HYDROLOGICAL PROCESSES
Hydrol. Process. **26**, 2733–2744 (2012)
Published online 18 November 2011 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.8378

Impact of climate change on streamflow in the arid Shiyang River Basin of northwest China

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Abstract:

Climate change may significantly affect the hydrological cycle and water resource management, especially in arid and semi-arid regions. In this paper, output from the Providing Regional Climates for Impacts Studies (PRECIS) regional climate model were used in conjunction with the Soil and Water Assessment Tool (SWAT) to analyse the effects of climate change on streamflow of the Xiying and Zamu rivers in the Shiyang River basin, an important arid region in northwest China. After SWAT model calibration and validation, streamflow in the Shiyang River Basin was simulated using the PRECIS climate model data for greenhouse gas emission scenarios A2 (high emission rate) and B2 (low emission rate) developed by Intergovernmental Panel on Climate Change. Monthly streamflow and hydrological extremes were compared for present-day years (1961–1990), the 2020s (2011–2040), 2050s (2041–2070) and 2080s (2071–2100). The results show that mean monthly streamflow in Shiyang River Basin generally increased in the 2020s, 2050s and 2080s between 0.7–6.1% at the Zamu gauging station and 0.1–4.8% at the Xiying gauging station. The monthly minimum streamflow increased persistently, but the maximum monthly streamflows increased in the 2020s and slightly decreased in the 2050s and 2080s. This study provides valuable information for guiding future water resource management in the Shiyang River Basin and other arid and semi-arid regions in China. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS climate change; streamflow; SWAT; PRECIS; Shiyang River Basin

Received 5 May 2011; Accepted 12 October 2011

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) concluded that it is more than 90% likely that accelerated warming of the past 50–60 years is caused by the anthropogenic release of greenhouse gases, such as CO_2 (IPCC, 2001, 2007). These greenhouse gas releases are largely from the burning of fossil fuels. Increases in temperature, along with altered precipitation patterns and intensities, from global warming have been widely recognized and may have a significant impact on regional hydrological cycles. These effects will be particularly severe in arid and semi-arid regions where low precipitation is the limiting factor for urban and agricultural development. Various climate research center analyses indicate that the global mean surface temperature in 2006 was approximately 0.42–0.54 °C above the 1961–1990 annual average (WMO, 2006). For the next century, the IPCC (IPCC, 2007) projects a warming of approximately 0.2 °C per decade based on a range of IPCC greenhouse gas emission scenarios. A further warming of about 0.1 °C per decade would be expected even if the concentrations of all greenhouse gases and aerosols remain constant at year 2000 levels. Global climate models (GCMs) indicate that it is very likely (greater than 90% probability) to expect more frequent regional extremes of heat and heat waves and heavy precipitation events (IPCC, 2007), which would lead to potentially large differences in regional precipitation amounts. Increases in temperature will cause increases in potential evapotranspiration and decreased snow pack in mountainous regions. Furthermore, it is generally understood that as the climate becomes drier, the sensitivity of the hydrological cycle increases (Chen *et al.*, 2005). These changes, along with altered precipitation patterns and intensities, are likely to cause significant changes in streamflow volume and timing, attributes which are extremely important for proper water reservoir management.

Future changes in streamflow and watershed hydrology caused by climate change have become increasingly important topics for water resource management. Numerous studies suggest that winter and spring discharge can be either increased or decreased by seasonal shifts in snow accumulation, snowmelt and discharge of winter precipitation as opposed to the formation of snowpack (e.g. Lettenmaier and Gan, 1990; Burn, 1994; Hagg *et al.*, 2007). Annual streamflow also may increase or decrease because of changes in precipitation and evapotranspiration (e.g. Singh and Kumar, 1997; Albek *et al.*, 2004). Using present day precipitation patterns, studies have shown that higher temperatures lead to increased evaporation rates,

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reduced stream flow and increased frequency of droughts (e.g. Rind *et al*., 1990; Schaake, 1990; Nash and Gleick, 1991, 1993). Therefore, there is great concern for water resource availability in arid river basins where climate change is expected to have a significant impact.

Much work has been performed on climate and streamflow changes for individual basins in arid and semi-arid regions throughout the world (e.g. Chen *et al*., 2006; Kader and Hiroshi, 2006; Li *et al*., 2006; Ma *et al*., 2008; Ficklin *et al*., 2009a). These studies show that climate changes have and will continue to influence streamflow discharge. Chen *et al*. (2005) analysed changes in mean temperature in northwest China and concluded that this region may be one of the most sensitive to global warming in the world. Li *et al*. (2008) examined streamflow discharge trends and found that annual and monthly streamflow of the Zamu, Huangyang and Gulang Rivers in northwest China show statistically significant decreasing trends since 1958 because of both human activities and climate changes. They found that between 21 and 79% of the reduction in runoff from the mainstream was cause by the impact of climate change during the past few decades. Lai and Ye (1995) investigated streamflow discharge time series at mountain outlets in northwest China from 1955 to 1985 and found mostly positive anomalies before 1973, whereas negative anomalies were most frequent after 1973. Shi and Zhang (1995) analysed several climate factor trends and concluded that the mountainous regions of northwest China will be approximately 1 °C warmer by 2030, leading to increases in evapotranspiration and subsequent streamflow changes.

The Shiyang River Basin in the Hexi corridor of China, a river basin in arid northwest China, was selected as the study area. This study builds upon previous work that has characterized the potential climate change impacts on water resources in this region (e.g. Chen *et al*., 2006; Huo *et al*., 2008; Li *et al*., 2008). In arid regions such as the Shiyang River Basin, where limited water resources inhibit suitable water use, it is important to understand hydrological responses to potential climate change to be able to develop sustainable water resource management strategies for the future. Specifically, for the years leading up to 2100, we want to determine the changes of climate change on streamflow that feed the reservoirs that deliver water to the downstream population. Although this time frame may be distant, the year 2100 is not beyond the lifetime of most water resource management infrastructure or the institutions that govern it. A century also is often required to develop and establish extensive innovations in water management (Tanaka *et al*., 2006). With the potential for increased human activity within the region, it is extremely important to determine what, if any, water resources will be available under a changing climate.

