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Effects of Climate Change on Surface Runoff and Soil Moisture in the Source Region of the Yellow River

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Abstract: The impact of climate change on surface runoff and soil moisture in the source region of the Yellow River is analyzed, which will provide a scientific basis for the rational use and protection of water resources in the source area. In this paper, the SWAT hydrological model was coupled with the Coupled Model Intercomparison Project (CMIP) to predict future changes in surface runoff and soil moisture in the source region of the Yellow River. The prediction of surface runoff and soil moisture in the Yellow River Basin was analyzed by a linear regression model. The SWAT model rate had a calibration period R^2 of 0.876 and a validation period R^2 of 0.972. The trend of surface runoff and annual mean temperature in the source region of the Yellow River from 2011 to 2022 showed an overall increasing trend, and soil moisture showed a general decreasing trend. 2011–2022 trends between surface runoff and annual mean temperature in the source region of the Yellow River showed a highly significant difference, indicating that surface runoff flow was significantly influenced by temperature. The difference between the trends in soil moisture and the annual mean temperature was highly significant. The surface runoff fluctuated greatly in different years, and the surface runoff changed greatly in different scenarios of CMIP5 (RCP2.6, RCP4.5, and RCP8.5). For all three climate change scenarios, the surface runoff displayed a downward trend. The surface runoff showed a similar uneven distribution for all scenarios on a yearly cycle. Under the three climate scenarios, the runoff was highest between May and August, with a slowly increasing trend from January to April and a slightly decreasing trend from September to December. The interannual and interannual distribution of soil water was basically consistent with the distribution of surface runoff, and there was an overall trend in the length of all soil water reduction scenarios. Surface runoff and soil moisture are and will be greatly affected by climate change (mainly temperature and precipitation). Under the three climate scenarios, the precipitation increases to some extent, but the surface runoff and soil moisture will both decrease, which may be attributed to the greater evaporation than the precipitation.

Keywords: SWAT; CMIP5; current status; future climate scenarios; projection; RCPs

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1. Introduction

Since the 21st century, significant changes have taken place in the global climate due to natural factors and human activities [1]. Impacts such as permafrost degradation, vegetation destruction, and disruption of biogeochemical cycles caused by climate change have seriously affected both human quality of life and ecosystem health. Future climate change and its series of consequences continue to threaten the living environment [2]. At the end of the 20th century, in order to promote the study of climate change, the World Climate Research Program (WCRP) organized the Coupled Model Intercomparison Project (CMIP). The CMIP5 was proposed by the WCRP and is often used to study the trends and characteristics of future climate change [3]. The future scenarios of RCP 2.6, RCP 4.5, and RCP 8.5 in CMIP 5 are widely used climate simulation prediction models at present [4].

Atmospheric circulation models (GCMs) are better able to simulate climate trends in future periods, but their output information has a low spatial resolution (generally 200 km $\times$ 200 km). Moreover, the data provided by various GCMs are grid data with a large scale, so the prediction of regional future climate scenarios often lacks accuracy [5]. Therefore, the Statistical Down Scaling Model method (SDSM) is needed to obtain more accurate regional climate scenarios [6]. The SDSM method can reduce the deviation of space climate data and improve the accuracy of GCM for future climate simulations. SDSM can improve regional resolution and reduce computational load, which can make up for the deficiency in the CMIP5 model [7]. By applying the SDSM method to the CMIP5 model, the simulated temperature data has good consistency with the measured data [8]. The SDSM uses large-scale meteorological factors and forecasts to establish statistical relationships and test the statistical relationships with site observations. The tested statistical relationships are applied to the GCM factors [9], and different future greenhouse gas emission scenarios are selected to generate future regional climate scenarios. In recent years, more and more research has been carried out to compare the simulation effects of different SDSM methods [10]. Extensive studies have been conducted on the simulation of air temperature, precipitation, runoff, etc. by using SDSM and GCMs [11,12].

The long-term distributed hydrological model SWAT (Soil and Water Assessment Tool) is applicable to complex watersheds with different soil types and land uses and is now widely used around the world. [13]. Remote sensing technology can transform the underlying surface information into pictures for use in combination with geographic information systems to provide supporting data in the construction of SWAT models [14]. Distributed hydrological models have been widely used to simulate runoff, climate, hydrology, soil, and vegetation at home and abroad, and a lot of results have been obtained [15,16]. Climate models and hydrological models are the main methods used to study the response of hydrological cycle processes to changing environments. Tomer et al. (2009) [17], Tolentino et al. (2016) [18] coupled the climate model with the eco-hydrological model to predict future rainfall, transpiration, and hydrological cycles, respectively, and the results were satisfactory.

Under the background of global warming, the climate of the Qinghai-Tibet Plateau, which is known as the “climate regulator” in China, is also changing. The source region of the Yellow River is located on the Tibetan Plateau. [19]. After the 1980s, because of global climate change and the impact of human activities, the ecological environment of the source area underwent significant changes. Lake shrinkage, land desertification, decreased groundwater storage, and glacial snow melt have been observed, making the ecological environment more fragile and sensitive [20,21]. In recent years, a number of studies have shown that temperatures in the source region of the Yellow River have generally increased, precipitation has decreased slightly, and river runoff has decreased frequently. Various ecosystems have been destroyed, and environmental problems have become increasingly prominent [22]. The changes in climate, water resources, and ecological environment in the Yellow River Basin do not only damage the ecological security of the source region of the Yellow River. It will also reduce the efficiency of water use in the middle and lower reaches of the Yellow River Basin and affect its sustainable development.

At present, there is little research on surface runoff and soil moisture in the source region of the Yellow River. Shi et al. [23] used climate diagnostics to estimate the effects of climate change on surface runoff and soil moisture. Sun et al. [24] used wavelet analysis and the surface model CLM4.0 [25] to estimate the impact of climate change on the hydrology of the Yellow River Basin. However, coupling the SWAT model with the CMIP5 climate model to study future surface runoff and soil moisture changes in the source region of the Yellow River has not been reported. In this study, three climate scenarios (RCP2.6, RCP4.5, and RCP8.5) were coupled with SWAT in the CMIP5 model to predict future surface runoff and soil moisture changes in the Yellow River source area and provide a theoretical basis for surface runoff and soil conservation in the Yellow River source area.

