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Impacts of 1.5°C and 2.0°C Global Warming on Runoff of Three Inland Rivers in the Hexi Corridor, Northwest China

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ABSTRACT

Basin-scale projections of river runoff at different warming levels provide useful information for climate change adaptation. In this study, we investigated changes in the projected climate and simulated runoff under 1.5°C and 2.0°C global warming of three inland rivers in the Hexi Corridor: the Shiyang River (SYR), the Heihe River (HHR), and the Shule River (SLR). The change in climate was projected based on five global climate models (GCMs) under three representative concentration pathways (RCPs), and the change in runoff was simulated based on the Soil and Water Assessment Tool (SWAT) hydrological model. Furthermore, the uncertainties in projected climate change and simulated runoff constrained by the GCMs and RCPs were quantified. The results indicate that, compared with the baseline period (1976–2005), there is a 1.42–1.54°C increase in annual air temperature and 4%–12% increase in annual mean precipitation in the three river basins under 1.5°C global warming, while there is a 2.09–2.36°C increase in annual air temperature and 5%–11% increase in annual mean precipitation under 2.0°C global warming. The simulated annual runoff of the SYR decreases by 4% under 1.5°C global warming, that of the HHR decreases by 3% and 4%, while that of the SLR increases considerably by 10% and 11% under 1.5°C and 2.0°C global warming, respectively. The additional 0.5°C global warming results in an annual air temperature increase of 0.67–0.82°C, a change of –1% to 1% in annual mean precipitation, and a change of –1% to 5% in simulated runoff. The simulated annual runoff has greater uncertainty. The simulations indicate substantial and consistent warming in autumn and winter in the three basins, relatively drier summer and autumn in the SYR and HHR basins, and a relatively drier autumn in the SLR basin. The simulated monthly runoff shows more complex changes with large uncertainties constrained mainly by the GCMs.

Key words: climate change, runoff, Shiyang River (SYR), Heihe River (HHR), Shule River (SLR)

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1. Introduction

To avoid dangerous climate change, the Paris Agreement proposed limiting the global temperature increase to below 2.0°C relative to preindustrial levels, with the aim of pursuing efforts to limit this increase to below 1.5°C for a more sustainable future (UNFCCC, 2015). The global mean temperature (GMT) has risen by 1.0°C

above preindustrial levels due to human activities, and is projected to reach 1.5°C between 2030 and 2052 (IPCC, 2018). Global warming has resulted in alterations to the hydrological cycle, which has consequences for river flow regimes (IPCC, 2014; Betts et al., 2018). A large part of the observed trend in streamflow might result from climate variations, anthropogenic climate change, and human activities, and the projected change in runoff

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at 1.5°C and 2.0°C global warming will be regionally dependent (Döll et al., 2018; Zhai et al., 2018).

China has experienced robust warming, especially in northern China, and an increased contrast in rainfall between northeastern and southern China (Piao et al., 2010). Climate change, combined with human activities, has resulted in a general reduction in observed annual runoff in the northern rivers of China, such as the Haihe, Yellow, and Liaohe rivers (CTNARCC, 2015). The 2.0°C warming threshold will be exceeded by 2033 ± 15 under RCP4.5, or by 2029 ± 10 under RCP8.5 averaged across China (Chen and Zhou, 2016). Simulations suggest that the annual runoff of the Yiluo River in northern China will reduce under warming of 1.5°C and 2.0°C, while that of the Beijiang River in southern China will increase slightly (Liu et al., 2017). The simulated runoff changes of the Yangtze River decrease under 1.5°C warming; however, it shows opposite changes under 2.0°C global warming (Chen et al., 2017).

Northwest China, with sparse precipitation and strong potential evaporation, is a typical water shortage area, as well as an area extremely vulnerable to climate change (Li et al., 2012). The Hexi Corridor is located in Gansu Province in Northwest China and is an important grain production base and local socioeconomic center. The Hexi Corridor receives sparse annual rainfall, and water from inland rivers is a vital resource for crop growth, urbanization, and sustainable development (Wang et al., 2009). However, water shortage can seriously affect agricultural production and the socio-economic system of the Hexi Corridor (Bao and Fang, 2007; Li X. L. et al., 2017). The climate in Northwest China has experienced a warming and wetting trend since 1961, characterized by warmer winter and wetter summer (Wang and Qin, 2017). During 1957–2010, there was an increasing trend in annual mean temperature, no significant trend in annual mean precipitation, and different runoff trends among the three inland rivers in the Hexi Corridor (Wang X. Q. et al., 2019). Under the changing climate, increasing population, and exacerbating water scarcity, water resources have become a key constraint to economic and social development in the region. Therefore, exploring the climate change impacts on runoff in the Hexi Corridor under 1.5°C and 2.0°C global warming is a topic of increasing interest.

This study focuses on the upper reaches of three inland rivers in the Hexi Corridor. From east to west, they are the Shiyang River (SYR), the Heihe River (HHR), and the Shule River (SLR). The objectives of this work are: (1) to detect changes in temperature and precipitation in the study area under 1.5°C and 2.0°C global

warming; (2) to simulate the changes in river runoff of the three inland rivers under 1.5°C and 2.0°C global warming, based on a validated hydrological model; (3) to quantify the uncertainties in climate change projection and runoff simulation constrained by global climate models (GCMs) and representative concentration pathways (RCPs); and (4) to explore the underlying reasons for simulated changes in runoff. The findings of this investigation can provide a scientific basis for water resource management and climate change adaptation for these three inland river basins in the Hexi Corridor.

2. Study basins, data, and methods

2.1 Study basins

The Hexi Corridor lies in the region (37°17'–42°48'N, 92°12'–104°20'E) in Gansu Province, Northwest China, and has a total area of $\sim 270,000$ km². It is a long corridor comprising the Qilian Mountains in the southern region, a plain oasis in the central region, and a mountainous region in the north, according to the geomorphic features and ecological factors. The Hexi Corridor has an arid continental climate, with an average annual air temperature of 5–9°C, annual mean precipitation of 50–150 mm, and annual evaporation of 1500–3200 mm. The rates of increase in temperature and precipitation in the Hexi Corridor during 1957–2010 are about 0.29°C (10 yr)^{−1} and 7.6 mm (10 yr)^{−1}, respectively (Li et al., 2012).

The SYR, HHR, and SLR all originate from the Qilian Mountains (Fig. 1). In the three inland river basins, the mean annual air temperature is 6.2–8.9°C (Table 1). Mean monthly air temperature ranges from −9.7 to 15.9°C in the SYR basin, from −10.4 to 21.6°C in the HHR basin, and from −9.7 to 20.5°C in the SLR basin. Annual mean precipitation is within the range of 77–212 mm from west to east, with more rainfall (152–352 mm) in the upper reaches (Table 1). Most precipitation occurs during June–September, accounting for approximately 58%, 69%, and 68% of the annual mean precipitation in the SYR, HHR, and SLR basins, respectively.