The objectives of this study were as follows: (i) to calibrate and validate the hydrological model in terms of streamflow for two rivers in the Shiyang River Basin; and (ii) to understand how climate change will affect future streamflow in the Shiyang River Basin, such as mean, minimum and maximum monthly streamflows. Climate and hydrological data over the past 20 years were used to initiate the hydrological model Soil and Water Assessment Tool (SWAT) to assess climate change impacts. Regional climate model (RCM) data from the Providing Regional Climate for Impact Studies (PRECIS) RCM for the greenhouse gas emission scenarios of A2 and B2 were incorporated into the calibrated and validated hydrological model. The A2 scenario represents a divided world, with a continuously increasing population with an emphasis on economic regional development. The B2 scenario represents a more integrated world with a slower rate of population increase than the A2 scenario, with an emphasis on environmental stability. The results can provide useful information for water resource managers to better understand the likely consequences of climate change in hydrological systems in other regions in China or other countries in the world with similar climatic conditions.

MATERIALS AND METHODS

Site description

The Shiyang River Basin (36°29'–39°27'N and 101°41'–104°16'E) occupies an area of 41 600 km^2 within the Hexi corridor in Gansu Province, west of Wushaoling city and north of the Qilian Mountains in China (Figure 1). The headwaters are derived from the cold and humid to semi-arid Qilian Mountain zone and flow to a downstream warm temperate zone in the Minqin Basin (Tang *et al*., 1992). The headwater rivers from east to west are Dajing, Gulang, Huangyang, Zamu, Jinta, Xiying, Dongda and Xidahe (Figure 1). These rivers can be divided according to hydrogeological units into the three separate river systems: Dajing River, Six River and Xidahe Rivers. The mean annual runoff is 1.575 billion m^3. Streamflow for the Shiyang River is mainly from the five tributaries of Gulang, Huangyang, Zamu, Jinta and Xiying (Li *et al*., 2008).

The mean annual precipitation varies, with 300–600 mm in the mountain regions, 150–300 mm in the Wuwei Basin and less than 100 mm in the Minqin Basin. The annual precipitation shows a seasonal distribution, with approximately 81–89% of the total rainfall occurring from May to October (Li *et al*., 2008). The annual potential evapotranspiration ranges from 700 mm in the mountains to more than 2600 mm in the desert plain. Therefore, water resources are primarily derived from precipitation and glacial melt in the Qilian Mountains.

The total population in the Shiyang River Basin in 2003 was approximately 2.27 million people, with urban and rural populations of 0.73 million and 1.54 million, respectively. The urban population is mostly concentrated in the Liangzhou and Jinchuan districts. The total agricultural irrigation area is approximately 304 500 ha. Twenty-four water reservoirs with a storage capacity of 478 million m^3 were built to meet water resource needs for the downstream populations.

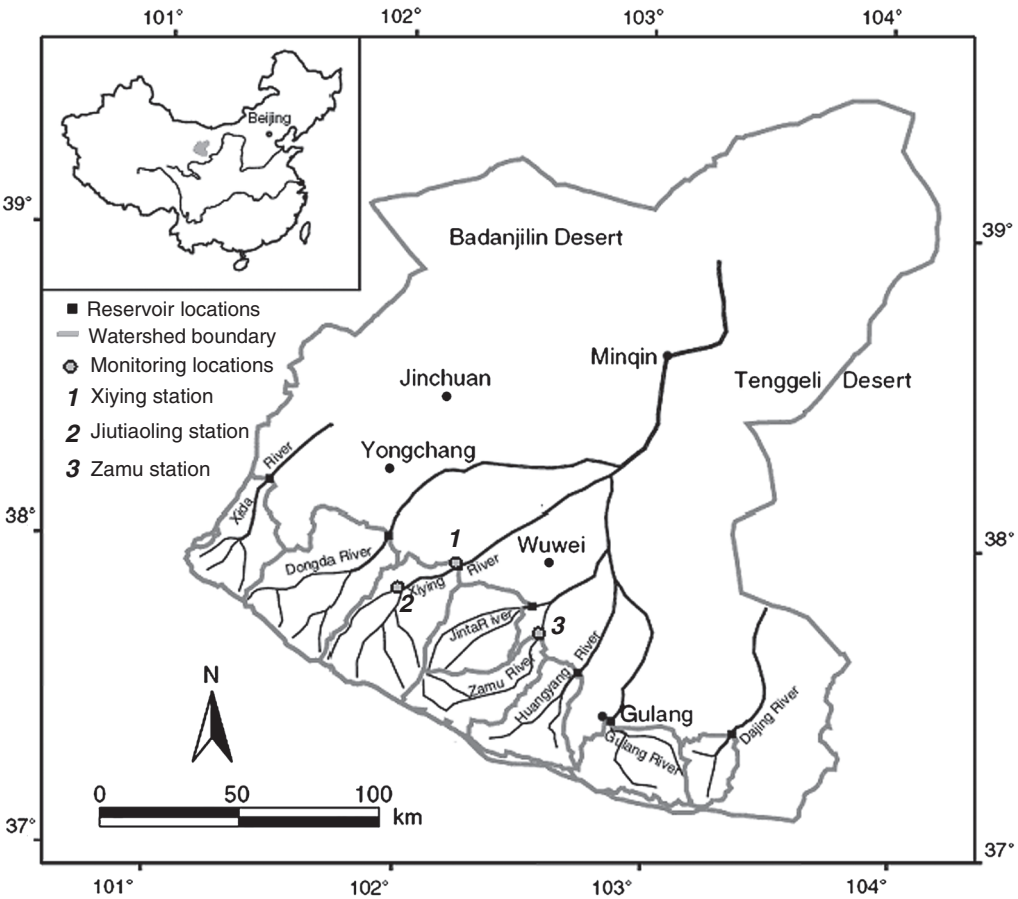

Figure 1. Location of the Shiyang River Basin and the monitoring locations used in the study (adapted from Ma *et al*., 2008)

SWAT model

The SWAT model was selected for this study because of its worldwide use and validation (Gassman *et al*., 2007). Also, SWAT has been used for numerous climate change case studies throughout the world (e.g. Fontaine *et al*., 2001; Eckhardt and Ulbrich, 2003; Chaplot, 2007; Guo *et al*., 2008; Schuol *et al*., 2008; Ficklin *et al*., 2009a, 2009b). SWAT is a hydrological/water quality model developed by the US Department of Agriculture–Agricultural Research Service (Arnold *et al*., 1998). The model is a continuous-time, spatially distributed simulator of the hydrological cycle and agricultural pollutant transport at the catchment scale. It runs on either a daily or a monthly time step. A monthly time step was used for this study. Major model components are weather conditions, hydrology, soil properties, plant growth and land management, as well as loads and flows of nutrients, pesticides, bacteria and other pathogens. A detailed description of SWAT can be found in Neitsch *et al*. (2005).

