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Response of Runoff and Sediment Yield from Climate Change in the Yanhe Watershed, China

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ABSTRACT

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Changes in temperature and precipitation in the Loess Plateau, China have been studied for many years. The runoff and sediment yield in the Loess Plateau are sensitive to global climate change. Understanding the characteristics of runoff and sediment will be of great importance in the future. The Soil and Water Assessment Tool (SWAT) was used to simulate the runoff and the sediment yield in the Yanhe watershed, a typical water basin with soil erosion in the Loess Plateau. The resulting statistics of the SWAT simulation of the runoff and sediment yield were acceptable. The rainfall for the period from 2010 to 2099, as predicted by the Statistical Down Scaling Model (SDSM), was used to simulate the runoff and sediment yield in the future, using SWAT. Compared with the period from the 1980 to 2000, the annual precipitation increased by 9.2% to 16.4%. Under simulated future climate change, the annual runoff of the Yanhe watershed changes averaged -2.6% to 52.7%, compared with the baseline period. In the context of future climate change, in general, the runoff distribution was more even within the year when it increased significantly from March to May and decreased from July to August. The variations of the sediment yield for the watershed were -31.3% to 62.5% compare with the period from the 1980 to 2000. Overall, the trends of the sediment yield for the watershed were consistent with the runoff.

ADDITIONAL INDEX WORDS: *Climate change, SWAT model, SDSM, runoff, sediment yield.*

INTRODUCTION

Global climate change has lead to changes in the temporal and spatial distribution of precipitation, evaporation, and runoff, which in turn contribute to environmental issues such as the frequent droughts, increased flooding, waterlogging disasters, and aggravated soil erosion (IPCC, 2007). Surface water resources play a key role in crop production and human survival, making regional water resources affected by climate change a key issue in global research. It is believed that global warming changes the regional water cycle and leads to an increase of river runoff at high altitudes, and a decrease of runoff in certain arid regions in middle latitudes and tropical regions (IPCC, 2007). In China, over the past 50 years, the combined influences of climate change and human activities have caused the total runoff of the Yangtze River to exhibit an increasing trend while the runoff of the Yellow River has shown a decreasing trend (Jiang, Su, and Hartmann, 2007; Piao *et al.*, 2010; Xu *et al.*, 2008; Yang *et al.*, 2004; Zhang, Xu, and Yang, 2009). This demonstrates the different effects that climate change has on runoff in different regions.

Precipitation and its intensity are the essential factors that climate change affects (Nearing, 2001; Zhang *et al.*, 2010). The uncertainties surrounding climate change and its impact on water resources and erosion make it necessary to conduct targeted studies on the effect of climate change on runoff and sediment yield. The Chinese Loess Plateau is an ideal area to study climate change, because it has an extremely fragile ecological environment. Clarification of the regional precipitation, trends, and the effect of climate change on runoff and sediment yield can provide important context in the study of global climate change. Prediction of the runoff and sediment yield in the Loess Plateau under future climate change scenarios is of great significance for establishing appropriate predictive measures.

METHODS

The Statistical Down Scaling Model and the Soil and Water Assessment Tool were used to study the effect of the climate change on the runoff and sediment yield, which were described in the following section.

Study Area

The Yanhe watershed is located between Hekou and Longmen town (108°38'~110°29' E, 36°21'~37°19' N, 560~1760 m altitude) (Figure 1), and is a tributary of the middle reaches of the Yellow River. The watershed has an area of 7725 km^2, and the river flows into the Yellow River at Nanhe channel in Yanchang County. The watershed has a warm temperate continental arid climate, and the mean annual temperature is

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9.3°C. The inter-annual precipitation varies greatly, but averages 514.0 mm per year. From 1952 to 2008, the highest annual precipitation was 803.0 mm and the lowest was 315.4 mm. About 70% of the annual precipitation falls between June and September, and the precipitation is distributed unevenly throughout the rest of the year. The frost-free period is approximately 170 days per year. The main terrain of the area is loess hills and gully landforms. The average gully density is 4.75 km/km^2, and the gullies occupy more than 90% of the total watershed. The main soil, silt loam loess, is extremely susceptible to erosion, and covers more than 85% of the watershed. A small amount of dark loessial soil, skeleton soil, and alluvial soil are also present in the watershed. Silt loam loess, with an average sediment transport modulus of 5300 t/km^{2}a, accounts for 93% of the watershed.

