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Key Points:

- CMIP5 GCM ensemble performance is assessed for the Hexi Corridor
- Flow regime characteristics are simulated by an integrated water system model
- Climate change impacts on flow regimes are clustered into three robust classes

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Simulation and classification of the impacts of projected climate change on flow regimes in the arid Hexi Corridor of Northwest China

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Abstract Traditional assessment approaches of climate change on flow regimes usually focus on flow magnitude and cannot capture the overall variation of flow regimes (e.g., variability, frequency, duration, timing, and rating). The Hexi Corridor, which is a typical arid and semiarid region in Northwest China, was selected as the study area. Streamflows were simulated by an integrated water system model in a historical period (1985–2005) and three future periods (2030s, 2050s, and 2070s). Twenty-nine global climate models were picked from the Coupled Model Intercomparison Project Phase 5 based on projection performance, and the high (RCP85) and intermediate (RCP45) ranges of Representative Concentration Pathways were selected for future scenario analysis. All the streamflows were characterized in detail by flow regime metrics, including the magnitude, variability, and frequency of the overall flow events. The regional impacts of climate change were assessed and clustered into several similar spatial patterns. Results showed that the projected climate change would sensibly increase the magnitudes of average and low flows (75th percentile), as well as the frequencies of low and high flows (25th percentile), but decrease the flow variability. By contrast, it would not sensibly change the magnitude of high-flow events. The flow regime variations of all scenarios and periods were clustered into three robust classes (highly, moderately, and slightly impacted classes) in the entire region. The flow regimes would be highly and moderately impacted in the middle stream and downstream with large-sized and semidesert catchments but slightly impacted in the upper and middle streams with small-sized and montane vegetation catchments. The impacted classes will sensibly vary at most stations in different future periods because of the spatial differences of climate change. This study would provide scientific support to implement the integrated adaptive water resource management for climate change at regional scales in the arid Hexi Corridor.

1. Introduction

Climate change is an undeniable phenomenon worldwide, especially in arid and semiarid regions [Intergovernmental Panel on Climate Change (IPCC), 2014; Rotenberg and Yakir, 2010]. The temperature in semiarid regions has increased by 1.53°C over the last century, 2 times the global average (0.7°C) [Trenberth, 2011; Huang et al., 2012]. Precipitation occurs more frequently and intensively as rain than as snow in early spring [Trenberth, 2011]. In the arid and semiarid regions of Northwest China, the climate pattern is changing from warm-dry to warm-wet climates [Shi et al., 2003]. Over the last half century, the average increase rate of temperature was 0.22–0.39°C/10 yr, which is greater than the average rate in the arid and semiarid regions of the world [Ren et al., 2005; Huang et al., 2012]. The average annual precipitation has also increased with obvious regional differences [Chen et al., 1991; Zhai et al., 2005].

The impact of climate change on streamflow has been addressed since the 1990s [IPCC, 1990]. IPCC [1990, 1996, 2001, 2007, 2014] regularly releases current studies at catchment, continental, or global scales. A large number of studies have reported that arid and semiarid regions are the most sensitive and important areas to global changes because of their fragile ecosystems [Whitford, 2002; Rotenberg and Yakir, 2010]. Climate change is a significant and direct threat to water resource security and creates serious repercussions to agricultural production and fragile ecosystems [Bates et al., 2008]. Climate-related water issues (i.e., droughts and floods) occur frequently and strongly in these regions [Zhai et al., 2005; Zou et al., 2005]. Therefore, climate change and its impact on streamflow are of great concern for water resource availability in arid and semiarid river basins.

The major approach for climate change assessment involves the prediction and comparison of hydrograph differences among different future time periods using the hydrological models driven by scenarios based on climate model simulations [Arnell, 1999a, 1999b, 2004; Leavesley, 1994; Bates *et al.*, 2008; Döll and Schmied, 2012; Dickerson Lange and Mitchell, 2014]. Most existing studies have focused on the magnitude and timing of flows for water resource management. However, in addition to magnitude and timing, other flow components (such as frequency, variability, duration, and rating of flow events) play important roles in the environmental, ecological, and biological processes of aquatic systems [Arthington *et al.*, 2010]. All of these mentioned flow components characterize the “flow regime” [Richter *et al.*, 1996; Poff *et al.*, 1997]. Along with the ecological and environmental benefits of streamflow that have been proposed and seriously addressed, assessing the impact of climate change on the overall characteristics of flow regime rather than the traditional water resource indicators (e.g., flow magnitude) is necessary to support further studies on the probable consequences of environment and ecosystem and integrated water resource management.