The modelled hydrological processes are divided into two phases: the land phase and the water routing phase. The land phase controls the timing and volume of water and pollutant load flow into the receiving waters. The water routing phase simulates movement through the river system. The streamflow volume is estimated using the modified SCS curve number method (SCS, 1984), a value that combines soil, land use, and management information. The curve number is adjusted at each time step based on the amount of soil water present. Routing in the channels can be divided into the four components of water, sediment, nutrients and organic chemicals. Multiple methods are available to calculate potential evapotranspiration and the Penman–Monteith (Penman, 1948; Monteith, 1965) method was used in this study.

In SWAT, a watershed is divided into multiple subwatersheds, which are then divided into units of unique soil/land use characteristics called hydrological response units (HRUs). These HRUs are defined as homogeneous spatial units characterized by similar geomorphological and hydrological properties (Flugel, 1995). In SWAT, HRUs are composed of a unique combination of homogeneous soil properties and land use. For example, a specific HRU land unit may contain a sandy loam and wheat fields. User-specified land cover and soil area thresholds can be applied that limit the number of HRUs in each subwatershed. For this study, only land use and soil properties that comprise over 10 and 20%, respectively, of the subbasin were used for HRU definition. Using these values yielded 147 subbasins and 676 HRUs. HRU water balance is represented by five storage components: canopy interception, snow, soil profile, shallow aquifer and deep aquifer. Flow generation is summed across all HRUs in a subwatershed, and the resulting flows are then routed through channels, ponds and/or reservoirs to the watershed outlet.

The plant growth component of SWAT utilizes routines for plant development based on plant-specific input parameters, which are summarized in the SWAT plant growth database. From these parameters, SWAT computes plant growth output characteristics such as biomass and leaf area index. The heat unit theory is used to regulate the plant growth cycle (Boswell, 1926; Magoon and Culpepper, 1932). In this theory, predictions of plant development are estimated based on the amount of heat absorbed by the plant. Potential plant growth is calculated at each time step of the simulation and is based on growth under ideal growing conditions, that is, adequate water and nutrient supply and a favorable climate.

It is important to note that the land use was assumed to remain constant throughout all climate change simulations. Implications of this assumption are widespread, as any change in urban or agricultural area will have a large effect on the hydrological cycle. For example, an increase in urban area will result in an increase in impermeable surfaces leading to an increase of surface runoff. However, because of the vast amounts of mountain and desert land, urbanization and agriculturalization may not be an issue, as the land is inhabitable.

Data sources

Soil and Water Assessment Tool input parameter values such as topography, landscape and weather data were compiled from various sources (Table I). Digital elevation models were obtained from the United States Geological Survey (USGS, 2009). Land use and soil property data were obtained from the Institute of Geographic Sciences and Natural Resources in the Chinese Academy of Sciences. The land use data contain a broad scale classification of land use within the study area. The soil property data contain soil physical property data such as maximum rooting depth, porosity and available water content. Land use and soil property spatial patterns are assumed to remain constant through the simulations. Weather data, such as precipitation, temperature, wind speed, solar radiation and relative humidity, were obtained from the Water Resources Bureau of the Shiyang River Basin and the China Meteorological Bureau. Model initialization and evaluation were based on water monitoring data obtained at gauges extracted from the Water Resources Bureau of the Shiyang River Basin. Table I summarizes the data sources and their resolution. Figure 1 displays the locations of the hydrology gauging stations.

SWAT model calibration and validation

Soil and Water Assessment Tool contains over 200 hydrological parameters, and therefore, the most sensitive parameters must be chosen for calibration. The calibration method used was the Latin hypercube-one-at-a-time (LH-OAT) analysis method developed by van Griensven *et al*. (2006). The LH-OAT method performs Latin hypercube sampling followed by one-at-a-time sampling. It starts by taking N Latin hypercube sample points for N intervals and then varying each Latin Hypercube sample point P times by changing each of the P parameters one at a time. Full details about the LH-OAT sensitivity analysis procedure can be found in van Griensven *et al*. (2006). Only the change of streamflow was used in the sensitivity analysis.

Model calibration was performed using the Shuffled Complex Evolution method developed by Duan *et al*. (1992). Model performance was defined based on three model evaluation indicators: volume error (rVol), correlation coefficient (R^2) and the Nash–Sutcliffe efficiency coefficient (NSEC). The definitions of these indicators are shown in Table II. After calibration and validation, we evaluated the simulated streamflow using root mean square error (RMSE) and mean absolute error (MAE). The calibration and validation periods are from 1988 to 1999 and 2000 to 2005, respectively. The subbasin calibration parameters based on Zamu and Jiutiaoling gauging stations (Figure 1) were populated and then input into the Xiying subbasin as initial calibration parameters. These base calibration sites were chosen because there are no reservoirs on their reach and are therefore assumed to mimic natural streamflow characteristics. These initial calibration parameters for the reservoir-affected subbasins were then adjusted accordingly to match observed discharge data.

Table I. Input data for Shiyang River Basin Soil and Water Assessment Tool model

Data type	Scale	Origin	Data attribute
Digital elevation model	1:24 000	United States Geological Survey	Elevation
Land use	1:1 000 000	Institute of Geographic Sciences and Natural Resources in the Chinese Academy of Sciences	Land use
Soil type	1:4 000 000	Institute of Geographic Sciences and Natural Resources in the Chinese Academy of Sciences	Soil physical and chemical data
Precipitation station	1988–2008	Water Resources Bureau of the Shiyang River Basin	Daily precipitation
Weather station	1988–2008	China Meteorological Bureau	Daily wind speed, maximum and minimum temperature, relative humidity, solar radiation
Hydrology station	1988–2005	Water Resources Bureau of the Shiyang River Basin	Daily quantity of runoff

Table II. Evaluating indicators of streamflow simulations

Formula	Name of indicator	Perfect simulation value
$rVol = \frac{\sum(Q_{ob,i}-Q_{si,i})}{\sum Q_{ob,i}}$	Volume error	0
$r = \frac{\sum(Q_{ob,i}-\bar{Q}_{ob})\cdot(Q_{si,i}-\bar{Q}_{si})}{\sqrt{\sum(Q_{ob,i}-\bar{Q}_{ob})^2\cdot\sum(Q_{si,i}-\bar{Q}_{si})^2}}$	Correlation coefficient	1
$NSEC = 1 - \frac{\sum(Q_{ob,i}-Q_{si,i})^2}{\sum(Q_{ob,i}-\bar{Q}_{ob})^2}$	Nash–Sutcliffe efficiency coefficient	1

Annotation: Q_{ob}-measured streamflow; $\bar{Q}_{ob}$-mean measured streamflow; Q_{si}-simulated streamflow; $\bar{Q}_{si}$-mean value of simulated streamflow

The results of the sensitivity analysis are listed in Table III based on their sensitivity ranking. A parameter ranked as 1 is considered the most important, and sensitivity decreases as the ranking decreases from 2 to 8. Full details of the parameters and their effect on the hydrological cycle can be found in Neitsch *et al.* (2005). The curve number for moisture condition II (CN2) shows high sensitivity for simulated streamflow (Table III). These results indicate that parameters representing surface streamflow, soil properties, evapotranspiration and groundwater are sensitive. Therefore, these parameters must be accurately estimated for an accurate simulation of streamflow.