2. Data Sources and Methods

2.1. Study Area

The source region of the Yellow River is located in the range of 32°09′~36°34′ N, 95°54′~103°24′ E (Figure 1), with an average elevation of more than 4 km [26]. The basin area of the source region is about 1.22×10^5 km^2 [27]. The climate is cold and subhumid, and the dry and wet conditions are obvious. The hot and cold seasons alternate, without obvious four seasons [28]. The annual average precipitation is 310 mm, the annual evaporation capacity of the water surface is 1300–1600 mm, and the annual average temperature is −4°C [29]. There are 54 main tributaries in the source area, with many tributaries at the second and lower levels, accounting for about 50% of the drainage area [30]. There are 5300 lakes in the source area, whose sizes vary from a few square meters to several square kilometers. The total area of the lakes is approximately 1270.77 km^2, mostly lactated near the tributaries or floodplains [31]. The source area belongs to the alpine vegetation area of the Qinghai-Tibet Plateau. The main vegetation types are swamps, wetlands, alpine meadows, and aquatic vegetation [32]. There are many species of animals in the source area, mainly mammals, birds, reptiles, and amphibians [33].

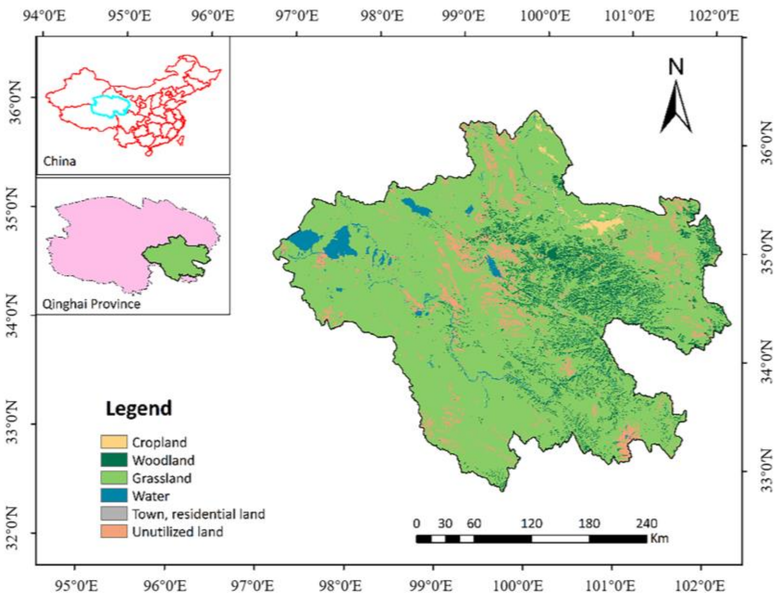

Figure 1. Location of the source region of the Yellow River.

2.2. Data Sources

The meteorological data (average annual temperature and average annual precipitation) for the historical period (1961–2022) of the source region of the Yellow River were obtained from the Climate Center of Qinghai Province, China, and the surface runoff (1961–2022) and soil moisture data (2011–2022) were obtained from the Qinghai Provincial Hydrological and Water Resources Survey Bureau, China.

2.3. Research Method

Three climate scenarios (RCP2.6, RCP4.5, and RCP8.5) under the CMIP5 climate model were adopted to predict future changes in surface runoff and soil moisture in the source region of the Yellow River. RCP2.6 represents the emission quantity and concentration of greenhouse gases (mainly CO_2, CH_4, and N_2O) at the lowest level. Under this climate scenario, the types and ways of using energy has changed globally, leading to a significant reduction in greenhouse gas emissions. RCP4.5 represents the climate change scenario under the intervention of climate policies. In this scenario, the utilization rate of coal and other non-renewable fossil energy decreases, and clean energy is used in large quantities, which significantly reduces greenhouse gas emissions. RCP8.5 represents that without the intervention of climate policy, the highest concentrations of greenhouse gas emissions occur and population increases substantially, which makes the emission concentration of greenhouse gases continuously intensified.

In this paper, the "Future Scenario Prediction Data Set" made by the China Climate Center was used. The data set is the simulation results of 21 CMIP5 global climate model. After interpolation calculation, the data were uniformly scaled down to the same resolution, and a set of monthly mean data under the discharge scenarios of RCP2.6, RCP4.5, and RCP8.5 in the source region of the Yellow River from 1901 to 2005 and from 2006 to 2100 was made by using the simple average method for multi-pattern collection. (The basic information about the 21 CMIP5 global climate model is in the Supplementary Materials, Table S1).

2.3.1. Database Construction, Calibration, and Validation of SWAT Model

(1) Establishment of source region database of Yellow River.

The soil database, meteorological database, and runoff database were established, respectively, in the source region of the Yellow River from 1961 to 2020. Projected the cropped soil type map of the source region of the Yellow River, read the corresponding values in the attribute table of the soil type map and the values in the reference table of soil data, and found out the soil types contained in the source region of the Yellow River. SPAW software was used to calculate the values, and three data sets including soil volume density (Sol-BD), available soil moisture (Sol-AWC), and saturated soil water conductivity (Sol-K), were obtained. The above three soil processed data sets were imported into SWAT model to build user soil and complete the construction of soil database. Data such as precipitation, air temperature, solar radiation, air pressure, relative humidity, evapotranspiration, and wind speed from eight meteorological stations in the source region of the Yellow River were collected, and corresponding index files were established. MATLAB and other software were used to calculate the data for each site and obtain the monthly average. The multi-year mean value of the data is used to fill in the missing data, and the obtained data was input into the SWAT model to complete the construction of the meteorological database.

(2) Establishment of SWAT model.

The preprocessed Digital Elevation Model of the source region of the Yellow River was used to extract the runoff network, and the total outlet of the Yellow River was defined as Tang Naihai Hydrological Station. The location coordinates of the cover hydrographic station were input into the model to divide the sub-basins of the water system. Then, the overall parameters of the basin were calculated, and the soil data, land use/land cover data, and surface runoff data were overlaid, and threshold values of the three thresholds to divide the hydrological response unit (HRU). In this paper, the water system is divided into 80 subbasins and 286 hydrological response units in the source region of the Yellow River (Figure 2). The measured runoff data from each hydrographic station can be used for parameter calibration and verification of the model after processing. The simulation time of the model is 1961–2013, in which 1961–1965 is the warm-up period of the model, and the verification time of the model is 2014–2019.

(3) Parameter sensitivity Analysis and Calibration of SWAT Model.

In this study, the parameter of runoff was analyzed using the self-contained module of the model, and the method of the module was the LH-OAT method. The optimal parameter values were obtained by using SWAT to rate the relevant sensitivity parameters (Table S2), such as soil bulk density (SOL-BD) and SCS runoff curve number (CN2). According to the value range of the parameter rate, the parameter range is continuously reduced by iterative analysis, and the optimal solution is finally obtained as the rate value of the input model (Table 1). According to the results of the rate values of the sensitivity parameters, the simulation of the model is better.