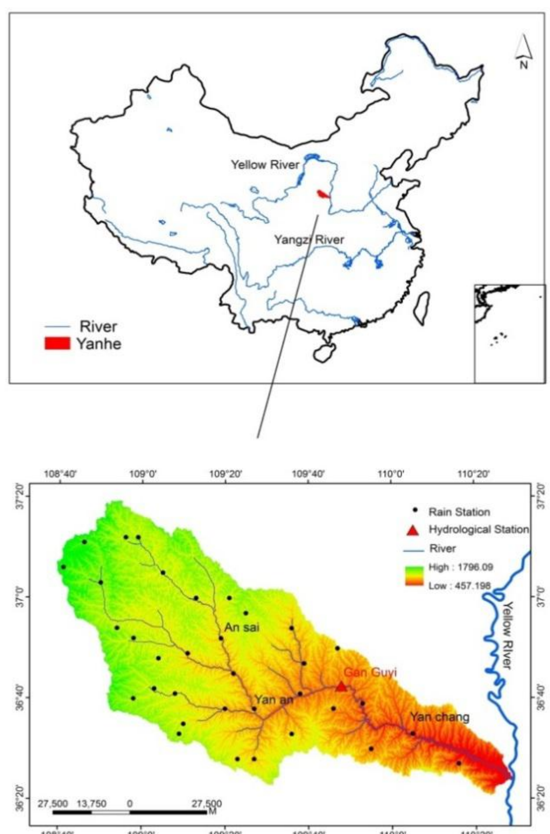

Figure 1. The location of the Yanhe watershed in the Loess Plateau of China and the hydrological and meteorological stations in the study area.

Predicted Precipitation

The Statistical Down Scaling Model （SDSM） combines the Multiply Linear Regression and the Stochastic Weather Generator. In the SDSM the Multiply Linear Regression generates statistical relationships between the National Center of Environmental Prediction (NCEP) predictors and predictands during the screening process of predictors, and the calibration process of SDSM results in regression parameters. SDSM has one conditional sub-model and one unconditional sub-model.

A dependent variable (*e.g.*, precipitation) uses the conditional sub-model, and an independent variable (*e.g.*, temperature) uses the unconditional sub-model. Then according to the predictands to choose the sub-model (Ashiq *et al.*, 2010; Wilby, Dawson, and Barrow, 2002). Both the NCEP predictor daily time series and observed daily time series are needed to run the SDSM (Huang *et al.*, 2011). Wilby, Hay, and Leavesley (1999) provide a thorough introduction of the model.

SWAT Model

The Soil and Water Assessment Tool (SWAT) was used to simulate the runoff and sediment yield of the Yanhe watershed. The NRCS curve number (CN) method was chosen to simulate the rain-runoff process. The Modified Universal Soil Loss Equation (MUSLE) was used to simulate the sediment yield. The determined coefficient (R^2) and the Nash-Sutcliffe coefficient (ENS) were the primary indicators for evaluating the accuracy of the model (Tan *et al.*, 2015). The criteria for monthly simulation results were satisfactory at $R^2 > 0.6$ and ENS >0.5.