The final parameter ranges and values are shown in Table III. The ranges in Table III indicate the range for the entire watershed, as subbasins may have different parameter values. The values in Table III indicate that the parameters were fitted to that value for the entire watershed. Figure 2 shows the SWAT-predicted monthly streamflows at the Xiying, Zamu and Jiutiaoling outlets compared with observed data in addition to the monthly precipitation totals at representative weather stations for the two watersheds.

Comparison of monthly observed and simulated streamflow values (Figure 2, Table IV) shows that the magnitude and trend in the simulated streamflows agreed with measured data quite well. The model evaluation indicators in Table IV indicate 'good' and 'satisfactory' simulations of hydrology at the entire watershed level, where the minimum of NSEC, R^2 and rVol during calibration was 0.65, 0.70 and −0.19, respectively, and 0.80, 0.84 and −0.04 during validation. Both watershed simulations are considered 'good' and 'satisfactory' based on the NSEC criteria developed by Moriasi *et al.* (2007), where a NSEC coefficient larger than 0.75 is considered 'good' and between 0.36 and 0.75 is considered 'satisfactory'. The RMSE and MAE statistics, where a value of 0 represents a perfect simulation, also indicate good streamflow simulation.

Climate change analyses

Soil and Water Assessment Tool was used to model the impact of climate change on streamflow at the Xiying and Zamu streamflow gauge sites in the Shiyang River Basin (Figure 1). Direct input of RCM precipitation and potential evapotranspiration data was used to simulate the hydrological cycle under climatic changes. The following indices were used for comparison between present-day and future streamflow scenarios: (i) annual mean monthly streamflow; (ii) mean monthly maximum streamflow; and (iii) mean monthly minimum streamflow at the Xiying and Zamu gauging stations within the Shiyang River Basin. Because of monthly streamflow simulations, we do not distinguish between an increase in 'extreme' hydrological events and an overall increase in streamflow average. The results were summarized for the periods of 2011–2040, 2041–2070 and 2071–2100, represented as the 2020s, 2050s and 2080s, respectively, and compared with the baseline years of 1961–1990. The baseline years were chosen because of GCM data availability, and the climate change periods were chosen so that all years in the 21st century are analysed and easily

Table III. Parameter sensitivity analysis based on the hydrological stations of Zamusi and Jiutiaoling

Name	Definition	Sensitivity rank	Final parameter value or range
CN2	Curve number	1	59.9–78.8*
SOL_AW	Effective water storage capacity of soil	2	0.01†
ESCO	Soil evaporation compensation factor	3	0.96
EPCO	Plant uptake compensation factor	3	0.77
CANMX	Maximum water storage capacity in canopy	4	0.57
SOL_K	Hydraulic conductivity of soil	5	52.1–86.8
SOL_Z	Depth of soil layer	6	138.4–222.7
GW_DELAY	Groundwater delay time	7	23.3–31
ALPHA_BF	Base flow coefficient	8	0.05–0.18

*The range values indicate that subbasins may have different values, and therefore, the minimum and maximum parameter values represent the range for the entire watershed.
† The fixed values indicate that a parameter was fitted and then fixed.