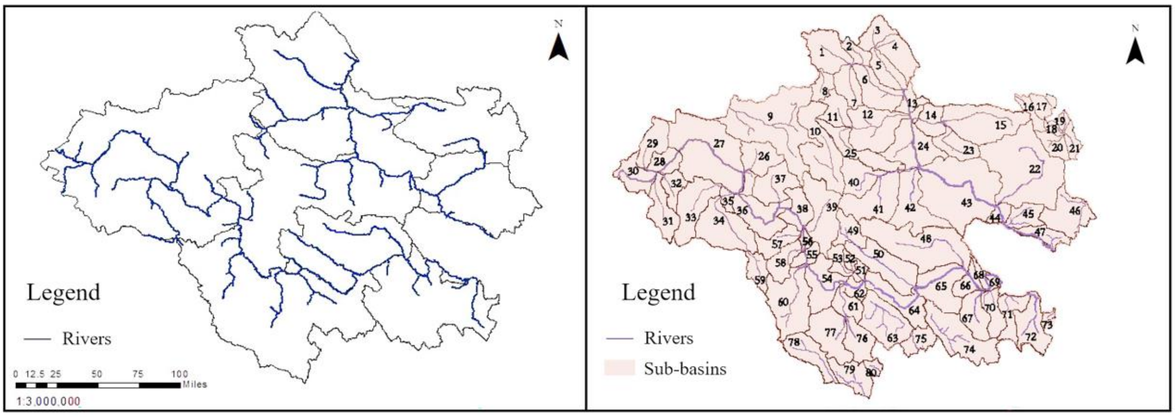

Figure 2. River network map of the source region of the Yellow River. The number represents the subbasins.

Table 1. SWAT model parameter calibration range and result.

Parameters of the Project	The Final Range	Rate Constant Value
SOL-BD	1.2–1.5	1.9
CN_2	35–90	73
ESCO	0.76–0.78	0.76
CH-K_2	110–125	121
SOL-K	10–80	39
SOL-AWC	0–0.25	0.23
ALPHA-BF	0.2–1	0.84
GWQMN	0–5000	1337.5
EPCO	0–0.8	0.37
REVAPMN	0–500	438

(4) Verification of SWAT Model

The model has a rate period of 1961–2013 and a validation period of 2014–2019. The deviation between the simulated values and the actual surface runoff observation data in the calibration periods and validation was controlled within $\pm 20\%$.

2.3.2. Coupling of CMIP5 Climate Model and SWAT Hydrological Model

By using the Future Scenario Forecast Data Set produced by China Climate Center, the monthly average data of the Yellow River under the emission scenarios of RCP2.6, RCP4.5, and RCP8.5 from 2023 to 2100 in the Future Scenario Forecast Data Set made by China Climate Center are introduced into the SWAT model to drive the standardized and verified SWAT model. The statistical downscaling method was adopted to downscale the output results. The meteorological data results after processing and the collected spatial, soil, and hydrological data of the source region of the Yellow River were taken as the initial data of the calibrated SWAT hydrological model and imported into the model for calculation. Then the data on surface runoff and soil moisture in the source region of the Yellow River from 2023 to 2100 were predicted (the flow chart is shown in Figure S1).

3. Results and Analysis

3.1. SWAT Model Rate Determination and Validation

The comparison between the simulated values at the calibration and verification periods and the actual observation values at the hydrological station is shown in Figures 3–5. There was a certain deviation between the numerical value simulated by the model and the actual observation data of the hydrological station, but the deviation was within ±20%.

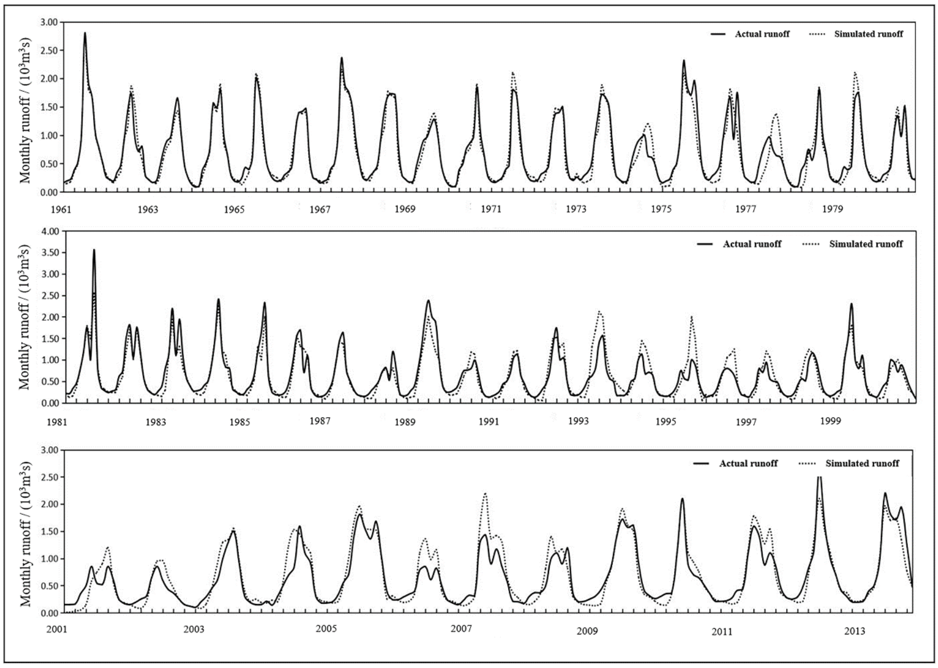

Figure 3. Simulated and measured values of monthly runoff in the Yellow River source area (calibration period).

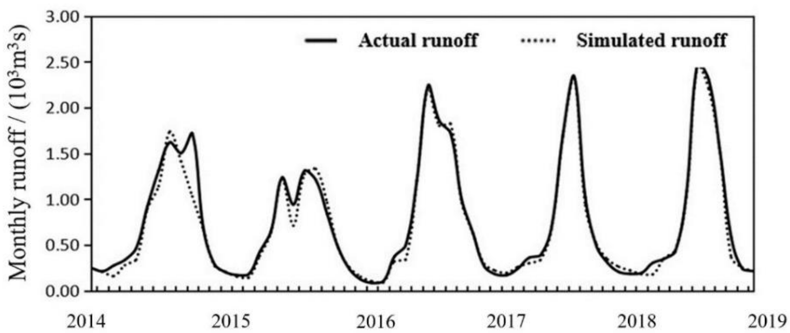

Figure 4. Simulated and measured values of monthly runoff in the Yellow River source area (Validation period).