The runoff of the three inland rivers is mainly formed in the upper Qilian Mountains and lost to the piedmont plains. Annual runoff in the upper reaches of the SYR, the HHR, and the SLR is about 180, 158, and 93 mm, respectively. In the SYR and HHR basins, the recharge source of runoff is mainly precipitation, with a small amount of meltwater, while in the SLR basin it is a combination of meltwater and precipitation. The runoff mainly occurs during the flood season (May–September), accounting for about 76%–78% of annual runoff in the three inland rivers.

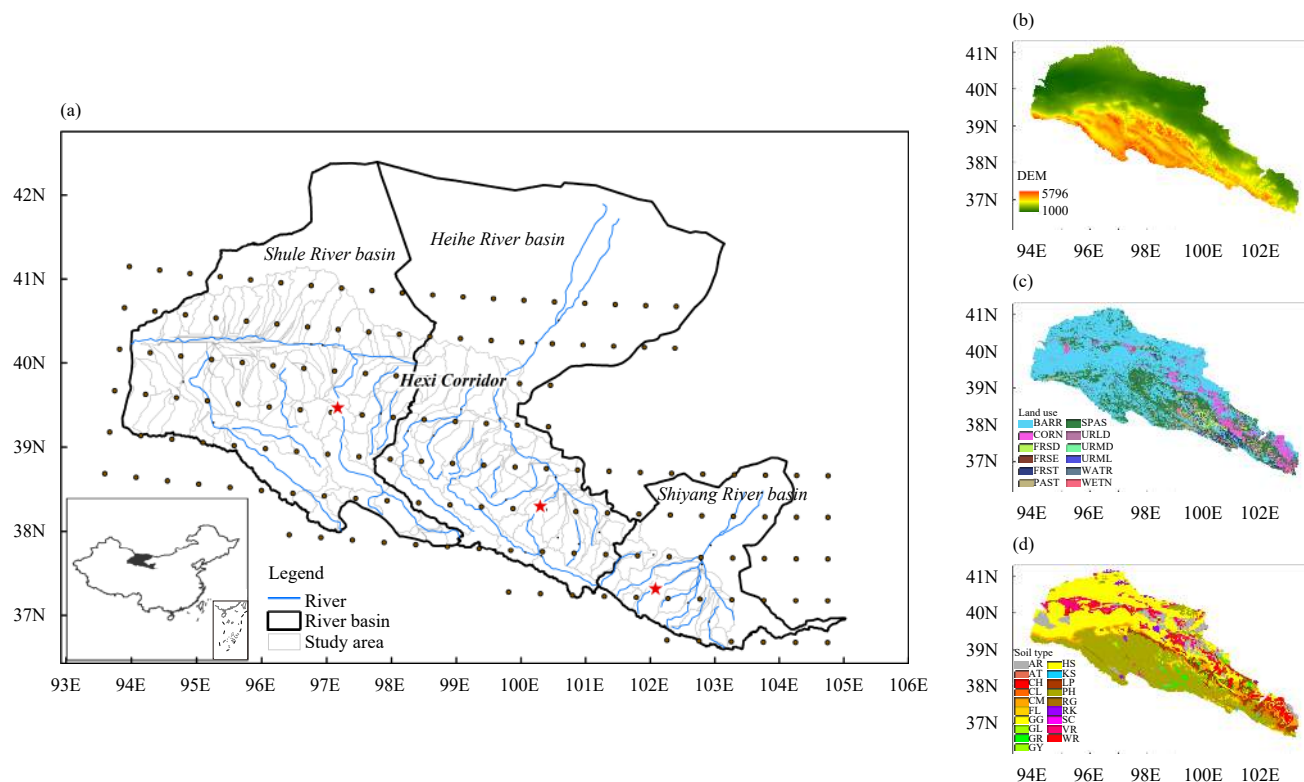


Fig. 1. Locations of the three inland river basins in China. (a) The study area (shown as sub-basins, as divided by the hydrological model) in the Hexi Corridor, and locations of the hydrological gauges (star) overlaid with the climate forcing data grid (dot). Spatial distributions of (b) elevation derived from the digital elevation model (DEM; m), (c) land use type, and (d) soil type in the study area.

Table 1. Climatic and hydrological characteristics of the three inland river basins in the Hexi Corridor based on observed data for 1981–2010

River	Basin			Study area (upper reaches)		
	Area (km ²)	T (°C)	P (mm)	Area (km ²)	P (mm)	Q (mm)
SYR	41,600	8.9	212	11,100	352	180
HHR	143,000	6.2	195	10,000	341	158
SLR	41,300	8.5	77	11,400	152	93

Note: T —average annual mean temperature; P —average annual mean precipitation; and Q —average annual mean runoff.

2.2 Data

2.2.1 Observed hydrological data

There are three typical hydrological stations in the study area: Jiutiaoling (37°52'N, 102°03'E), located in the SYR basin; Yingluoxia (38°14'N, 100°11'E), located in the HHR basin; and Changmapu (39°39'N, 96°51'E), located in the SLR basin (Li et al., 2016a). The monthly and annual discharge observed data (1961–2015) of these three hydrological stations were provided by the Water Resources Department of Gansu Province. The discharge observations were used to calibrate and validate the hydrological model.

2.2.2 Gridded climate data

Climate data are a crucial forcing for hydrological models. However, the relatively sparse distribution of gauges often leads to poor spatial representation of climate patterns (Dile and Srinivasan, 2014; Grusson et al.,

2017). Therefore, the developed gridded climate datasets are widely used to force hydrological models (Javanmard et al., 2010; Duan et al., 2016), especially in models of data-sparse or ungauged regions (Essou et al., 2016).

The daily climate data used to force the hydrological model were derived from the Water and Global Change Program meteorological forcing datasets (WFD; Weedon et al., 2010). This dataset is also the basis for the bias correction of the climate model output adopted in this study. WFD data are derived from the ECMWF ERA-40 reanalysis product via sequential interpolation to a $0.5^\circ \times 0.5^\circ$ resolution, elevation correction, and monthly-scale adjustments based on Climate Research Unit (CRU; corrected-temperature) and Global Precipitation Climatology Centre (GPCC; precipitation) monthly observations. WFD is regarded as an acceptable dataset for the forcing of hydrological models in comparison with observational

databases at the global scale (Weedon et al., 2010).

2.2.3 Climate model data

GCMs, which can provide useful information with regards to historical and future climate, have been widely applied to study water resources and regional hydrological responses under different scenarios. Considering the uncertainties in climate change projection, multiple combinations of GCMs and emission scenarios have been used to quantify the uncertainties in climate change impact assessments of water resources (Arnell, 2016).