Data Source

NCEP and HadCM3 data are necessary to predict future precipitation. The website was used to gather the 26 predictors of HadCM3 for the period of 1961-2099 under A2 and B2 scenarios and the 26 predictors of NCEP for the period of 1961-2000 (http://www.cics.uvic.ca/scenarios/sdsm/select.cgi). In order to prepare the data, and to eliminate the spatial mismatch, the NCEP predictors were sampled in the same grid resolution of HadCM3 (2.50°×3.75°). In this study, the Yanhe watershed was located in one grid. There were 23 weather stations in the watershed. We used the Ansai and Yan'an stations to screen the best predictors from 1971 to 1990 and validate the data from 1991 to 2000. The daily and monthly precipitation data for the Ansai station and Yan'an stations (1971-2000) were obtained from the China meteorological data center to obtain the screening predictors in SDSM. Then the screening predictors were used to predict the precipitation of the 21 other weather stations from 2010 to 2099, based on the data from 1980 to 2000. If $R^2 > 0.6$, the simulation results were regarded as credible.

In order to run the SWAT model, data regarding meteorological information, land use type, soil data, and topography were needed. Land use maps (1986 and 1997) containing 6 land use classifications (forest, grassland, farmland, residential areas, unused land, and water bodies) were used to provide vegetation information. A Digital Elevation Model (DEM) with a resolution of 30×30 m providing the topographical information, the soil type map (1:100,000) and soil properties was obtained from the ecological environment database of the Loess Plateau (http://www.loess.csdb.cn/pdmp/index.action). Meteorological information from 1971 to 2000, for both the Ansai station and Yan'an station, were prepared for the weather generator of the SWAT to simulate climatic features of the watershed. The monthly runoff and sediment yield measurement data from 1980 to 2000 for the Ganguyi hydrologic station were also obtained from the ecological environment database of the Loess Plateau. Since the land use map obtained in this study was for the years of 1986 and 1997, we used the monthly runoff and sediment yield of Ganguyi hydrologic station from 1984-1988 to calibrate the SWAT model and from 1995-1999 to validate the model.

RESULTS

The SWAT model and SDSM are performed well in Yanhe basin, the runoff and sediment ediment yield of the Yanhe basin can be predicted from 2010 to 2099.

Calibration and Validation of SWAT

The measurement data of the monthly runoff of the Ganguyi hydrologic station from 1984 to 1988 and from 1995 to 1999 were respectively used for calibration and validatation of the SWAT model. The simulation data of the monthly runoff showed high consistency with the measurement data. During the calibration period the model's performance evaluation index R^2 and NSE coefficients were respectively 0.89 and 0.75, while during the validation period R^2 and NSE coefficients were respectively 0.85 and 0.70 (Table 1). Although the model slightly overestimated the runoff in some months, the statistical values indicate that the SWAT model generally performed well in the simulation of monthly runoff in the watershed (Figure 2). Therefore, the model was applied in this study to predict the response of the runoff in the Yanhe watershed to future climate change.

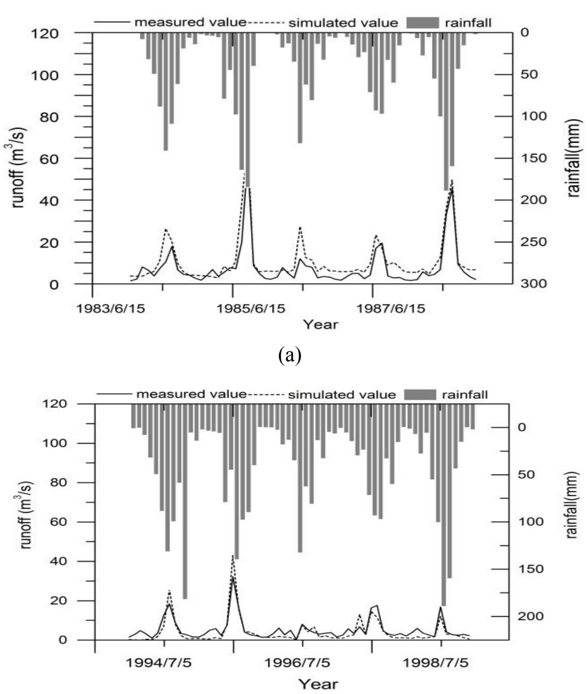

Figure 2. Observed and simulated monthly runoff during the calibration (a) and validation (b) period.