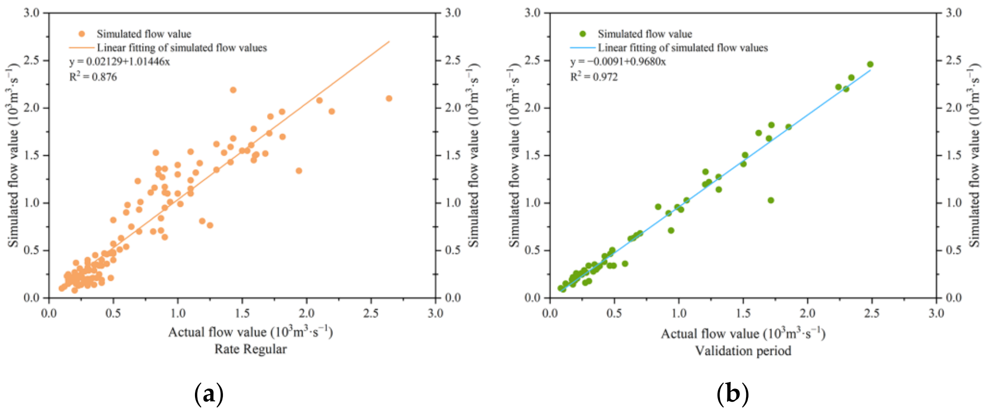

Figure 5. Scatter plot of simulated and measured monthly runoff in the source region of the Yellow River. (**a**) is the calibration period (1961–2013); (**b**) is the verification period (2014–2019).

The simulation and evaluation results of monthly runoff in the source region of the Yellow River are shown in Table 2. The R^2 was 0.876 in the calibration period, and 0.972 in the verification period, both of which reached good standards, indicating that the model has high credibility. Although the periodic error values of the rates are within a more reasonable range, the runoff from the source region of the Yellow River for 2014–2019 (the validation period) derived from the model simulation is higher than the actual values.

Table 2. Simulation and evaluation results of monthly runoff in the source region of the Yellow River.

Time Frame	R^2	Simulated Mean	Actual Mean
Calibration period (1961–2013)	0.876	672.63	682.47
Verification period (2014–2019)	0.972	657.06	632.64

3.2. Analysis of the Situation of Surface Runoff and Soil Moisture in the Source Region of the Yellow River

3.2.1. Current Status of Surface Runoff and Soil Moisture in the Source Region of the Yellow River

Figure 6a indicates that the surface runoff in the source region of the Yellow River shows an overall increasing trend from 2011 to 2022, but the interannual runoff increases or decreases more, and the runoff distribution is not uniform. It was the lowest in 2015 and started an increasing trend in 2016 to reach this 7-year high of 45.2 billion m^3 in 2021. It starts to decrease again in 2022, down to 39 billion m^3. According to Figure 6b, the soil moisture in the source region of the Yellow River showed an overall decreasing trend, reaching the highest soil moisture content in 2016. Soil moisture levels in 2017 and 2018 were the lowest in 12 years. Starting in 2018, the soil moisture content showed an increasing trend year by year.

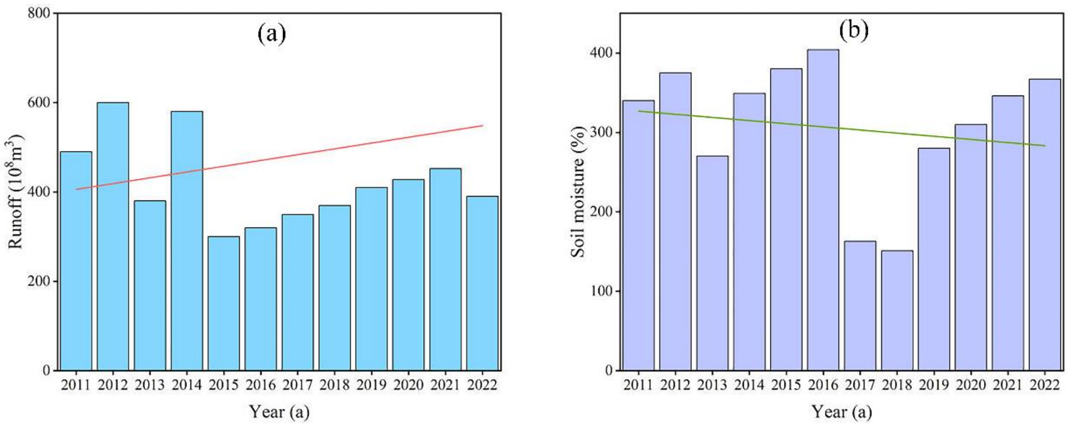

Figure 6. Interannual variability of surface runoff and soil moisture. (**a**) surface runoff; (**b**) soil moisture.

3.2.2. Trend Analysis of Surface Runoff versus Average Annual Precipitation and Average Annual Temperature from 2011 to 2022

According to Table 3, there is a highly significant difference in the trend between surface runoff and average annual temperature in the source region of the Yellow River from 2011–2022, indicating that surface runoff flow is more significantly influenced by temperature ($p < 0.01$). The trends between surface runoff and annual precipitation do not have significant differences, among which only the differences between surface runoff and annual precipitation are significant in 2017–2018 ($p < 0.05$).

Table 3. Trend analysis of surface runoff and annual mean temperature and annual mean precipitation.

Year	Surface Runoff (10^8 m^3)	Annual Mean Temperature (°C)	$P_{temperature}$	Average Annual Precipitation (mm)	$P_{precipitation}$
2011	490	−0.2671	0.032	461.45	0.196
2012	600	−0.1433		433.27	
2013	380	0.0171	0.065	401.74	0.309
2014	580	−0.0796		464.48	
2015	300	0.1352	0.010	451.55	0.050
2016	320	0.5506		429.81	
2017	350	1.1497	0.009	424.21	0.009
2018	370	1.3270		448.98	
2019	410	1.4235	0.007	495.01	0.286
2020	428	1.1235		418.28	
2021	452	1.1345	0.024	471.78	0.151
2022	390	1.4584		451.53	
2011–2022			<0.01		0.198

3.2.3. Trend Analysis of Soil Moisture in Relation to Average Annual Precipitation and Average Annual Temperature from 2011 to 2022

According to Table 4, the difference in the trend between soil moisture and average annual temperature in the source region of the Yellow River from 2011 to 2022 is highly significant, and the effect of the change in mean temperature on soil moisture is highly significant (p < 0.01) in 2015−2016 and 2021−2022, and only in 2017-the reason may be that the high temperature throughout the year increased transpiration of alpine grassland plants, resulting in increased evaporation of soil moisture, which led to a decrease in soil moisture, and the change was not significant. It can be seen that soil moisture responds to the changes inf temperature. From 2011 to 2022, the trend of annual average precipitation and soil moisture is significant, and from 2015 to 2016 and 2019 to 2020, the trend of annual precipitation and soil moisture is not significant (p > 0.05). With the slow increase in annual precipitation, the soil moisture content showed an overall decreasing trend.

Table 4. Trend analysis of soil moisture and annual mean temperature and annual mean precipitation.