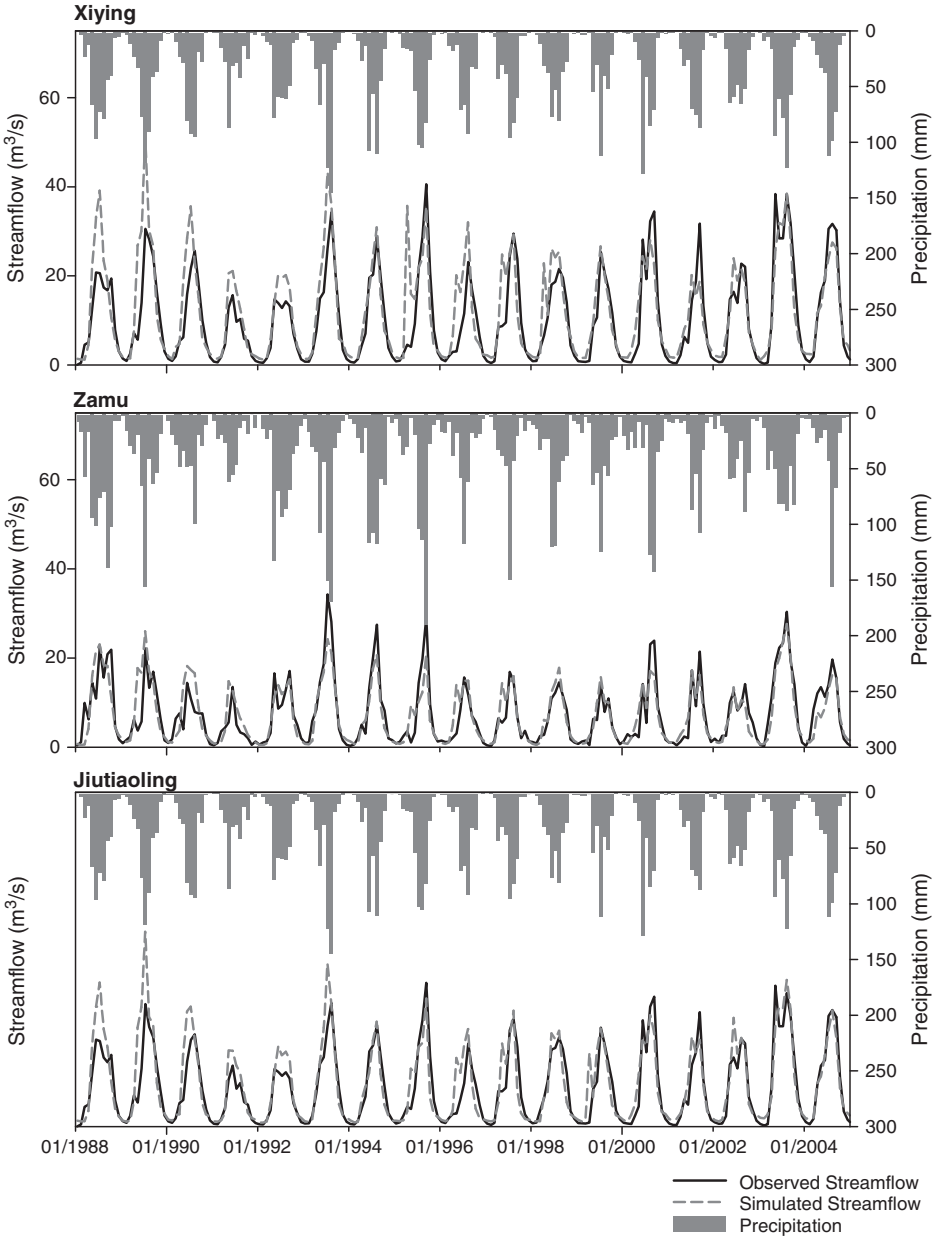

Figure 2. Observed and predicted monthly streamflows for the monitoring sites used in the study

comparable. These periods also are recommended by the IPCC (IPCC, 2007).

The climate model used in this study is the PRECIS climate model. The PRECIS RCM is a third-generation RCM of Hadley Centre, UK. This atmospheric and land surface model is based on the Hadley Center's latest GCM, HadCM3 (Gordon *et al.*, 2000) and has a high resolution of 0.44° and 0.22° with 19 levels in the atmosphere, up to 30 km for the surface, and four levels of soil. The climate output from the A2 and B2 emission scenarios was used. Precipitation and potential evapotranspiration output data from the RCM were used. Differences between the scenarios were tested using the Wilcoxon rank sum test at alpha = 0.05 (Mann and Whitney, 1947)

Table IV. Calibration and validation statistics of the Shiyang River Basin Soil and Water Assessment Tool hydrological model

	Calibration (1988–1999)			Validation (2000–2005)			1998–2005	
Station	NSEC	R^2	rVol	NSEC	R^2	rVol	RMSE (m^3/s)	MAE (m^3/s)
Xiying	0.65	0.70	−0.19	0.83	0.88	−0.02	5.9	3.7
Zamusi	0.68	0.72	−0.03	0.80	0.84	0.10	3.5	2.3
Jiutiaoling	0.73	0.75	−0.12	0.88	0.90	−0.04	4.3	2.7

MAE: mean absolute error; NSEC, Nash–Sutcliffe efficiency coefficient; R^2, correlation coefficient; RMSE, root mean square error; rVol, volume error.

RESULTS

Precipitation and potential evapotranspiration data from the PRECIS climate simulations

Providing Regional Climates for Impacts Studies precipitation, temperature and potential evapotranspiration output are presented in Table V. The Wilcoxon rank sum test showed no statistically significant differences (a = 0.05) between all scenarios for streamflow, precipitation, temperature and evapotranspiration. However, the changes in precipitation, temperature and potential evapotranspiration did result in meaningful changes in streamflow. The simulated mean annual temperature by PRECIS for the baseline period is 6.8 °C for the entire basin. Under the A2 scenario, simulated mean annual temperature increases by 1.4 °C for the 2020s, 2.9 °C for the 2050s and 4.9 °C for the 2080s. Under the B2 scenario, simulated mean annual temperature increases by 1.6 °C for the 2020s, 2.7 °C for the 2050s and 3.6 °C for the 2080s. For the A2 scenario, average annual precipitation from the baseline years to the 2080s increased from 262 to 283 mm for the Xiying area and 290 to 303 for the Zamu area. For the B2 scenario, average annual precipitation increases from the baseline years to the 2080s were 262–269 mm for the Xiying area and 290–292 for the Zamu area. Changes in potential evapotranspiration fluctuated among the scenarios. The A2 scenario led to larger annual precipitation and potential evapotranspiration in the region than that of the B2 scenario.

Mean monthly streamflow

Xiying station. The present-day (baseline) mean monthly streamflow at the Xiying station was 6.78 m^3/s (Table V). Differences between the scenarios were found to not be statistically significant (a = 0.05). For the A2 scenario, the increases in precipitation for all periods resulted in an increase in mean monthly streamflow, with the largest monthly streamflow increase of 7.11 m^3/s occurring in the 2080s. For the B2 scenario, mean monthly streamflow increased relative to the baseline scenario during the 2020s and 2080s and decreased by 0.03 m^3/s during the 2050s. This can potentially be explained by a large increase in temperature resulting in an increase in potential evapotranspiration during this period for the B2 scenario. The Zamu station shows similar results. As expected, the mean monthly streamflow for the climate change periods was closer to the mean under the B2 scenario than the A2 scenario, where a streamflow increase occurred for every period.

Zamu station

The baseline Zamu station mean monthly streamflow was 5.52 m^3/s (Table V). The A2 scenario resulted in a continual streamflow increase for all periods, with the largest occurring during the 2080s. However, these differences in streamflow were not statistically significant (a = 0.05). Increases in streamflow can be explained by increases in precipitation coupled with fluctuating

Table V. Mean monthly streamflow and mean annual precipitation and potential evapotranspiration for both outlets and climate change scenarios

Xiying Outlet	A2 Scenario				B2 Scenario			
Period	Streamflow (m^3/s)	Precipitation (mm)	Temperature (°C)	Potential evaporaton (mm)	Streamflow (m^3/s)	Precipitation (mm)	Temperature (°C)	Potential evaporation (mm)
Baseline	6.78	262	6.8	216	6.78	262	6.8	216
2020s	6.99	268	8.2	216	6.79	264	8.4	215
2050s	7.03	274	9.7	220	6.75	267	9.5	218
2080s	7.11	283	11.7	226	6.8	269	10.4	220
Zamusi Outlet	A2 Scenario				B2 Scenario			
Period	Streamflow (m^3/s)	Precipitation (mm)	Temperature (°C)	Potential evaporation (mm)	Streamflow (m^3/s)	Precipitation (mm)	Temperature (°C)	Potential evaporation (mm)
Baseline	5.52	290	6.8	154	5.52	290	6.8	154
2020s	5.73	296	8.2	151	5.58	289	8.4	149
2050s	5.77	299	9.7	153	5.56	290	9.5	150
2080s	5.86	303	11.7	156	5.58	292	10.4	151

No statistical difference was found between any scenario using the Wilcoxon rank sum test at alpha = 0.05.

potential evapotranspiration rates. For the B2 scenario, the mean monthly streamflow for the baseline scenario was 5.52 m^3/s, and the mean monthly streamflow for the 2020s, 2050s and 2080s was 5.58, 5.56 and 5.58 m^3/s, respectively, each greater than the baseline scenario. The streamflow decrease during the 2050s can be attributed to an increase in potential evapotranspiration after a decrease during the 2020s. The A2 scenario exhibited higher variation under climate change than the B2 scenario.