Table 1. *The modeling efficiencies of the calibration and validation period.*

Period	Runoff		Sediment Yield	
	R^2	NSE	R^2	NSE
Calibration (1984-1988)	0.89	0.75	0.71	0.69
Validation (1995-1999)	0.85	0.70	0.61	0.57

The simulation of the monthly sediment yield of the Yanhe basin was also calibrated and validated with the measurement data of the Ganguyi hydrological station from 1984 to 1988 and from 1995 to 1999, respectively. The accuracy of the simulated sediment yield was lower than the accuracy of the simulated runoff in the watershed. In the calibration period the R^2 and NSE were 0.71 and 0.69, respectively, and 0.61 and 0.57 in the validation period, respectively. Yet both the R^2 and NSE indicated that the simulation of the monthly sediment yield was acceptable in the watershed. Further, the simulation results were consistent with the measurement data during the non-flood period, though it was not as consistent in the flood period, especially in the simulation of the peak sediment yield (Figure 3).

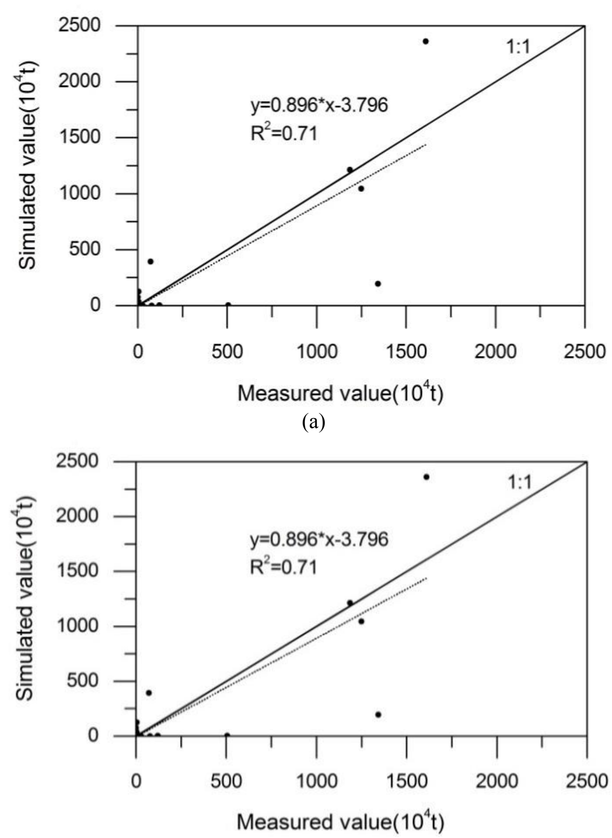

Figure 3. Scattergrams of the monthly observed and simulated sediment yield of the calibration (a) and validation (b) period.

Precipitation Predicted with SDSM

The precipitation data from 1971 to 1990 of the Yanan and Ansai stations were employed to calibrate and validate SDSM. The screening predictors were relative humidity of 500 hPa, 850 hPa, near-surface and the near-surface specific humidity, and zonal wind speed of the ground. The determinate coefficient of the average amount and probability of precipitation in wet days were both more than 80% for the two stations, which satisfied the simulation requirement (Table 2). Although it was difficult to obtain an accurate prediction of the daily precipitation, the precipitation variation could be well simulated by SDSM. Therefore, based on the selected predictors, SDSM projected the future precipitation of the Yanhe watershed under the A2 and B2 scenarios.