Year	Soil Moisture (%)	Annual Mean Temperature (°C)	$P_{temperature}$	Average Annual Precipitation (mm)	$P_{precipitation}$
2011	340	−0.115	0.016	436.6250	0.049
2012	375	−0.1362		507.2875	
2013	270	−0.0087	0.040	416.9375	0.016
2014	349	−0.0125		481.3625	
2015	380	−0.0912	0.009	391.1375	0.200
2016	404	0.6312		474.6375	
2017	163	0.3125	0.053	524.8125	0.013
2018	151	0.9125		517.4625	
2019	280	0.8375	0.016	408.3964	0.054
2020	310	0.9625		400.8529	
2021	346	1.1345	0.009	486.4561	0.059
2022	367	0.9845		462.8502	
2011–2022			<0.01		0.0002

3.3. Characteristics of Surface Runoff in the Source Region of the Yellow River

3.3.1. Interannual Variation Characteristics of Surface Runoff

The interannual distributions of future (2023–2100) surface runoff in three scenarios (RCP2.6, RCP4.5, and RCP8.5) were simulated (Figure 7). The results showed that the interannual surface runoff varied greatly under different scenarios, but the annual interannual runoff under the three scenarios was generally reduced by RCP8.5 > RCP4.5 > RCP2.6. With the passage of time, the surface runoff decreased gradually. The three scenarios of RCP2.6, RCP4.5, and RCP8.5 reach their maximums in 2034, 2034 and 2048 respectively. The maximum values had a certain increase compared with the previous year, but the increase was not large. The significance tests of the variation trend of surface runoff in the three scenarios (RCP2.6, RCP4.5, and RCP8.5) are shown in Table 5. The prediction of future surface runoff changes under the three scenarios was significant at the significance level of 0.05, which indicated that there was a 95% possibility that the future (2023–2100) surface runoff would decline.

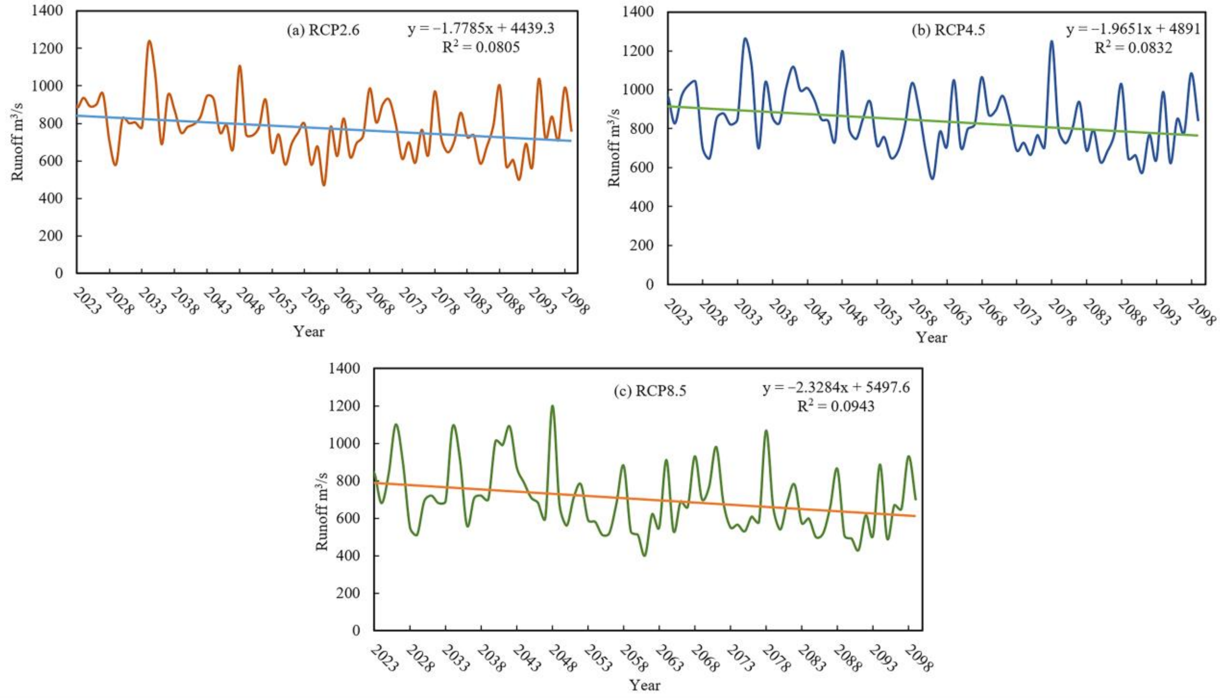

Figure 7. Interannual distribution of surface runoff under three scenarios. (**a**): Surface runoff in the RCP2.6 scenario; (**b**): Surface runoff in the RCP4.5 scenario; (**c**): Surface runoff in the RCP8.5 scenario.

Table 5. Significance test of surface runoff change trend under the RCPs climate model scenario.

RCPs Climate Model Scenarios	p Value	F Value	Degrees of Fredom
RCP 2.6	0.01076	6.829	1
PCP 4.5	0.00948	7.0748	1
RCP 8.5	0.00559	8.1215	1

3.3.2. Characteristics of Annual Variation of Surface Runoff

The annual variation trend of surface runoff is shown in the following figure (Figure 8). Under the three scenarios, the annual distribution of surface runoff had a certain amount of volatility. There were certain differences in the monthly runoff for different scenarios. The monthly runoff increased and decreased in RCP4.5 scenarios and increased the most and decreased the least in RCP8.5 scenarios. Under the three scenarios, the annual distributions of surface runoff in different periods were uneven. The net runoff from January to March showed a gradual increase and accumulation. The maximum runoff occurred in June and August, while the runoff decreased from September to December, and the minimum runoff occurred during this period. In January, February, November, and December, the overall surface runoff was on a downward trend. Compared with the middle of the 21st century, the reduction in surface runoff was larger than that in late 21st century. In the middle of the 21st century, the surface runoff from June to December accounted for about 65% of the annual runoff, while in the late 21st century, the proportion of the surface runoff from June to December in the annual runoff decreased to 60%. Both the 2040s and 2050s surface runoff peaks in June and August. And the 2050s surface runoff in June and August has a decreasing trend compared to the 2040s. The annual surface runoff in the 2050s will be smaller than that in the 2040s.