Climate model data used to estimate projected climate change and to force the hydrological model were derived from five GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M) under three RCPs (RCP4.5, RCP6.0, and RCP8.5) of the Coupled Model Intercomparison Project Phase 5 (CMIP5) within the framework of the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP; Warszawski et al., 2014). These five models were selected to more effectively span the GMT change and relative changes in precipitation than any five GCMs selected randomly (McSweeney and Jones, 2016). The low-resolution GCM outputs were interpolated to a $0.5^\circ \times 0.5^\circ$ resolution and corrected based on the WFD reference dataset by using the trend-preserving bias correction method (Hempel et al., 2013). The trend-preserving bias correction method derived based on the reference period, was applied to bias-correct the output of the five GCMs for the past, present, and future (application period 1950–2099). The climate variables used in this study include daily average, maximum, and minimum temperatures, and daily precipitation.

The applicability of WFD meteorological data and climate model data from ISI-MIP has been tested at the global scale (Weedon et al., 2011; McSweeney and Jones, 2016). Furthermore, these datasets have been widely used in climate change impact assessments at the regional or catchment scale in China (Chen et al., 2017; Liu et al., 2017; Su et al., 2017; Hao et al., 2018; Liu et al., 2018).

2.2.4 Geographic data

The spatial data for the parameterization of the hydrological model include the DEM, land-use, and soil-type data. The DEM, with scale of 1:250,000, was developed by the National Geomatics Center of China. Land-use data for the 2000s, with a spatial resolution of 1 km, were compiled by the Western China Environmental and Ecological Science Data Center (<http://westdc.westgis.ac.cn>). The land-use types were reclassified according to the Soil and Water Assessment Tool (SWAT) hydrological model land use/land cover system. Soil data were derived from the homogenization world soil dataset

provided by the Food and Agriculture Organization (FAO) of the United Nations (<http://www.fao.org/>; FAO et al., 2008). The soil types followed the classification of the homogenization world soil data. Changes in land use were not considered in the modeling of baseline and future river runoff.

2.3 Methods

The use of climate variables downscaled from GCMs to drive validated hydrological models is a common method to understand the impact of climate change on basin-scale hydrological processes.

2.3.1 Application of the SWAT hydrological model

Hydrological models are a popular tool supporting water management at the watershed scale (Nilawar and Waikar, 2019; Pandey et al., 2019). The SWAT is a physically based semi-distributed hydrological model, which has been widely used with varying watershed scales and for a wide range of environmental conditions (Arnold et al., 2012).

For specified hydrological response units (HRUs), the SWAT model calculates water balance components that include precipitation (snow), irrigation water, evapotranspiration (ET), infiltration, soil water redistribution, lateral subsurface flow, and return flow (Neitsch et al., 2011). Model parameterization of the three inland rivers was specified by using ArcSWAT (an ArcGIS extension and interface for SWAT). The upper reaches of the three inland rivers were divided into 228 sub-basins based on the DEM, and 2529 HRUs based on land-use and soil characteristics. In the hydrological simulation used in this study, the snowmelt module was based on the temperature calculation module, by using the degree-day factor method to calculate snowmelt runoff; surface runoff was calculated by using the Soil Conservation Service (SCS) curve number method (USDA-NRCS, 2004); the potential ET was calculated by the Hargreaves method (Hargreaves and Samani, 1985); while the route process was calculated by using the Muskingum method (Neitsch et al., 2005).

The performance of the SWAT runoff simulations was evaluated based on the Nash–Sutcliffe efficiency coefficient (Ens), the coefficient of determination (R^2), and percent bias (PBIAS), which are calculated as follows:

$$\text{Ens} = 1 - \frac{\sum_{i=1}^n (Q_{\text{obs},i} - Q_{\text{sim},i})^2}{\sum_{i=1}^n (Q_{\text{obs},i} - \bar{Q}_{\text{obs}})^2}, \quad (1)$$

$$R^2 = \frac{\left[\sum_{i=1}^n (Q_{\text{obs},i} - \bar{Q}_{\text{obs}})(Q_{\text{sim},i} - \bar{Q}_{\text{sim}}) \right]^2}{\sum_{i=1}^n (Q_{\text{obs},i} - \bar{Q}_{\text{obs}})^2 \sum_{i=1}^n (Q_{\text{sim},i} - \bar{Q}_{\text{sim}})^2}, \quad (2)$$

$$\text{PBIAS} = 100 \times \frac{\sum_{i=1}^n Q_{\text{sim},i} - \sum_{i=1}^n Q_{\text{obs},i}}{\sum_{i=1}^n Q_{\text{obs},i}}, \quad (3)$$

where Q_{sim} and Q_{obs} are the simulated and observed monthly runoff, respectively, $\bar{Q}$ is the mean monthly runoff, i is the month, and n is the length of the monthly runoff series in the calibration or validation period.

No absolute criteria for judging model performance have been firmly established. However, R^2 values exceeding 0.6, Ens values exceeding 0.5, and PBIAS values less than $\pm 20\%$ have been widely reported in successful applications of SWAT in previous studies (Arnold et al., 2012). The performance of SWAT runoff simulations was also evaluated based on a comparison of observed and modeled monthly discharge time series, mean monthly runoff distributions, and flow duration curves.

The SWAT models were forced by WFD climate data at a daily time step. The SWAT models were spun up for the period 1958–1960, then calibrated for 1961–1990, and validated for 1991–2001, by using the monthly river runoff data from the three typical hydrological gauging stations.

2.3.2 Climate projection under 1.5°C and 2.0°C global warming

Using the climate model data from the five GCMs under the three RCPs of ISI-MIP, the future time horizon of 1.5°C and 2.0°C global warming was derived based on the 30-yr running mean of GMT for each one of the 15 climate projection combinations and the historical run. When the GMT anomaly of the 30-yr running mean relative to the preindustrial level reached the threshold of 1.5°C or 2.0°C, the 30-yr window was sampled as the corresponding time period of the global warming scenario. All 15 combined scenarios showed GMT increases exceeding the threshold of 1.5°C above the preindustrial level, and 14 combined scenarios exceeded the threshold of 2.0°C. The changes in projected monthly and annual air temperature and precipitation were quantified relative to the baseline period (1976–2005) in further analysis of the projected climate change in this study.

2.3.3 Runoff simulation under 1.5°C and 2.0°C global warming

The daily temperature and precipitation data during the historical period and daily climate projection scenarios under 1.5°C and 2.0°C global warming derived from the

five GCMs were used to force the calibrated and validated SWAT model. The mean annual runoff and mean monthly runoff of the three rivers were calculated to quantify the hydrological response to 1.5°C and 2.0°C global warming. To facilitate the inter-model comparisons, the percentage changes in annual and monthly runoff were compared with the baseline period (1976–2005).