Mean monthly maximum streamflow

Xiying station. The mean monthly maximum streamflow for the baseline years at the Xiying station was 19.69 m^3/s (Table VI). Mean monthly maximum streamflow for the A2 scenario was larger than the baseline for every period. The largest increase occurred during the 2020s and decreased for the remaining periods. Similar trends were found for the B2 scenario, with an increase during the 2020s and a linear decrease for the remaining periods. For the 2050s and 2080s, the B2 scenario resulted in decreases compared with the baseline scenario. Compared with the baseline years, climate change resulted in less than a 5% change for mean monthly maximum streamflow, suggesting that changes in flood discharges or increases in mean maximum streamflow may not be considerable.

The maximum streamflow percentage duration at the Xiying station exhibits similar trends as the Zamu station (Figure 3); however, the differences in streamflow between the climate change and baseline scenarios were larger in some cases. Mean monthly maximum streamflow for the baseline years at the Xiying station was higher for streamflows that flowed approximately 83–100% of the time, with a greater difference for the B2 scenario than the A2 scenario. The climate change mean monthly maximum streamflows were higher than the baseline for streamflow that flowed approximately 1–20% and 1–7% of the time for the A2 and B2 scenarios, respectively. The difference between climate change and baseline mean monthly maximum streamflows was higher for the A2 scenario than the B2 scenario. The mean monthly maximum streamflows that occurred between 30 and 85% of the time were similar for all scenarios. These results suggest that the extreme streamflows (maximum discharges that occur less than 20% of the time) will increase under climate change, but the maximum discharges that occur over 20% will be similar or less than the baseline scenario (Figure 4).

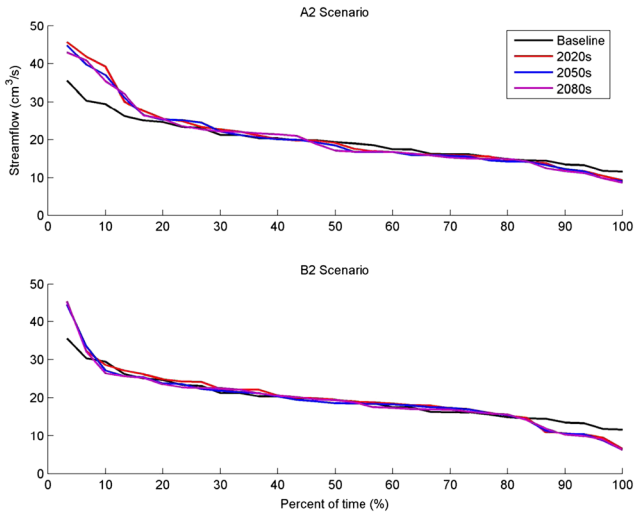

Figure 3. Percentage flow duration of maximum streamflow for each year at the Xiying outlet for both climate change scenarios

Zamu station

The mean monthly maximum streamflow for the baseline years at the Zamu station was 18.85 m^3/s (Table VI). Monthly maximum streamflow was greater

Table VI. The monthly maximum/ minimum streamflow percentage changes for the A2 and B2 climate scenarios relative to the baseline years

Xiying Outlet					
Period		Monthly minimum streamflow (m^3/s)	Percentage change from baseline (%)	Monthly maximum streamflow (m^3/s)	Percentage change from baseline (%)
Baseline		0.34	—	19.69	—
A2 Scenario	2020s	0.34	0.0	20.66	4.92
	2050s	0.36	7.9	20.29	3.04
	2080s	0.4	18.4	20.17	2.42
B2 Scenario	2020s	0.35	2.6	19.99	1.54
	2050s	0.36	7.3	19.52	−0.87
	2080s	0.38	13.2	19.42	−1.36
Zamusi Outlet					
Period		Monthly minimum streamflow (m^3/s)	Percentage change from baseline (%)	Monthly maximum streamflow (m^3/s)	Percentage change from baseline (%)
Baseline		0.17	—	18.85	—
A2 Scenario	2020s	0.19	14.9	19.99	6.04
	2050s	0.22	28.4	19.77	4.87
	2080s	0.24	44.8	19.63	4.12
B2 Scenario	2020s	0.19	15.3	19.62	4.09
	2050s	0.19	15.3	19.25	2.12
	2080s	0.22	29.8	19.07	1.15

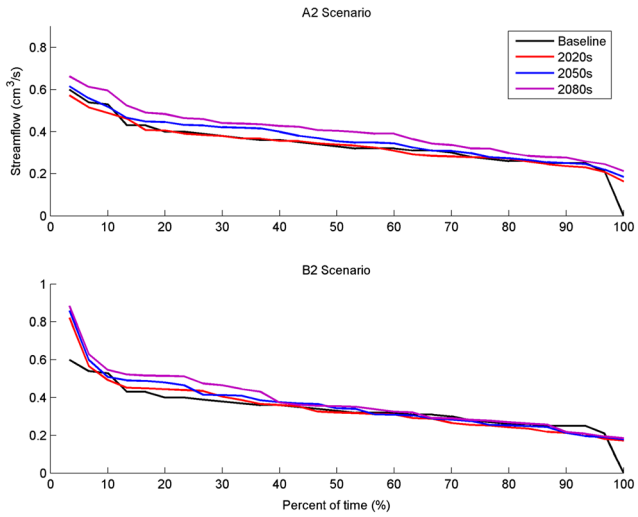

Figure 4. Percentage flow duration of minimum streamflow for each year at the Xiying outlet for both climate change scenarios

than the baseline scenario for every period. For both scenarios, the mean monthly maximum streamflow exhibited similar trends as the Xiying station with an initial increase during the 2020s followed by decreases during the 2050s and 2080s. Similar to the Xiying station, changes in maximum monthly flows were not large.