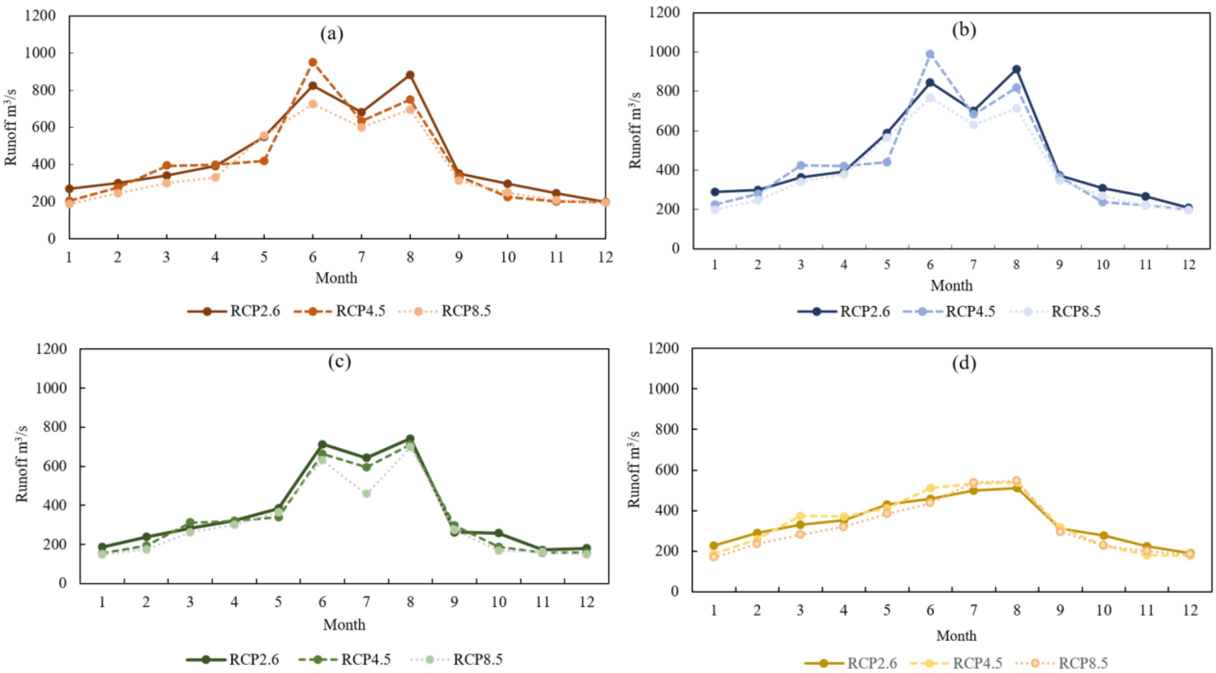

Figure 8. Annual distribution of surface runoff under three scenarios. (**a**): Annual distribution of surface runoff under three scenarios (2023–2100); (**b**): Annual distribution of surface runoff under three scenarios of the 2040s (2041–2050); (**c**): Annual distribution of surface runoff under three scenarios of the 2050s (2051–2060); (**d**): Annual distribution of surface runoff under three scenarios of the 2080s (2081–2090).

3.4. Characteristics of Soil Moisture in the Source Region of the Yellow River

3.4.1. Interannual Variation Characteristics of Soil Moisture

The interannual variation characteristics of soil moisture are shown in Figure 9. The response of soil moisture to climate change was more complicated. The inter-annual fluctuations of soil moisture were different under the three scenarios. Some years were more humid, and some years were dry, fluctuating between 100~500 mm and generally showing a decreasing trend. The reduction of soil moisture was consistent with that of surface runoff under three scenarios: RCP8.5 > RCP4.5 > RCP2.6. The soil moisture of RCP2.6, RCP4.5, and RCP8.5 reached their maximums in 2041, 2042, and 2052 respectively. After that, the soil moisture showed a decreasing trend, and the reduction was smaller than the surface runoff.

The prediction of future soil moisture changes in the source area under the three scenarios was significant at the significance level of 0.05 (Table 6). In other words, there was a 95% possibility that the soil moisture would decrease in the future (2023–2100).

Table 6. Significance test of soil moisture change trend under the RCPs climate scenarios.

RCPs Climate Model Scenarios	*p* Value	F Value	Degrees of Fredom
RCP 2.6	0.01278	6.4957	1
PCP 4.5	0.03019	4.8748	1
RCP 8.5	0.00535	8.2076	1

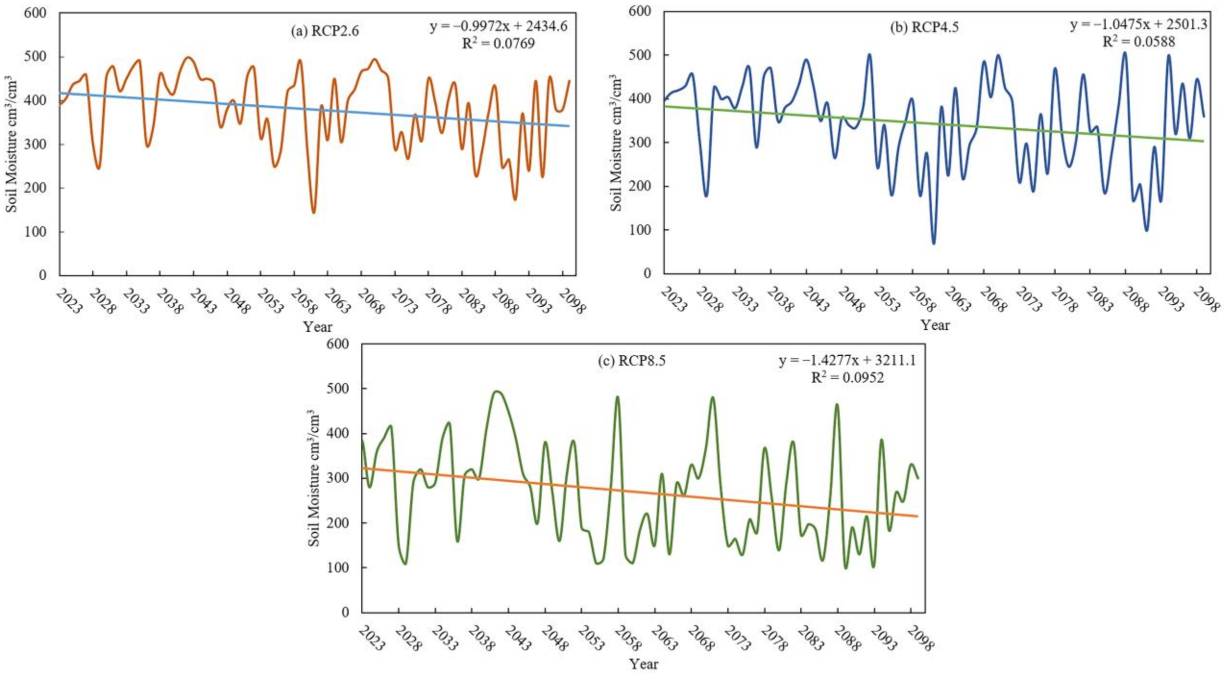

Figure 9. Interannual distribution of soil moisture under three climatic scenarios. (**a**): Soil moisture in the RCP2.6 scenario; (**b**): Soil moisture in the RCP4.5 scenario; (**c**): Soil moisture in the RCP8.5 scenario.