2.3.4 Quantification of uncertainties

The uncertainty envelope of each climate projection and the subsequent runoff simulation is shown as a function of each GCM–RCP combination under the assumption that each scenario had an equal probability of occurrence. The uncertainty of all simulations was estimated by using the standard deviation (SD) of all combined scenarios simulated under 1.5°C and 2.0°C global warming, respectively, whereas the uncertainty of the GCM structure was quantified by using the SD of the mean of all RCPs under 1.5°C and 2.0°C global warming, and the uncertainty of RCPs was estimated by using the SD of the mean of all GCMs under each level of global warming.

3. Results

3.1 Hydrological model calibration and validation

According to the statistical results, the performances of the SWAT model in simulating monthly runoff over the calibration and validation period are generally acceptable (Table 2), with Ens generally larger than 0.5 (except for the SLR and HHR basins in the calibration period), R^2 larger than 0.6 (except for the HHR basin in the calibration period), and PBIAS less than $\pm 15\%$.

The monthly mean discharge, which reflects the basic hydrological characteristics of the river discharge distribution, shows close agreement between the observed and simulated values during 1961–2001 (Fig. 2a). The frequency distributions of simulated river discharge in all three basins closely approximate those of the observed discharge records as indicated by the flow duration curves for the period 1961–2001 (Fig. 2b). There is a general overestimation of discharge in the high flow for the three inland rivers, and a slight underestimation of discharge in the low flow of the SLR. Despite the good agreement of the monthly mean discharge and flow duration curves, occasionally poor month-to-month agree-

Table 2. Goodness of fit for SWAT simulations for monthly runoff in the SYR, HHR, and SLR basins

Period	SYR			HHR			SLR		
	Ens	R^2	PBIAS (%)	Ens	R^2	PBIAS (%)	Ens	R^2	PBIAS (%)
Calibration	0.67	0.73	−3.0	0.35	0.50	7.3	0.32	0.60	−10.5
Validation	0.52	0.69	−14.0	0.51	0.64	11.0	0.52	0.62	−1.9

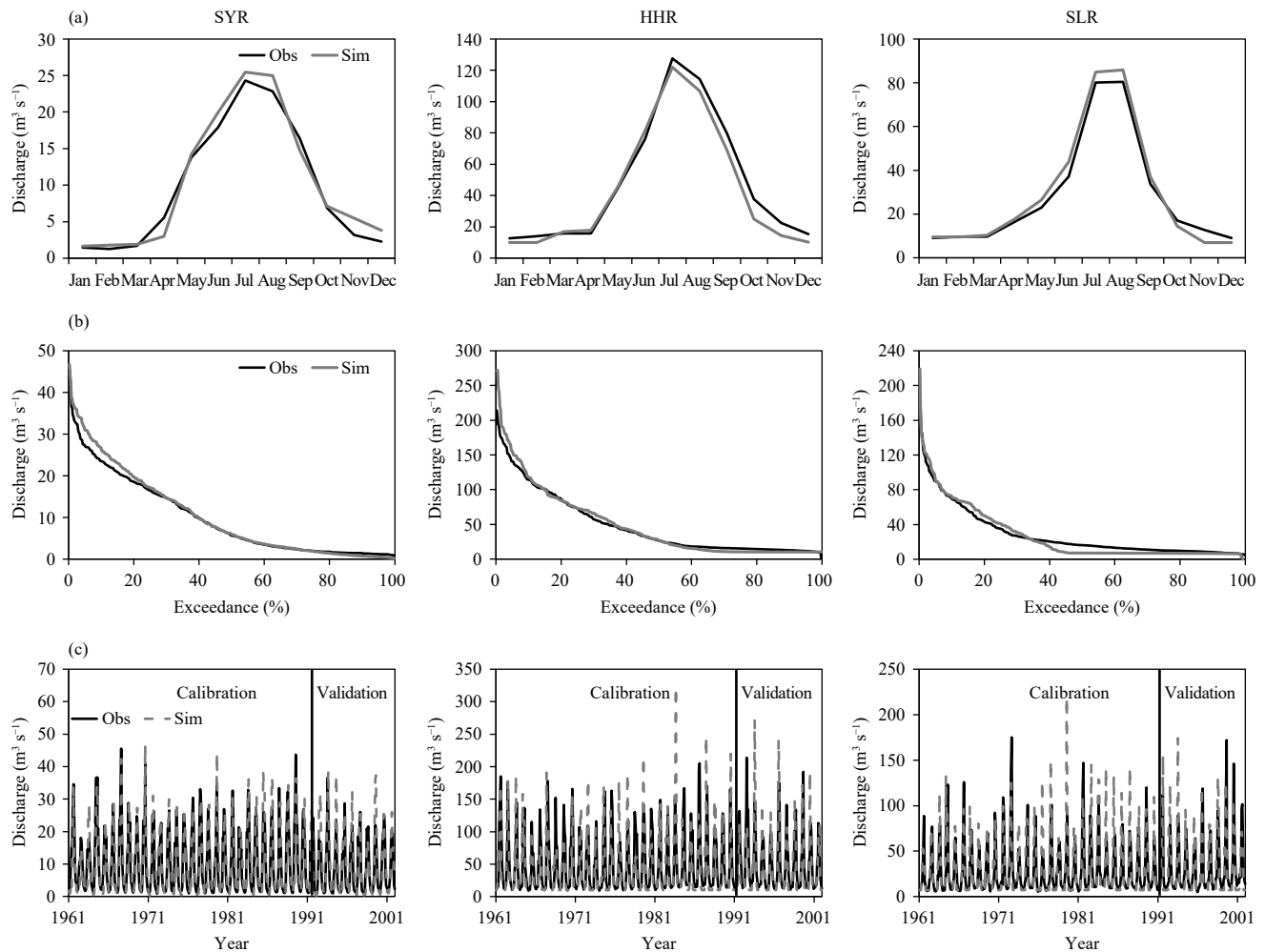


Fig. 2. Comparison of observed and simulated (a) monthly mean discharge, (b) flow duration curves, and (c) discharge time series for the SYR (left panels), HHR (center panels), and SLR (right panels) over the period 1961–2001.

ment exists (Fig. 2c). This is reflected by the low Ens for the HHR and SLR in the calibration period.

In summary, the SWAT model appears to successfully capture the underlying hydrology of the three inland rivers, as evaluated by the statistical metrics R^2 and PBIAS, and the simulated long-term monthly mean discharge and flow duration curves. The simulated runoff under the climate change scenario runs will be evaluated within this context.

3.2 Changes in climate change projection

3.2.1 Projected changes in annual air temperature and precipitation

Table 3 shows the projected changes in the ensemble mean and range of annual mean air temperature and annual mean precipitation in the SYR, HHR, and SLR basins, along with the uncertainties based on all climate scenarios, and those constrained by the GCMs and RCPs.

