |
| v__SMFMX.bsn         | -0.88         | 0.13   | 0.9     |
| r__SOL_AWC(1).sol    | -3.88         | -0.04  | 0.97    |
| v__TIMP.bsn          | 0.76          | 0.03   | 0.98    |
| v__SURLAG.bsn        | 719.8         | 0.01   | 0.99    |

r_ means an existing parameter value is multiplied by (1 + given value); v_ means the existing parameter value is to be replaced by a given value (Neitsch et al. 2011; Arnold et al. 2012).

### Figure 4 | Daily simulation results of runoff during the calibration period (1969–1979).
less than the measured runoff in the dry season. This lower runoff may be attributed to the large contribution of high flow in the flood season to the simulation error evaluation. Simultaneously, the contribution of low flow in the dry season to the simulation error evaluation is small. This phenomenon is also observed in similar studies (Chen et al. 2017; Mohammed et al. 2017).

Prediction of future runoff change in the study area

A comparison between the annual runoff in the study area in the historical period and in the future scenario (Figure 6) reveals that the annual runoff shows an upward trend in the future. With the increase in emissions, the upward trend of runoff is more prominent. Comparing the monthly runoff of the two periods (Figure 7), the increase in runoff is most evident from November to April of the following year. From June to July, under the trend of annual runoff increase in different scenarios, the monthly runoff decreases compared with
the base period by more than 10%. From June to July in summer, the temperature and precipitation increase, and the runoff decreases, indicating that the precipitation rise cannot compensate for the influence of temperature rise on evapotranspiration. From April to May in spring, the temperature and runoff increases and the precipitation decreases, suggesting that the temperature rise on the snow melting process is more significant than that on evapotranspiration in spring. The increase in snow melting amount increases the runoff. The peak period of agricultural irrigation and water diversion from the Minjiang River downstream is from June to July. The decrease in runoff will affect the agricultural irrigation water, thereby reducing agricultural production. Simultaneously, it will affect the water distribution downstream and may worsen the improved ecology.

**DISCUSSION**

From 2020 to 2050, the temperature in the study area shows an upward trend under climate change. The upward trend is consistent with the increasing trend of emissions; this indicates that under the high emission scenario, there is more carbon dioxide emission, more greenhouse activity, and greater temperature rise (Qin et al. 2019). The temperature rise will enhance the snowmelt and evapotranspiration, of which the increase in snowmelt is more apparent in spring and evapotranspiration in summer.

From 2020 to 2050, the precipitation in the study area shows an increasing trend, which is consistent with the response results of most basins under climate change (Gu et al. 2015; Chen et al. 2017; Yang et al. 2019a, 2019b). Simultaneously, the study shows that the temporal and spatial variations show strong heterogeneity (Huang et al. 2010). The study area trend is different from the upper reaches of the Yangtze River, which has unique characteristics. The precipitation decreases from April to May in spring and increases in other months, especially in July and August. Such precipitation fluctuations reveal that the impact of climate change on precipitation is more complex, and there are large spatial differences in annual and seasonal changes.

The results show that the seasonal distribution of runoff change is consistent with the seasonal variation in precipitation, indicating that precipitation contributes greatly to the increase of the runoff (Gu et al. 2015; Yang et al. 2019a, 2019b). In autumn and winter, the rising trend of runoff in the study area is consistent with the rising trend of precipitation. The increase in runoff in winter is mainly due to the increase in precipitation by 20%, and the increase in temperature causes the precipitation to become runoff instead of snow (Gu et al. 2015). From June to July, the precipitation in the study area increased; however, the runoff decreased, suggesting that the increase in temperature increased evaporation, and the increase in precipitation could not compensate for the increase in evapotranspiration. The research results of the upper reaches of the Yangtze River show similar findings (Birkinshaw et al. 2017) but contrary to the summer runoff increase in the Minjiang River Basin (Chen et al. 2014; Yang et al. 2015). From April to May, the precipitation decreased, and the runoff increased in the study area, indicating that the increase in temperature increased the snowmelt and runoff. The seasonal variation of runoff in the study area is affected by the geographical location. The upper reaches of the Minjiang River are characterized by high mountain and gorge landforms, and the evapotranspiration and snow melting process