3.4.2. Characteristics of Soil Moisture during the Year

The annual variation characteristics of soil moisture are shown in Figure 10. Under the three scenarios, the soil moisture fluctuated greatly in each month and was unevenly distributed throughout the year, which was similar to the surface runoff, and was affected by the combined effects of precipitation and temperature. The peak appeared in June and August, with a gradual decrease from September to December, and the largest decrease occurred in August and September. The lowest value appeared in January and December, and the overall trend showed a decreasing trend. At the end of the 21st century, the soil moisture content was lower than that in the middle of the century. From April to September in the middle of the 21st century, the soil moisture content accounted for about 65% of the total soil moisture for the whole year. By the end of 21st, the soil moisture content had decreased to 60% of the annual total soil moisture from April to September. Over time, soil moisture would decrease, and the soil would become arid. It is worth mentioning that soil moisture is generally lower in the 2050s than in the 2040s. The 2050s are a turning point in soil moisture change. Until the 2050s, the trend of soil moisture changes within the year was generally consistent.

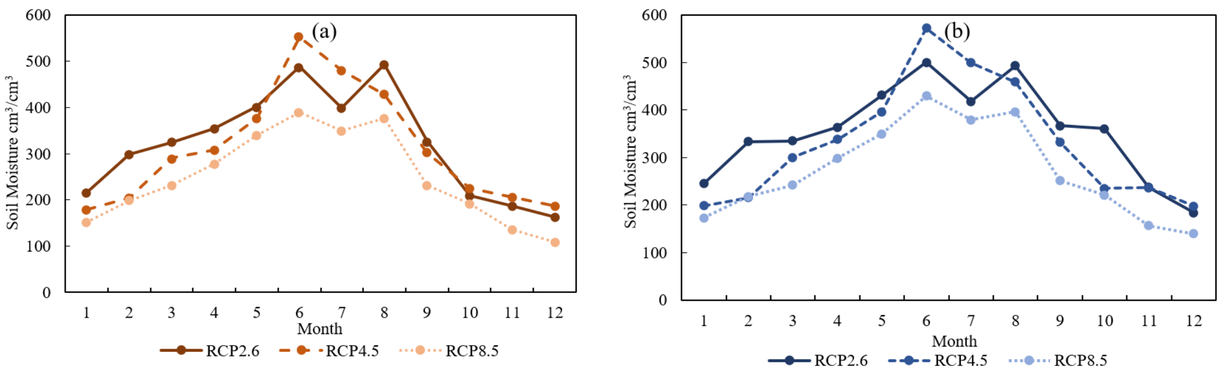

Figure 10. *Cont.*

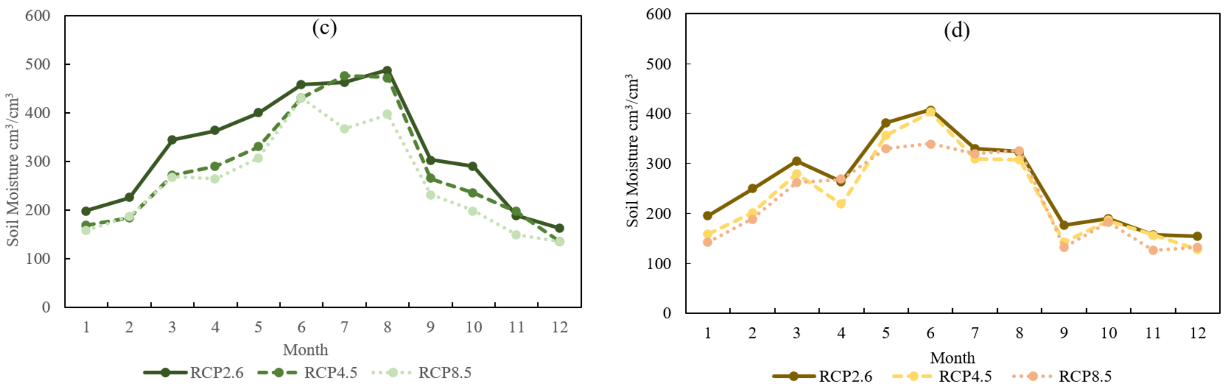

Figure 10. The annual distribution of soil moisture under the three scenarios. (**a**): The annual distribution of soil moisture under the three scenarios (2023–2100); (**b**): Soil moisture under three scenarios of 2040s (2041–2050); (**c**): Soil moisture under three scenarios of 2050s (2051–2060); (**d**): Soil moisture under three scenarios of 2080s (2081–2090).

4. Discussion

4.1. Discussion on Applicability of Downscaling Model

Compared with CMIP 3, RCPs in CMIP 5, as a concentration scenario, can more truly reflect the atmospheric greenhouse gas concentration. The types of GCMs contained in the CMIP 5 plan are more diverse, and the models are more advanced, which can better fit the regional climate characteristics and geographical characteristics.

In this paper, we modeled the temperature and precipitation in the Yellow River source area based on the emission scenarios under CMIP5. The future climate scenarios were s output in the HadCM3 model. The results showed that the SDSM model had a better simulation effect on temperature than precipitation, and temperature was more regular than precipitation, which was consistent with the results of previous findings [34]. Liu et al. [35] also showed that the SDSM model had good applicability in the source region of the Yellow River under RCP4.5. It was also found in this study that the simulation value of the SDSM model on precipitation was too high, and the application of the SDSM model can be further improved in the source region of the Yellow River.

4.2. Discussion on Applicability of SWAT Hydrological Model

In this study, the database construction process and parameter selection of the SWAT model were calibrated and verified. Similar research results have also been found in previous studies [36,37], but they were slightly different from the results of Che et al. [38] in terms of parameter selection, error value and fitting value. The reason may be that Che et al. only simulated the daily runoff process from 1998 to 2003, and did not consider the influence of meteorological and land use factors on precipitation, runoff, evapotranspiration and other environmental factors in the source region of the Yellow River over a long period of time. In this case and the simulation results were more consistent with the actual measurement results. Some scholars put forward the standard that the relative error of runoff simulation in the basin using hydrological models was less than 20%. However, in the actual research process, it was found that the data for most research results were lower than 10% [37,38]. The relative error in this study was within the range of ±5%, indicating that the data obtained by model simulation in a longer time scale was more accurate. Increasing the accuracy of the model by improving the applicability criteria of the SWAT model is of great importance in future research.

The rivers in the Yellow River source area are recharged by glacial snowmelt. Moreover, due to the spring flood, the measured value from March to May is smaller than the simulated value. Wang et al. [39] used the SWAT model to simulate the surface runoff in the Yellow River source area and found that the SWAT model has glacier and snowmelt operational modules. However, the module structure is relatively simple and cannot accurately simulate the glacier snowmelt process. Moreover, due to the spring flood, the measured value from March to May is smaller than the simulated value. This is consistent with the comparison between simulated and observed values in this paper. In future research, the model can be further improved to carry out spring melt snow and ice runoff simulations, set different underlying surface change scenarios, and quantitatively evaluate the impact of underlying surface change on the hydrological process, so as to further improve the simulation accuracy.