Under 1.5°C global warming, the projected increase in

the ensemble mean annual air temperature is 1.42, 1.45, and 1.54°C in the SYR, HHR, and SLR basins, respectively, while the projected change in the ensemble mean annual mean precipitation shows an increase of 4%, 5%, and 12% in the SYR, HHR, and SLR basins, respectively. Under 2.0°C global warming, the ensemble mean annual air temperature increased by 2.09, 2.15, and 2.36°C in the SYR, HHR, and SLR basins, respectively, while the ensemble mean annual mean precipitation increases by 5%, 6%, and 11% in the SYR, HHR, and SLR basins, respectively. The additional 0.5°C of warming results in a rise in the annual air temperature of 0.67, 0.7, and 0.82°C in the SYR, HHR, and SLR basins, respectively. The same additional warming results in about a 1% change in annual mean precipitation in the SYR, HHR, and SLR basins.

Under global warming of 2.0°C, the ranges for the projected warming are larger than those under 1.5°C global warming. Under 1.5°C global warming, the range

Table 3. Projected changes and uncertainties in annual mean air temperature and annual mean precipitation in the SYR, HHR, and SLR basins under 1.5°C and 2.0°C global warming

Basin	Global warming	Annual mean temperature					
		Change (°C)				Uncertainty	
		Avg	Max	Min	All	GCMs	RCPs
SYR	1.5°C	1.42	1.65	0.95	0.21	0.19	0.06
	2.0°C	2.09	2.54	1.68	0.25	0.23	0.28
HHR	1.5°C	1.45	1.72	1.11	0.20	0.17	0.07
	2.0°C	2.15	2.65	1.61	0.29	0.27	0.24
SLR	1.5°C	1.54	1.85	1.24	0.21	0.18	0.07
	2.0°C	2.36	2.80	1.80	0.32	0.31	0.19
Basin	Global warming	Annual mean precipitation					
		Change (%)				Uncertainty	
		Avg	Max	Min	All	GCMs	RCPs
SYR	1.5°C	4	18	-7	6.31	6.25	0.57
	2.0°C	5	15	-6	6.05	6.20	0.60
HHR	1.5°C	5	13	-5	5.60	5.84	1.04
	2.0°C	6	17	-4	6.48	6.18	2.33
SLR	1.5°C	12	22	-2	8.34	8.73	1.29
	2.0°C	11	24	-2	8.56	8.83	2.57

Note: Avg, Max, and Min represent ensemble mean, maximum, and minimum of all scenarios, respectively.

in projected annual air temperature is 0.7°C (0.95–1.65°C) in the SYR basin, and ~0.6°C in both the HHR (1.11–1.72°C) and SLR (1.24–1.85°C) basins. Under 2.0°C global warming, the range in projected warming is 0.9°C (1.68–2.54°C) in the SYR basin, and ~1.0°C in both the HHR (1.61–2.65°C) and the SLR (1.80–2.80°C) basins. Based on SD values, there are larger uncertainties in these values under 2.0°C global warming. These uncertainties are mainly contributed by the GCMs rather than the RCPs under the two warming thresholds.

Under 1.5°C global warming, the ranges for the projected changes in annual mean precipitation are 25% (–7% to 18%) in the SYR basin, 18% (–5% to 13%) in the HHR basin, and 24% (–2% to 22%) in the SLR basin. Under 2.0°C global warming, the ranges for the projected changes in annual mean precipitation are 21% (–6% to 15%) in the SYR basin, 21% (–4% to 17%) in the HHR basin, and 26% (–2% to 24%) in the SLR basin. The uncertainties in the projected annual mean precipitation changes are larger than those of the projected annual air temperature changes. The uncertainty in annual mean precipitation is mainly contributed by the GCMs. Comparing the uncertainty in projected annual mean precipitation under 1.5°C and 2.0°C global warming, there is larger uncertainty in the HHR and SLR basins and less uncertainty in the SYR basin under 2.0°C global warming.

3.2.2 Projected changes in monthly air temperature and precipitation

Figure 3a shows the projected changes in monthly air temperature and the associated ranges for all scenarios. The projected ensemble mean monthly air temperature increases by 1.2–1.7°C in the SYR basin, 1.2–1.8°C in the HHR basin, and 1.2–1.9°C in the SLR basin under 1.5°C global warming, while the increase is 1.8–2.5°C in

the SYR basin, 1.9–2.6°C in the HHR basin, and 1.9–2.7°C in the SLR basin under 2.0°C global warming. There is substantial and consistent warming from August to December (larger than 1.5°C) under 1.5°C global warming, and from August to November (larger than 2.2°C) under 2.0°C global warming, according to the projected changes in ensemble mean monthly mean temperature compared with the projected changes in annual mean temperature relative to the baseline. The ranges of the projected change in monthly mean temperature are consistently larger than those for the projected annual mean temperature changes under 1.5°C and 2.0°C global warming, being generally larger than 1.0°C and with substantially larger ranges under 2.0°C global warming. Under 1.5°C global warming, the largest ranges (> 1.9°C) in projected monthly mean temperature change in the SYR and HHR basins are in winter, while for the SLR basin, the range is the largest in February and April. Under 2.0°C global warming, for all three river basins, the largest range (> 2.6°C) occurs in July.

Figure 3b shows the projected changes in monthly precipitation and the associated ranges under the two global warming scenarios. The projected change in ensemble mean monthly precipitation is 1%–26% in the SYR basin, –1% to 21% in the HHR basin, and 4%–27% in the SLR basin under 1.5°C global warming. Under 2.0°C global warming, the projected change is 3%–40% in the SYR basin, 0–30% in the HHR basin, and 4%–31% in the SLR basin. There is a small increase in the ensemble mean monthly precipitation during May–October in the SYR and HHR basins (< 6%, except July in the HHR basin) under both global warming scenarios, while in the SLR basin the smallest increase occurs during September–October. These results imply a relatively drier sum-