![Figure 7](http://iwaponline.com/jwcc/article-pdf/doi/10.2166/wcc.2021.038/906961/jwc2021038.pdf)
are more vulnerable to climate change. From April to May, the precipitation in the study area decreased and the runoff increased, revealing that the increase in temperature increases snow melting. The temperature rise in the entire Yangtze River Basin will cause the precipitation to increase in the future; however, the uneven change in precipitation in time and space will cause uneven runoff change (Huang et al. 2010). At the same time, relevant research shows that the change in runoff is primarily affected by climate change, and changes in the annual distribution of runoff are mainly affected by human activities (Qin et al. 2019). The study area is rich in hydropower energy. To develop a local economy, utilize water resources, and avoid and mitigate floods, many water projects have been built in the mainstream and tributaries of the upper reaches of the Minjiang River, which play a key role in water storage and peak regulation. However, to a certain extent, especially in the dry season, the natural runoff pattern is affected by human activities.

In this study, SDSM is used to downscale the future climate scenarios predicted by CanESM2. However, there are some uncertainties in the prediction results and downscaling models of CanESM2. At the same time, SWAT is selected to simulate the runoff in the upper reaches of the Minjiang River, which also has some uncertainty. The uncertainties of future climate scenarios, downscaling models, and hydrological models make it uncertain to study the response of the upper Minjiang River to climate change. Based on the uncertainty of the study, the response of the upper reaches of the Minjiang River to climate change will be further studied using the results of multi-mode climate prediction.

CONCLUSIONS

From the simulation results of the study area, SDSM can simulate the monthly and annual variation trends of the temperature and precipitation at each station. The deterministic coefficient of runoff simulation by using SWAT is 0.79. The Naxi efficiency was 0.77 in the verification period, indicating that the SWAT model can accurately simulate the daily runoff and be used to study the response of water resources to climate change.

In the future scenario, the maximum temperature shows an upward trend. The largest temperature rise was from December to January by 2.6–3.2 °C, followed by June–August, with an increase of 2.5–2.7 °C. The increase in the minimum temperature is higher than the highest temperature. The temperature rise is the most obvious from December to January, up to 2.7–2.9 °C, followed by June to August, with an increase of 2–2.6 °C. Except for spring, the daily precipitation decreased from April to May and increased in other periods, especially from July to August, with an increase of 0.8–1.2 mm/day.

In the future scenario, the runoff in the study area will increase most significantly from November to April, whereas the runoff from June to July will decrease by more than 10% compared with the historical period. From June to July, the temperature increases, the precipitation increases, and the runoff decreases, indicating that the precipitation rise cannot compensate for the influence of temperature rise on evapotranspiration. From April to May, the temperature increases, the precipitation decreases, and the runoff increases, indicating that the influence of temperature rise on the snow melting process is greater than that on evapotranspiration during spring. Also, the increase in the amount of snow melting increases the runoff. June to July in summer is the peak period of agricultural irrigation in the Minjiang River; it is also the period of water diversion from the Minjiang River downstream. The decrease in runoff will affect the agricultural irrigation water, thereby reducing agricultural production; furthermore, it also affects the water distribution downstream and may worsen the improved ecology.

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AUTHOR CONTRIBUTIONS

Kebi Yang (PhD candidate) conducted the writing of the original draft. Ting Chen (PhD) conducted the writing of review and editing. Tianqi Ao (PhD supervisor, professor) conducted the supervision of the draft. Xu Zhang (PhD candidate) conducted the part of the experiments. Li Zhou (PhD candidate) conducted the part of the experiments. Danyang Gao (Master candidate) conducted the data validation.
DATA AVAILABILITY STATEMENT

The daily temperature and precipitation data used in this paper are provided by the State Meteorological Administration of China. Relevant station data are available at https://data.cma.cn/ through registered scientific research users. CanESM2 simulation results and NCEP reanalysis data are obtained from http://climate-scenarios.canada.ca/?page=pred-canescm2.

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