The mean monthly maximum streamflow for the baseline years for flows of approximately 83–100% of the total time was higher than the maximum streamflows for both climate change scenarios (Figure 5). Conversely, the mean monthly maximum streamflow that flows 1–17% of the time was higher for both climate change scenarios than the baseline years. Mean monthly maximum streamflow for the baseline and climate change scenarios that flow 18–73% of the time were approximately equivalent. These corresponding differences in extreme events resulted in a change from baseline of approximately 6% or less. These results suggest that overall differences of monthly maximum streamflow that flow more than 20% of the time may be negligible, with the potential for decreases in

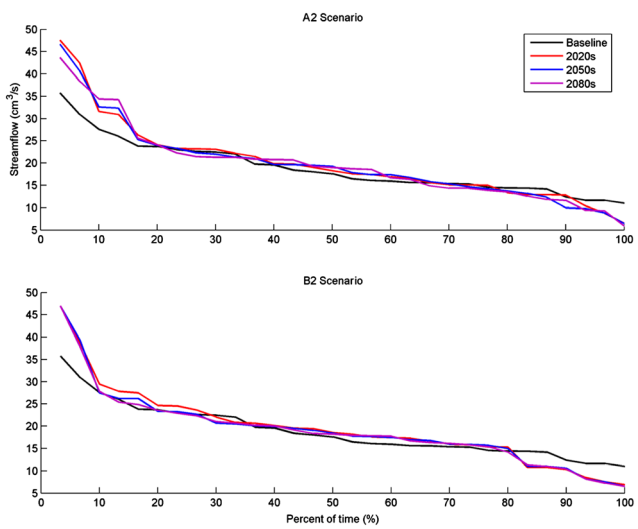

Figure 5. Percentage flow duration of maximum streamflow for each year at the Zamu outlet for both climate change scenarios

maximum streamflow, but that for extreme events (maximum streamflows that occur less than 20% of the time) have the potential to increase by 10 m^3/s. This potentially may have major implications for water resource management. For example, an increase in maximum streamflow may quickly decrease reservoir storage capacity and flood protection. To counter this, water resource managers may need to release more water out of the reservoir during a time when the reservoir inflow needs to be conserved for the upcoming dry season. Furthermore, changes in reservoir management during the wet season can potentially impact hydropower generation.

Mean monthly minimum streamflow

Xiying station. The mean monthly minimum streamflow for the baseline years at the Xiying station was 0.34 m^3/s (Table VI). Compared with the baseline scenario, the mean monthly minimum streamflow for the A2 scenario did not change for the 2020s. For the 2050s and 2080s, mean monthly minimum streamflow increased to 0.36 and 0.40 m^3/s, respectively. For the B2 scenario, mean monthly minimum streamflow increased for every period, with the largest streamflow changing to 0.38 m^3/s occurring during the 2080s. These results suggest that under drought and low streamflow conditions, mean monthly minimum streamflow will be larger when compared with present-day conditions.

The minimum streamflow percentage duration for the Xiying station exhibited different trends than the Zamu station (Figure 4). In general, the mean monthly minimum streamflow for the baseline and climate change scenarios had a difference of less than 0.1 m^3/s for all streamflow durations. The largest difference between the baseline and climate change years was for the streamflow that occurred below 60% of the time for the A2 scenario and 37% for the B2 scenario. There was a large increase below 10% for the B2 scenario, suggesting that the highest minimum streamflow for the Xiying station will be larger under climate change. For some mean monthly minimum streamflow durations, the baseline mean monthly minimum streamflow was higher than the climate change mean monthly minimum streamflows, which is largely the reason why the percentage difference between the climate change and baseline mean monthly minimum streamflows was negligible.

Zamu station

The mean monthly minimum streamflow for the baseline years at the Zamu station was 0.17 m^3/s (Table VI). Both climate change scenarios resulted in monthly minimum streamflow increases for every period compared with the baseline scenario. Similar to the Xiying station, the largest monthly minimum streamflow increase occurred in the 2080s. For the B2 scenario, the monthly minimum discharge was the same for 2020s and 2050s, suggesting that the conditions controlling the minimum streamflow for the Zamu station will be similar for these periods. In

general, the results indicate that climate change may lead to a gradual increase in minimum streamflows.

Figure 6 shows that all periods and scenarios exhibited an increase in mean monthly minimum streamflow relative to the baseline years the Zamu station. Generally, the mean monthly minimum streamflow increases from the 2020s to the 2080s for all percentage time durations. The A2 scenario shows a much larger variation than the B2 scenario, especially in mean monthly minimum streamflows that occur less than 60% of the time. This accounts for the major difference in mean monthly streamflow between the two scenarios. Large changes in minimum streamflow will result in significant changes for water resource management.

DISCUSSION

The results of several previous studies indicate that the arid basins in northwest China may be potentially very sensitive to changes in climate (Chen *et al*., 2006; Huo *et al*., 2008; Li *et al*., 2008). However, our findings indicate that the Shiyang River Basin may be less sensitive to climate change than previously thought. In the past, water resource managers seldom cared about future changes of the hydrological cycle for this arid region because of a lack of quantitative data to determine future management scenarios. This study is the first of its kind to study the effects of climate change on the hydrological cycle in this important arid river basin.

Analysis of the trends in the average annual precipitation amounts indicates that precipitation may increase with climate change, whereas potential evapotranspiration may fluctuate from year to year. This could foreshadow more extreme flooding events or an increase in average streamflow in the future for this region, which will certainly change reservoir management operations to achieve maximum efficiency and flood control. The increase in precipitation for all scenarios led to increased streamflow for most climate change scenarios. Even minor changes in average monthly streamflow may result in major differences in the amount of water resources for agricultural and human consumption. Similar trends are likely to occur in the other rivers in the Shiyang River Basin as a result of changing climatic conditions. The consequences of changing flows can be significant for rivers already at their limits in terms of water resources. Conversely, the increase in mean monthly minimum flows may be beneficial for ecosystems within the streams and rivers in the basin.