Table 2. *The modeling efficiencies of SDSM in the validation period.*

Station	Monthly Precipitation of Wet Days (mm/d)			Probability of Precipitation (%)		
	R^2	E_r	E_s	R^2	E_r	E_s
Yan'an	0.95	0.35	0.79	0.94	0.04	0.05
An sai	0.93	-0.12	0.71	0.84	0.08	0.10

From 1980 to 2000, the annual precipitation in the Yanhe watershed averaged 473.6 mm. 80% of the annual precipitation occurred in months 5-9. Here, this period was used as a base line to analyze the precipitation trend in the Yanhe watershed over the next 90 years. Under the A2 and B2 scenarios, the precipitation in the watershed generally increased over the next 90 years (Figure 4). The precipitation of the 2020s, 2050s, and 2080s increased by 9.21%, 12.51%, and 16.38%, respectively under the A2 scenario, while it increased 9.24%, 13.17%, and 13.68%, respectively under the B2 scenario. In the 2020s and 2050s, the difference of the increased precipitation was not so remarkable. The increasing trend of the A2 scenario was more significant than the B2 scenario only in the 2080s. Further, the increase of precipitation mainly occurred from the 3rd through 5th months, which showed an increase of 12% to 41%. Compared with the results above, the increase in months 6-9 was smaller, with a value from 0.35% to 9.9%.

The simulation results of this study were consistent with results that have been reported by other scholars. Using the SDSM method, Zhao *et al.* (2008) predicted that the precipitation in Northwest China over the next 30 years would increase compared with the period of 1950 to 2000. Based on the CLIGEN and GCM model, Zheng *et al.* (2009) also predicted the precipitation of the Ansai County in the Loess Plateau would have a clear increase in the next four decades. The simulation results of precipitation in this study were acceptable when compared to previous research. The SWAT model could be used to predict the runoff and sediment yield trends in this study area.

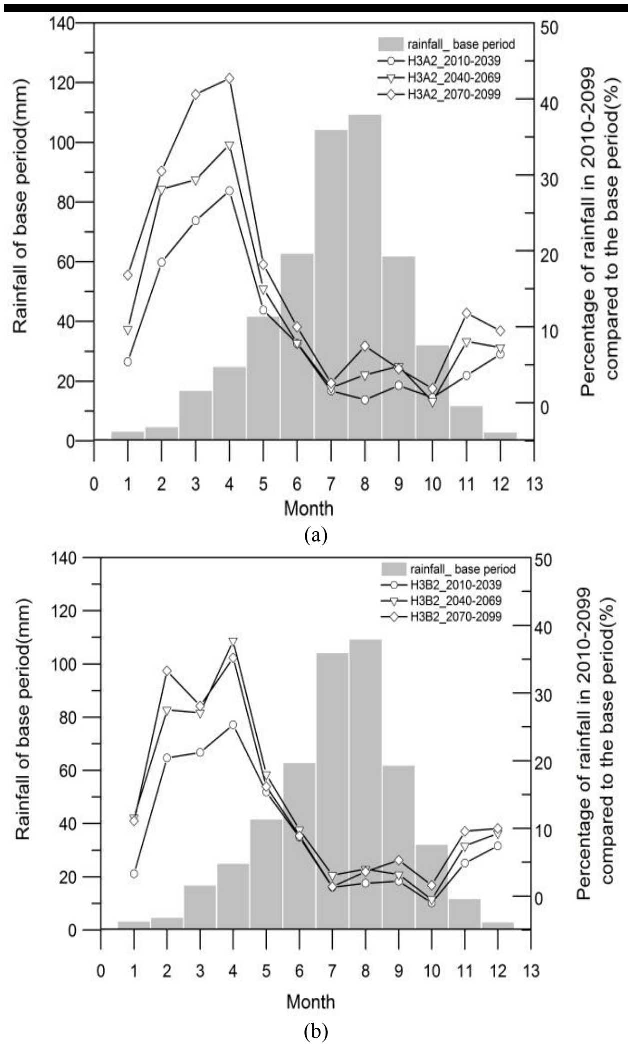

Figure 4. The relative change of monthly precipitation comparing the base period in A2(a) and B2(b) scenarios over the next 90 years.