Based on the actual observation of the hydrographic station in the source area and the simulation of the SWAT model, this study concluded that the runoff showed a fluctuating rising trend from 1961 to 1975, did not change in a wide range, and showed a stable trend from 1975 to 1990, but showed a downward trend after 1990. The result of this study was basically consistent with many previous studies [40,41]. At the same time, the results of monthly runoff results in the source region of the Yellow River were evaluated. The difference between the simulated and actual total water amounts in the periodic and verification periods was −1.4% and 3.9%, respectively. The difference values obtained were within a reasonable range.

4.3. Discussion on the Change Trend of Surface Runoff in the Source Region of the Yellow River

An analysis of precipitation and temperature data from 1956 to 2010 showed a distinct historical decrease in runoff, which is consistent with the results of Li et al. [42]. Cheng et al. [43] used the VIC hydrological model to predict future runoff in the source region of the Yellow River and Yangtze River. They concluded that there is a subtle difference in the overall trend of runoff reduction and that precipitation will increase in both areas. However, the Yellow River basin runoff is expected to decrease by 1.98% by 2080–2099. Several studies suggest that the main drivers of future decreases in surface runoff in the region are decreases in precipitation and increases in evaporation [44]. Chen et al. [45], Wei, et al. [46] collected meteorological data from eight representative sites in the source area, calculated the temperature and precipitation by the Thiessen polygon method, and studied the relationship between temperature, precipitation, and surface runoff using linear regression. They predicted that the increase in the runoff of the source region of the Yellow River would show an increasing trend in the immediate future, which contradicts the results of this study. This is possible because surface runoff is mainly affected by precipitation and temperature, and temperature itself mainly affects evaporation [47], so it is possible that precipitation increases while evaporation decreases. Alternatively, it could be the result of their model running over a shorter period. This may be attributed to the fact that from March to May every year, the glacier snowmelt increases the runoff, while the glacier snowmelt module in the SWAT model is relatively simple, so the simulated result is lower than the actual runoff. In summer and autumn, from June to October, the rainfall began to increase, and the simulated value simulated by the model was close to the actual measured value. However, floods sometimes occurr due to excessive rainfall. As the water volume was adjusted by Zaling Lake and Ealing Lake in the upstream region of the Yellow River, the simulated large flood value was high, while the medium flood value was low. From November to February of the next year, the temperature decreased, the runoff began to decrease, and the simulated value was not far from the actual value.

4.4. Discussion on the Change Trend of Soil Moisture in the Source Region of the Yellow River

Jin et al. [48] analyzed the trend of local precipitation by the non-parametric test method and established a VIC model to simulate the runoff and soil in the source region of the Yellow River in the future using the temperature, runoff, and rainfall data observed by 21 meteorological stations. They also found that soil moisture was predicted to generally decrease in the future. A pattern of lower soil content in winter and higher water soil water content in summer was suggested by Liu [49], who studied data from the source region of the Yellow River from 1992 to 2000. As can be seen from our results, this pattern was predicted to become less pronounced in the future, which could have implications for flood management planning and for wildlife adapted to the current conditions. This change in pattern and predicted general lowering of flow could have significantly reduced sediment load in the river. Such a reduction would have significant impacts on a river that transports high sediment loads, such as the Yellow River. The soil surface moisture in the whole Yellow River basin is lower in the northwest and higher in the southeast. Liu et al. [41] analyzed the variation characteristics of the water resources cycle in the Yellow River Basin by using the Mann-Kendall method. The results found that both runoff and soil moisture showed a decreasing trend, and the decrease in soil moisture was less significant. Chen et al. [50] combined the data of soil moisture and meteorological station data and argued that increasing temperatures in the region would lead to an increase in soil moisture rather than decrease. This conclusion was contrary to the downward trend of soil moisture obtained in our study. The apparent contradiction may be related to the complex effects of climate change on soil moisture, mainly temperature, precipitation [51]. Temperature and precipitation have significant effects on soil moisture. Increased precipitation increases soil moisture, and higher temperatures led to increased evaporation in the summer but may also increase sources of frozen precipitation in the winter. As reported by Shao et al. [52], if the evaporation of water was greater than the increase in precipitation, the soil moisture decreased. Further study should be undertaken to clarify some of the interrelationships between evaporation, sunshine hours, grazing, and other land uses, and their impacts on both soil moisture and runoff.

A limitation of this paper is that the changes in surface runoff and soil moisture between scenarios under the CMIP6 climate model were not compared. The multi-model, integrated CMIP6 could greatly improve the simulation ability of climate and interannual variability. Based on previous comparisons, CMIP6 was found to enhance the ability to simulate the spatial distribution of rainfall in humid and semi-humid areas under future scenarios [53], while there was no significant difference in the prediction and simulation capabilities between CMIP6 and CMIP5 in the high-altitude cold region [54]. However, the differences in predictions of the latest and more perfect CMIP6 model for high altitude/cold regions are yet to be further developed. The CMIP5 model (which has been applied maturely in China) was adopted to improve the ability to simulate and forecast climate elements. The understanding of the mechanisms of climate system change has also been enhanced [55]. However, due to the high altitude and cold region of the study area, the simulation results were still uncertain. Therefore, the adaptation evaluation of CMIP5 to climate change simulation results in high-altitude cold areas is the focus of further improvement and application of the current climate models.

5. Conclusions

The SWAT model rate had a regular R^2 of 0.876 and a validation period R^2 of 0.972, both of which met the criteria of goodness, which indicated the strong applicability and credibility of the model in the source region of the Yellow River.

The surface runoff in the source region of the Yellow River from 2011 to 2022 shows an overall increasing trend, and the soil moisture content shows an increasing trend year by year. The trends between surface runoff and mean annual temperature from 2011 to 2022 are highly significant, indicating that surface runoff flow is more significantly influenced by temperature. The trends between surface runoff and average annual precipitation were not significantly different. The difference in trends between soil moisture and average annual temperature was highly significant. The trends in average annual precipitation and soil moisture were not significant.

The Interannual difference of surface runoff from 2021 to 2100 would be large in the source region of the Yellow River, and the overall distribution showed a downward trend; and the decrease rate was RCP8.5 > RCP4.5 > RCP2.6. The interannual variation of soil moisture showed a downward trend, and the interannual variation was relatively large, with a decreasing range of RCP8.5 > RCP4.5 > RCP2.6. It is urgent to strengthen water resources and soil protection and management.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15112104/s1, Figure S1: Flow Chart; Table S1: The basic information about 21 CMIP5 global climate model.; Table S2: SWAT model parameters and their implications.

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