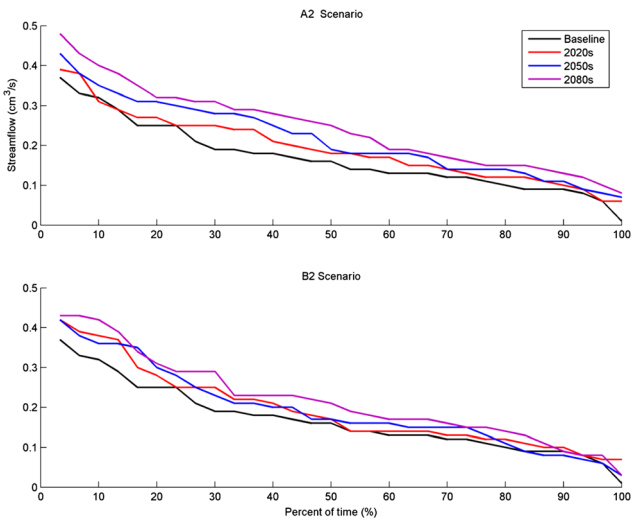

Figure 6. Percentage flow duration of minimum streamflow for each year at the Zamu outlet for both climate change scenarios

For both scenarios and both stations, mean monthly maximum and minimum streamflows exhibited change from the baseline years. The mean monthly maximum and minimum streamflow generally increased for all scenarios at both stations, which leads to increased runoff out of the watersheds. In arid regions, changes in hydrology, including maximum and minimum streamflows, may have detrimental effects on in-stream ecosystems, which were already determined to be at their ecological threshold because of human activities (Su *et al*., 2009). Life cycles of aquatic species in the mountainous regions have evolved over thousands of years to match these wet and dry cycles (Erman, 1996), and changes in these cycles may have a significant effect on the health of aquatic species. Also, increases in mean monthly maximum and minimum streamflow indicate that extreme runoff events from increased precipitation and snowmelt are likely to occur. Mitigating these events is an important topic in reservoir management operations. More work needs to carried out on the capability of handling extreme precipitation and flood events in the Shiyang River Basin.

Streamflow is a result of catchment processes and is affected by multiple factors. Changes in such factors, such as land use, will result in changes to the hydrological cycle. Because these basin system changes are dependent on many impact factors, such as land use, social and economic development and basin management, it is extremely difficult and almost impossible to forecast with much certainty. Theoretically, the SWAT model parameters should change with the changes of Shiyang River Basin system in the future. The sensitivity analysis determined that the curve number was the most sensitive parameter in determining streamflow. The curve number is the function of soil and vegetation, and therefore, any changes in these factors will then change the streamflow. A full description of the issues of using the curve number method can be found in Garen and Moore (2005). The Green–Ampt infiltration model within SWAT may have been a better option for predicting surface water runoff because it is largely based on physical soil parameters and less on land use properties. In this method, the amount of water that infiltrates is estimated first, and the remaining water from a precipitation event is assumed to be a surface runoff. Results from previous studies indicate that using Green–Ampt method is just as satisfactory as using the curve number (King *et al*., 1999). However, the Green–Ampt method requires subdaily precipitation data, which often is lacking from datasets. This study gives an analysis on the effects of streamflow to climate change under present-day land use conditions.

The analyses preformed in this study are perhaps still too uncertain for detailed water management purposes. However, this study gives insight on the sensitivity of this region and other arid watersheds in northwestern China (Heihe River Basin, Talimu River Basin, etc) on the effects of climate change. The results of this study underscore the need to perform more extensive assessments of potential climate change impacts on the Shiyang River Basin. Simulating climate change scenarios with other global or RCMs will yield a larger picture of the impact of climate change, as the various models may have conflicting precipitation and potential evapotranspiration patterns. However, based on the work of Maurer (2007) who downscaled precipitation and temperature outputs for 16 GCMs at the global scale, we compared precipitation and temperature output from 16 GCMs. Although the RCM used in this study projects a lower end-of-century precipitation projection than the mean of the 16 GCMs, the end-of-century precipitation projections are within the 1st and 3rd precipitation projection quartiles, indicating a reasonable precipitation projection. For end-of-century temperature projections, the RCM used within this study is within 0.86 °C of the mean precipitation projection of the 16 GCMs, also indicating a reasonable projection. Thus, we can conclude, based on the output of an ensemble of GCMs, that the streamflow projections for this study are realistic. Future Shiyang River Basin climate change studies should include improved land use data with future scenario projections, facilitating the assessment of both flow and environmental impacts for current and potential future climate patterns. There also is a need to simulate the effects of increased atmospheric CO_2 concentrations on streamflow. We assume a constant atmospheric CO_2 concentration within SWAT throughout all model simulations. The effect of CO_2 on plant growth and transpiration, and thus evapotranspiration, was found to be significant in vegetated watersheds (e.g. Morison and Gifford, 1983; Medlyn *et al*., 2001; Ficklin *et al*., 2009a, 2009b).

CONCLUSIONS

The arid Shiyang River Basin in northwest China was selected as the study site to assess the potential impacts of climate change on streamflow. PRECIS climate model output data were applied to the SWAT model of Shiyang River Basin. Using A2 and B2 climate change scenarios, we show a range of results aimed at water resource planning and management in the Shiyang River Basin in northwestern China.

The results show that SWAT is a useful tool for assessing the impacts of climate change on the hydrological cycle in this arid region. Comparing the climate change simulations of the 2020s, 2050s and 2080s to base year simulations (1961–1990), several conclusions can be made. For this region, the A2 emission scenario leads to more annual precipitation and potential evapotranspiration than the B2 emission scenario, thus leading to differences in streamflow. Generally, the mean monthly streamflow in Shiyang River Basin increased in the 2020s, 2050s and 2080s compared with the baseline period between 0.7 and 6.1% at the Zamu gauging station and 0.1 and 4.8% at the Xiying gauging station. The monthly minimum streamflow increased continually throughout the 21st century and the maximum monthly streamflows increased in the 2020s and decreased in the 2050s and 2080s.

As temperatures rise throughout the 21st century, we can expect slightly higher streamflows in the Shiyang River Basin regardless of the emissions scenario (A2 or B2) in PRECIS climate model. Thus, the current water resource shortage situation and eco-deterioration have the potential to be improved. However, water use efficiency standards should still be established with, for example, the use of drip or pipe irrigation for agriculture.

Uncertainties still exist within this study using one RCM to analyse the effects of climate change on streamflow, although comparable results were obtained after we tested the statistical significance between the 16 GCMs. There also are uncertainties in the SWAT hydrological model calibration, as well as the lack of land use change. However, this study is still useful as it gives an indication of the streamflow sensitivity of the Shiyang River Basin to changes in climate. In future studies, model uncertainty analysis, including the use of multiple climate model projections, will be strengthened.

ACKNOWLEDGEMENTS

The authors would like to acknowledge funding support from the National Key Basic Research Development Program of China 2009CB421305 and 2012CB955300 and the Natural Sciences Foundation of China (40730632 and 40701027).

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