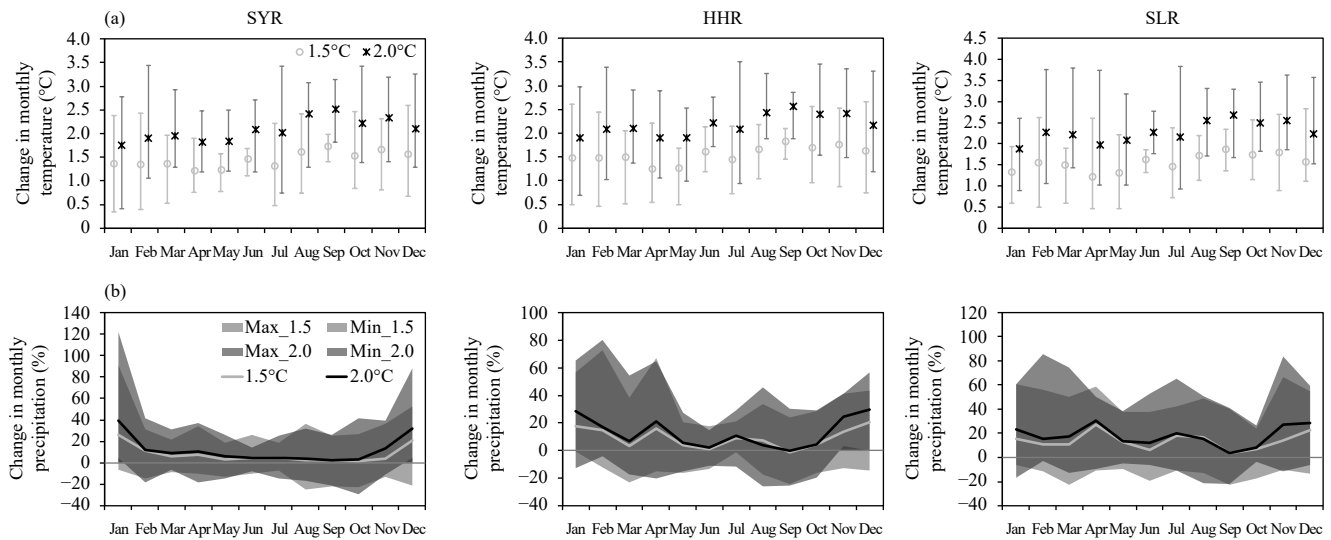


Fig. 3. Changes in the ensemble mean, maximum, and minimum values of all projected (a) monthly mean temperatures and (b) monthly mean precipitation in the SYR (left panels), HHR (center panels), and SLR (right panels) basins under 1.5°C and 2.0°C global warming compared with 1976–2005.

mer and autumn in the SYR and HHR basins, and a relatively drier autumn in the SLR basin. The projected ranges of the monthly precipitation change are 25%–97% and 22%–117% in the SYR basin, 22%–85% and 26%–85% in the HHR basin, and 42%–77% and 30%–95% in the SLR basin under 1.5°C and 2.0°C global warming, respectively. Under both global warming scenarios, the range of projected monthly precipitation change is small in June and July in the SYR and HHR basins, and is small in October in the SLR basin.

3.3 Changes in simulated runoff

3.3.1 Simulated changes in annual runoff

Under 1.5°C and 2.0°C global warming, there is generally a slight decrease in the simulated ensemble mean annual runoff in the SYR and HHR basins, and substantial increase of that in the SLR basin (Table 4). Under 1.5°C global warming, the simulated ensemble mean annual runoff decreases slightly by approximately 4% and 3% in the SYR and HHR basins, respectively, while it increases by 10% in the SLR basin. Under 2.0°C global warming, the simulated ensemble mean annual runoff

shows nearly no change in the SYR basin, decreases by 4% in the HHR basin, and increases by 11% in the SLR basin. The additional 0.5°C of warming leads to an increase in simulated annual runoff of ~5% in the SYR basin and a change of 1% in the HHR and SLR basins.

Under 1.5°C global warming, the range for the projected change in annual runoff is 28% (–15% to 13%) in the SYR basin, 28% (–18% to 10%) in the HHR basin, and 36% (–14% to 22%) in the SLR basin. Under 2.0°C global warming, the range is 24% (–12% to 12%) in the SYR basin, 39% (–17% to 22%) in the HHR basin, and 46% (–17% to 29%) in the SLR basin for the projected change in annual runoff. In the HHR and SLR basins, there are larger uncertainties in the simulated mean annual runoff under 2.0°C global warming compared with 1.5°C global warming, as quantified by using the SD. In contrast, the uncertainties are larger under 1.5°C global warming in the SYR basin. For all three rivers, there is less uncertainty in simulated runoff as constrained by the RCPs compared with the GCMs.

3.3.2 Simulated changes in monthly runoff

Figure 4 shows the simulated changes in ensemble

Table 4. Changes in simulated annual runoff in the SYR, HHR, and SLR basins under 1.5°C and 2.0°C global warming compared with 1976–2005

Basin	Global warming	Annual mean runoff					
		Change (%)				Uncertainty	
		Avg	Max	Min	All	GCMs	RCPs
SYR	1.5°C	–4	13	–15	9.3	9.2	2.7
	2.0°C	1	12	–12	7.2	6.9	1.7
HHR	1.5°C	–3	10	–18	8.9	8.9	1.6
	2.0°C	–4	22	–17	10.8	10.0	3.0
SLR	1.5°C	10	22	–14	11.4	11.3	2.2
	2.0°C	11	29	–17	14.5	13.9	5.5

mean monthly runoff and the associated ranges under the two warming thresholds. In general, there is a slight decrease in the simulated ensemble mean monthly runoff under 1.5°C global warming in the SYR basin. In contrast, most months show a slight increase in runoff under 2.0°C global warming, especially from January to March. In the HHR basin, there are only slight changes in the ensemble mean monthly runoff. The magnitude of the changes in the months with decreased runoff is larger than those with increased runoff under the two warming thresholds. There is a consistent slight increase in the simulated ensemble mean monthly runoff in the SLR basin under both 1.5°C and 2.0°C global warming. There are large uncertainties in simulated monthly runoff in the three basins, especially in March for the HHR basin and in winter and spring for the SLR basin.

4. Discussion

4.1 Future changes in climate and runoff

The projection of climate change in this study indicates a generally warm and wet trend in the three inland river basins in the Hexi Corridor under 1.5°C and 2.0°C global warming, which is similar to the findings of previous studies (Wang and Chen, 2014; Sun et al., 2015; Wang R. T. et al., 2019). Our results show that the mean temperature and precipitation are projected to increase by 1.42–1.54°C and 4%–12%, respectively, under 1.5°C global warming in the three inland river basins in the Hexi Corridor, while under 2.0°C global warming the increases are 2.09–2.36°C and 5%–11%, respectively. The projected changes in temperature and precipitation are consistent and comparable with observed changes in Northwest China (Lan et al., 2013; Wang et al., 2013). The generally increasing precipitation in Northwest China may be caused by increased atmospheric water vapor and an enhanced hydrological cycle altered by global warming (Shi et al., 2007). The difference in the increasing precipitation trend mainly relates to the source of atmospheric water vapor being dominated by atmo-

spheric circulation in each river basin (Lan et al., 2013). The changes in atmospheric conditions and the consequences for precipitation in the three inland rivers against the background of global warming need further exploration.