Runoff and Sediment Yield Predicted with SWAT

During the base period, the annual average runoff of Yanhe watershed was 2.05×10^8 m^3 of which was mainly distributed in months 3-10. The runoff was highest in August with a value of 0.51×10^8 m^3 and the next highest runoff was in July with a value of 0.41×10^8 m^3. The runoff of those two months accounted for 50% of the total annual runoff. Compared to the base period, the annual average runoff for the 2020s, 2050s, and 2080s had a change of -3.9%, 15.7%, and 129.9%, respectively under the A2 scenario, and -2.6%, 52.7%, and 41.8%, respectively under the B2 scenario (Figure 5). The increase in the annual average runoff was significant in the 2050s and 2080s. The increase in the 2080s is particularly notable, as, under the A2 scenario, the annual average runoff was double that of the base period.

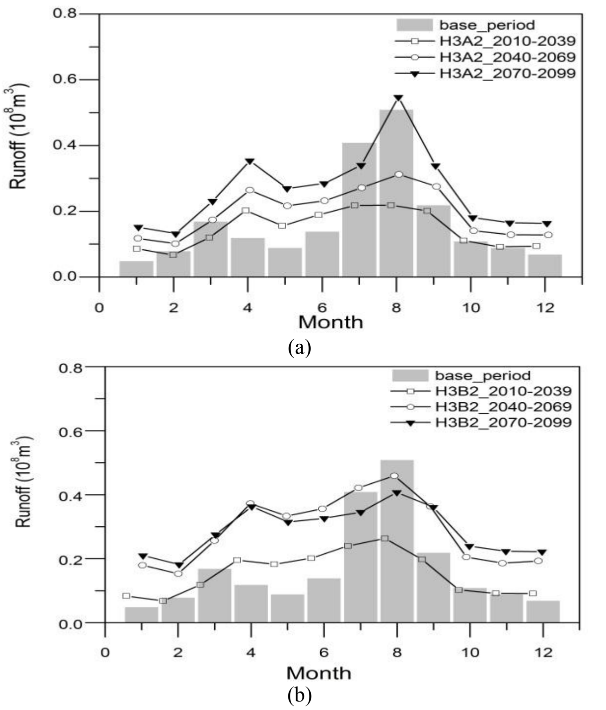

Figure 5. The monthly runoff of the base period and 2010-2099 in the A2(a) and B2(b) scenario.

The variation of the monthly runoff in the Yanhe watershed showed that the increase of runoff mainly occurred in months 4-6. The runoff in the other months was generally less than the base period, except in months 7-8 in the 2080s under the A2 scenario. Compared with the base period, in the future climate conditions, the distribution of runoff within a year would change such that it would increase in months 3-5 then decrease in months 7-8. The increased runoff in months 3-5 could be attributed to the increase of precipitation in those months under the future climate scenarios. Additionally, the vegetation coverage during this period remains small, which is conducive of conversion of precipitation to runoff, resulting in an increase in runoff during this period.

During the base period, the Yanhe watershed had an annual average sediment yield of 0.32×10^8 t. Compared with the base period, the sediment yield had a variation in the 2020s, 2050s, and 2080s of -34.3%, 18.7%, and 34.3%, respectively under the A2 scenario and -31.3%, 62.5%, and 62.5%, respectively under the B2 scenario (Figure 6). Generally, the variation trend of the annual sediment yield was similar to the runoff trend, but the amplitude of variation in the annual sediment yield was smaller than runoff in the A2 and B2 scenarios.

In the base period, the sediment yield of the watershed mainly occurred in months 6-9 while other months had a yield that was almost zero. The distribution range of the sediment yield within a given year expanded to months 3-10 in future climate condition under the A2 and B2 scenarios. The sediment yield apparently increased in months 4-5 while it decreased in months 7-8. This appeared to be consistent with the variation trend of the runoff.