The impact assessment of climate change on streamflow remains an important issue in arid and semiarid regions because of the complexities of precipitation changes, underlying surface conditions, and interactions between climate change and hydrological cycle [Pilgrim *et al.*, 1988; Lioubimtseva, 2004]. Arnell [2004] presented some anomalies of annual mean precipitation and runoff between different climate models in arid regions. Bates *et al.* [2008] found that the change sign of future annual runoff was different among 12 climate models, particularly in high-latitude semiarid and arid rivers. The major problems include hydrological calibration, future climate change projection and downscaling, and detailed characterization of flow regimes [Pilgrim *et al.*, 1988; Leavesley, 1994; Xu, 1999; Lioubimtseva, 2004].

The Hexi Corridor is a typical arid and semiarid region in Northwest China and is divided into three main basins, namely, Shiyang River Basin (SYRB), Hei River Basin (HRB), and Shule River Basin (SLRB) from east to west. Most existing studies were to qualitatively analyze the impact of climate change by making comparison of the trends between the long-term historical flow magnitude and climate variables of individual stations in SYRB and HRB because of the severe water issues in these areas [Shi and Zhang, 1995; Zhang *et al.*, 2003; Ma *et al.*, 2008; Huo *et al.*, 2008; Li *et al.*, 2008]. Some studies have also been conducted to assess the impact of climate change on flow magnitude at individual stations using a distributed hydrological model and a single-climate model (e.g., General Circulation Model (GCM)-HadCM2, PRECIS) [Wu *et al.*, 2010; Wang *et al.*, 2012]. Wu *et al.* [2010] reported that the mean annual flow magnitude would decrease at Yingluoxia station in HRB, while Wang *et al.* [2012] found that the magnitude would increase slightly at Zamusi station in the upper stream of SYRB. The uncertainties of future climate variables would inevitably affect the assessment results directly.

In this study, the impact of the projected climate change on flow regime was comprehensively assessed in the entire Hexi Corridor by hydrological simulation and statistical classification. The objectives of this study were as follows: (1) to fully characterize the streamflow of individual stations using flow regime metrics, including the magnitude, frequency, duration, timing, and rating of flow events; (2) to evaluate the performance of GCM ensemble and choose the reasonable future projection of climate variables (precipitation and temperature) in our study area; and (3) to classify all metric differences between future and baseline streamflows by hierarchical clustering method to assess the spatial impact of climate change on flow regimes in the entire region. This study would provide a reference to assess the impact of climate change on streamflow and scientific support to implement the integrated adaptive water resource management facing climate change in the arid Hexi Corridor.

2. Material and Methods

2.1. Study Area

The Hexi Corridor (37°17′–42°48′N, 93°23′–104°12′E) is a typical arid and semiarid region in Northwest China (Figure 1). This region is located in the northwest of the Yellow River with a long, narrow passage stretching for over 1000 km from east (Gulang) to west (Yumen) and 100–200 km from south (Qilian Mountain) to north (North Mountain). The corridor is the most important route from North China to Central Asia for traders and militaries, is an important part of the historic Silk Road, and contains a famous granary in the northwest.

Figure 1. The location of the study area.

The weather in this region belongs to continental arid climate with minimal precipitation, strong potential evaporation, and dramatic temperature variability. The spatial variations of precipitation and drought are remarkable from east to west. For example, the average annual precipitation is 158.4 mm in Wuwei City in the east but is only 36.8 mm in Dunhuang City in the west. The aridity index (the ratio of annual precipitation and annual potential evapotranspiration) decreases approximately from 1/4 (semiarid) in the east to 1/24 (hyperarid) in the west. The intra-annual precipitation variability is distinct with proportions of 50%–60% in summer, 15%–25% in spring, 10%–25% in autumn, and 3%–16% in winter. The average annual temperature is 5.8–9.3°C with maximum and minimum values of 42.8 and −29.3°C, respectively.

The three main basins (i.e., SYRB, HRB, and SLRB) are separated by the Hei, Kuantai, and Dahuang Mountains, respectively. All of these rivers originate from the meltwater and precipitation of the Qilian Mountains and provide continuous flows for downstream oases and farmlands. However, most rivers disappear in the Gobi Desert after flowing out of the mountains because of infiltration and irrigation consumption, except the mainstems that reach rump lakes.

A strikingly inhospitable environment surrounds the entire region, e.g., the snow-capped Qilian Mountains in the south and the vast Gobi Desert in the other directions. Several prominent ecological issues have emerged in the upstream, including snow lines accumulation, glacial recession, grassland degradation, and forest reduction. In the downstream region, over 30,000 ha of natural forests have deteriorated because of water shortage, and 20,000 ha of farmland have become deserts by wind erosion. The severe ecological crises have become the primary bottleneck for the sustainable development of the Hexi Corridor and have drawn attention in the entire country.