The simulated ensemble mean annual average runoff shows a slight decrease in the east and a substantial increase in the west of the Hexi Corridor, which is comparable with previous estimations of runoff changes in Northwest China (Shi et al., 2007; Qin et al., 2016). The annual runoff is projected to change by –4% to 10% under 1.5°C global warming and by –4% to 11% under 2.0°C global warming among the three inland river basins, which is similar to their historical trends (Shi et al., 2007; Wang et al., 2013). Previous studies have shown that change in runoff is affected by both temperature and precipitation and related to the runoff recharge proportions from meltwater and precipitation in the Qilian Mountains area (Li et al., 2012; Li et al., 2016b). As glaciers in the eastern part of the Qilian Mountains are almost exhausted, runoff from the SYR and HHR is primarily affected by precipitation. However, meltwater also contributes to the seasonal runoff of the SLR in the western part of the Qilian Mountains (Ma et al., 2008). An important reason for the observed increase in runoff in the SLR basin is the increased precipitation and accelerated glacial and snow melt (Li et al., 2016a). However, the estimated changes in glaciers, snow cover, and permafrost caused by global warming need to be quantified in further research, especially in meltwater-dominated river basins.

4.2 Response of runoff to climate change

Precipitation is the main input of surface water resources and ET is the main output, and the balance of precipitation and ET determines runoff generation. In this study, the response of annual runoff to annual mean precipitation is roughly linear: a 10% increase in annual mean precipitation leads to annual runoff increases of 11% and 9% in the SYR basin, increases of 15% and

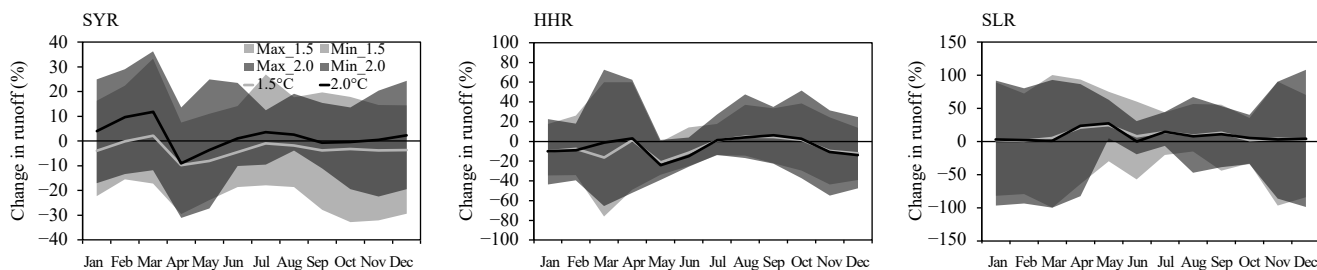


Fig. 4. Changes in ensemble mean, maximum, and minimum values of simulated monthly runoff in the SYR, HHR, and SLR basins under 1.5°C and 2.0°C global warming compared with 1976–2005.

16% in the HHR basin, and increases of 13% and 14% in the SLR basin under 1.5°C and 2.0°C global warming, respectively (Fig. 5). This is comparable with the observed response of runoff to precipitation (about a 10% increase in annual mean precipitation leads to a 10.4%–14.0% increase in annual runoff) in the three inland river basins of the Hexi Corridor during 1960–2012 (He et al., 2019).

In this study, there is a relatively strong response of runoff to increased temperature in the HHR basin: without considering changes in precipitation, 1.5°C and 2.0°C global warming result in a decrease in runoff of about 11% and 13%, respectively. There is a relatively weak response of runoff to increased temperature in the SLR basin, with a decrease in runoff of about 5% under both 1.5°C and 2.0°C global warming. The response of runoff to temperature in the SYR basin manifests as de-

crease in runoff by about 8% and 4% under 1.5°C and 2.0°C global warming, respectively (Fig. 5).

ET is a key component of the expected response of the water cycle to global warming. The ensemble mean simulated actual ET increases about 22% and 16% in the SYR basin under 1.5°C and 2.0°C global warming relative to the baseline, respectively, while in the HHR basin it increases by about 5% and 6%, and in the SLR basin it increases about 13% and 12% (Fig. 6). This is comparable with the observed increasing trend of actual ET under the historical climate during 2000–2009 in the SYR and HHR basins based on various methods (Cheng et al., 2007; Matin and Bourque, 2013; Lu et al., 2015; Li G. et al., 2017). Also, this is consistent with the increase in ET over the Heihe agricultural region, which is caused by the increase in temperature and precipitation under RCP2.6, RCP4.5, and RCP8.5 for the period 2021–2050

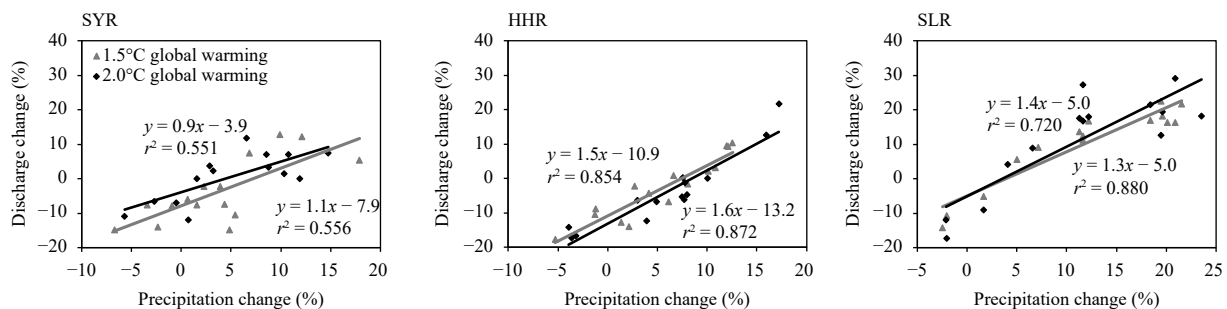


Fig. 5. Relationship between projected changes in annual mean precipitation (x axis; %) and river runoff (y axis; %) averaged over the SYR, HHR, and SLR basins under 1.5°C (triangle) and 2.0°C (diamond) global warming relative to a baseline of 1976–2005.