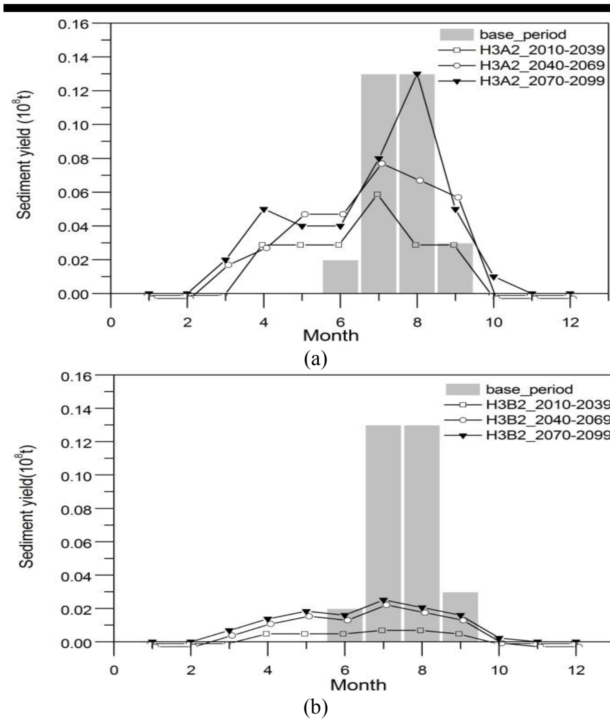

Figure 6. The monthly sediment yield of the base period and 2010-2099 in A2(a) and B2(b) scenarios.

DISCUSSION

Under the A2 and B2 scenarios the annual average runoff of the Yanhe watershed during 2010 to 2099 changed, compared with the base period, from -3.9% to 129.9% and from -2.6% to 41.8%, while the average annual sediment yield changed from -34.3% to 34.3% and -31.3% to 62.5%, respectively. These results were in agreement with previous studies in the Yellow River watershed. Zhang *et al.* (2007) predicted that the annual runoff would have a tendency to increase during the period of 2006 to 2095, with a variation of -48% to 203% in different areas of Yellow River. Coupling the SWAT model with four GCMs, Li *et al.* (2009) predicted that the annual runoff would change from -19.8% to 37% in the Heihe river during the period 2010 to 2039. Furthermore, Cao, Zhang, and Luo (2010) simulated the annual runoff and sediment yield in the Jinghe River of the Loess Plateau, and found that, based on the output of 5 GCMs' climate results, in the period of 2010 to 2099, the variation of annual runoff and sediment yield ranged from -9.3% to 53.4% and from -11.1% to 64.6%, respectively. It should be noted that due to the differences of study areas and methods, the variation of predicted runoff and sediment yield in the above research are not completely consistent with the findings of this study, but the variation trends are in close agreement with our results, which increases the credibility of research into the prediction results of runoff and sediment of Yanhe watershed. The accuracy of the simulation of future climate change directly influences predictions of the runoff and sediment yield. Reducing the uncertainty of climate change simulation remains a key issue for predicting the watershed hydrological processes with regard to future climate change.

CONCLUSIONS

The SWAT model is used for simulating the monthly runoff and sediment yield in the Yanhe watershed. The simulation results in the monthly runoff were better than the results of the monthly sediment yield. The maximum deviation mostly occurred in modeling the peak runoff and sediment yield during the flood season.

The precipitation of the Yanhe watershed during the period of 2010 to 2099 showed an increasing trend in the A2 and B2 scenarios. The increased precipitation of the watershed was concentrated on months 3-5 over the next 90 years. Compared with the base period, the annual average runoff of the Yanhe watershed changed from -3.9% to 129.9% and from -2.6% to 41.8% in the A2 and B2 scenarios during the period of 2010 to 2099. The distribution of the runoff would be more even within a year that had an increase in precipitation in months 3-5 but a decrease in months 7-8. The variation of sediment yield relative to the base period ranged from -34.3% to 34.3% under the A2 scenarios and -31.3% to 62.5% under the B2 scenarios, which was small compared with that of the runoff. The sediment yield in the study area showed an increase in months 4-5 but a decrease in months 7-8, which was in close agreement with the changes of the runoff. Future companion papers in this series will address a more complete description of these nearshore wave processes.

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