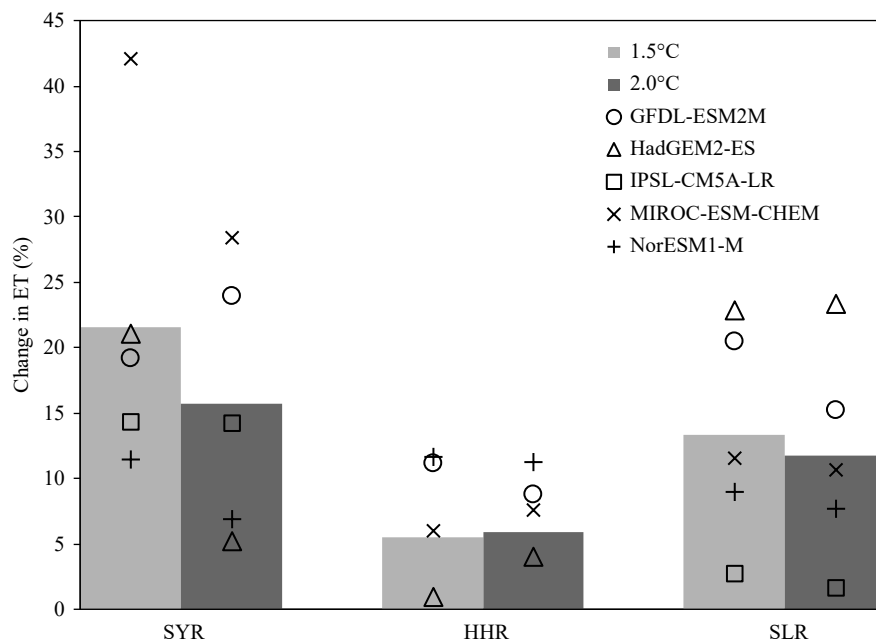


Fig. 6. Projected changes in actual ET across the five GCMs in the SYR, HHR, and SLR basins under 1.5°C and 2.0°C global warming compared with 1976–2005.

(Zou et al., 2020).

Global warming drives an increase in ET until soil moisture availability becomes a strong limitation in areas with dry climate (Berg and Sheffield, 2018). Currently, there are several in situ techniques that exist for ET measurements at the local to regional scale (Zeng et al., 2018), which make it possible to validate the accuracy of ET simulations in further research. Moreover, the different response mechanisms of ET to climate change need to be explored in future research.

The differences in the runoff recharge mechanism and response of runoff to global warming result in the differences in the simulated runoff of the three inland rivers between the two global warming scenarios. The runoff in the HHR and SYR is mainly contributed by precipitation; the lower increase in projected annual mean precipitation combined with the robust response of runoff to global warming may result in the slight decrease in simulated runoff in the HHR basin under 1.5°C and 2.0°C global warming and in the SYR basin under 1.5°C global warming. This is comparable with the observed increase in ET caused by global warming, which contributes to the change in runoff in the SYR basin (Wang and Qin, 2017), and coincides with the decreased precipitation and increased potential ET contributing most to the observed reduction in runoff in the tributaries of the SYR basin (Ma et al., 2008).

4.3 Uncertainties in hydrological simulations

The complex processes and feedbacks in the interaction between climate and the water system imply that there are multiple sources of uncertainty in the assessment of the climate change impact on water resources. This research has followed the top-down methodology that was widely used in the Fourth and Fifth Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) by Working Group II, and some of the techniques used are similar to previous case studies related to climate impacts on water resources under ISI-MIP at either the global or regional scale (Schewe et al., 2014; Vetter et al., 2015; Gosling et al., 2017; Hattermann et al., 2017; Vetter et al., 2017). Previous research has indicated that the main factors contributing to climate change impact uncertainty include GCMs, greenhouse gas emission scenarios, the downscaling method, hydrological model structure, parameterization, and forcing data. In this study, we have focused on the uncertainties constrained by GCMs and RCP scenarios, and used five GCMs under three RCPs to quantify the uncertainties in climate change projection and runoff simulation.

GCM selection is the largest source of uncertainty in climate change impact research. CMIP5 provided multiple GCMs for projections under different RCPs, which can help capture the large range of variation in climate simulation outputs. The climate projection information of the five GCMs in this study was derived from the fast-tracked phase of ISI-MIP. Although the ISI-MIP five-model subset can be expected to underestimate the total uncertainty in future climate impact for many regions and seasons, 60% to 90% of the full range of future projections of the 36 CMIP5 GCMs is captured by the five-model subset used for temperature, while for precipitation this figure is 40% to 80% (McSweeney and Jones, 2016), which contributes to constraining the uncertainties from the GCMs dataset.

Improving our understanding of climate impacts on the water cycle and better quantifying the uncertainties will benefit watershed management and improve climate change adaptation. The river runoff from the three inland rivers in this study is the main water source in the Hexi Corridor, especially for agricultural irrigation. Although there are uncertainties in the projected changes in precipitation and runoff, the substantial warming and slight decrease in simulated runoff in the SYR and HHR basins nonetheless imply that water scarcity will remain a challenge for sustainable development of the Hexi Corridor in the future. Improving the efficiency of water resources and strengthening the utilization of rainfall resources will be useful adaptations to climate change.

5. Conclusions

Under 1.5°C and 2.0°C global warming, all three inland river basins of the Hexi Corridor examined in the present study are projected to be warmer and wetter compared with the baseline period of 1976–2005. The projected warming and changes in annual mean precipitation increase from east to west and are more robust under 2.0°C global warming.

Under global warming of 1.5°C, the projected annual air temperature increase in the SYR, HHR, and SLR basins relative to 1976–2005 is 1.42, 1.45, and 1.54°C, respectively; the increase in annual average precipitation is approximately 4%, 5%, and 12%, respectively; and the annual runoff in the SYR and HHR basins is projected to decrease slightly by 4% and 3%, respectively, whereas there is an increase of ~10% in the SLR basin. Under global warming of 2.0°C, the projected annual air temperature increase in the SYR, HHR, and SLR basins relative to 1976–2005 is 2.09, 2.15, and 2.36°C, respectively, and the annual average precipitation increases by

approximately 5%, 6%, and 11%, respectively. The simulated annual runoff shows no change in the SYR basin, decreases slightly by 4% in the HHR basin, and shows a large increase of 11% in the SLR basin under 2.0°C global warming.

There is substantial and consistent warming from August to December (larger than 1.5°C) under 1.5°C global warming, and from August to November (larger than 2.2°C) under 2.0°C global warming in the three inland river basins. There are smaller increases in the ensemble mean monthly precipitation during May–October in the SYR and HHR basins (less than 6%, except for July in the HHR basin), and during September–October in the SLR basin, under the two warming scenarios. There is a slight decrease in the simulated ensemble mean monthly runoff under 1.5°C global warming in the SYR basin, whereas the majority of months see a slight increase in runoff under 2.0°C global warming. There are small changes in the ensemble mean monthly runoff in the HHR basin, and there are consistent slight increases in the simulated ensemble mean monthly runoff in the SLR basin under 1.5°C and 2.0°C global warming.

Uncertainty exists in the projections of annual air temperature, precipitation, and runoff. Whether under 1.5°C or 2.0°C global warming, the uncertainty in the estimated annual mean precipitation and runoff is larger than that of the temperature projections in these three inland river basins of the Hexi Corridor, which is mainly constrained by the GCMs. The ranges of the projected changes in monthly air temperature, precipitation, and runoff are consistently larger than those of annual values both under 1.5°C and 2.0°C global warming.

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