2.2. Data Sources

Geographic, streamflow, and meteorological data sources were collected for hydrological simulation and climate change assessment. Geographic data included the digital elevation model (DEM), land use, digital river network, and hydrological gauge positions, which were used to delineate the spatial characteristics and subbasins of our study area for the construction of a distributed water system model. The monthly streamflow series of 20 gauges were collected for hydrological model calibration and validation, including 10 gauges from 1988 to 2005 in SYRB, eight gauges from 1990 to 2000 in HRB, and two gauges from 1971 to 1987 in SLRB. The basic geographic information of all the stations are shown in Table 1. The calibration

Table 1. The Selected Stations and the Basic Geographic Information of Their Controlled Catchments

Basins	Stations	Catchment Area (km ²)	Evaluation (m)	Major Land Use	Location
Shiyang River Basin	Xiamt	319	3,096	Forest (47%) and desert (33%)	upper stream
	Jiutl	1,120	2,473	Grass (41%) and desert (39%)	middle stream
	Zams	848	3,021	Grass (37%) and desert (33%)	upper stream
	Dajx	392	2,490	Farm land (30%) and desert (28%)	upper stream
	Caojh	312	2,833	Farm land (38%) and forest (27%)	upper stream
	Shibl	446	2,368	Farm land (37%) and forest (29%)	upper stream
	Gul	841	2,381	Farm land (31%) and forest (26%)	upper stream
	Huangyh	1,110	2,349	Farm land (42%) and forest (25%)	downstream
	Nany	846	2,468	Desert (42%) and grass (34%)	upper stream
	Xidh	649	3,775	Forest (40%) and desert (38%)	upper stream
Hei River Basin	Zamsk	3,497	3,863	Grass (52%) and desert (40%)	upper stream
	Yinglx	8,877	2,516	Desert (39%) and grass (38%)	downstream
	Qil	2,450	3,030	Desert (38%) and forest (31%)	upper stream
	Shuangss	617	2,937	Forest (59%) and desert (29%)	upper stream
	Sun	1,899	2,673	Desert (52%) and grass (30%)	downstream
	Wafc	270	3,609	Desert (70%) and forest (20%)	upper stream
	Gaoy	16,080	1,462	Desert (43%) and grass (32%)	downstream
	Bingg	6,831	2,826	Grass (53%) and desert (47%)	downstream
Shule River Basin	Changmb	13,779	3,175	Desert (65%) and grass (33%)	middle stream
	Dangcw	11,143	3,117	Desert (69%) and grass (30%)	middle stream

period was from 1988 to 1999 in SYRB, from 1990 to 1995 in HRB, and from 1971 to 1979 in SLRB. The validation period was from 2000 to 2005 in SYRB, from 1996 to 2000 in HRB, and from 1980 to 1987 in SLRB. The meteorological data contained the historically observed daily precipitation, the maximum, minimum, and mean temperatures from 1971 to 2005 at 14 weather stations that were collected from the China Meteorological Administration, the simulated historical monthly data in the same periods of 41 GCMs of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Table 2), and the projected future monthly data from 2006 to 2099 in RCP45 and RCP85 emission scenarios. The projected monthly variables at grid scale were interpolated to each station for the evaluation of GCM performance and all meteorological data at these stations were further interpolated to each subbasin using the inverse distance and elevation weighting method to drive the hydrological model [Daly *et al.*, 2002]. In this study, the median condition of climate change (50%) was used for future impact analysis, which was determined by the frequency analysis curve of projected changes from all suitable GCMs for the arid Hexi Corridor.

2.3. Impact Assessment Approach

The impact assessment of climate change on flow regimes was performed on the basis of the hydrological simulation of different future periods and scenarios. The streamflow was fully characterized by flow regime metrics. The metric differences between the future and baseline periods were obtained for individual stations and clustered into some typical classes for the entire region to assess the impact of climate change.

2.3.1. Distributed Water System Model (HEQM)

The HEQM (H indicates Hydrological modules, E indicates Ecological modules and Q indicates water Quality modules) is a semidistributed and integrated water system model that couples multiscale water-related processes, including hydrology, biogeochemistry, water environment, and ecology, and human interferences at the basin scale [Zhang *et al.*, 2014]. The current version of HEQM comprises seven modules (i.e., hydrological cycle module, soil biochemical module, crop growth module, soil erosion module, overland water quality module, dams regulation module, and water quality module in water bodies) and a parameter analysis tool (Figure 2).

The hydrological cycle module of HEQM was adopted to reproduce hydrographs for this study. In this module, the basic water balance equation is expressed as follows:

$$P_i + SW_i = SW_{i-1} + Rs_i + Ea_i + Rss_i + Rg_i + In_i \quad (1)$$

where P is the precipitation (mm); SW is the soil water moisture (mm); Ea is the actual evapotranspiration including soil evaporation and plant transpiration (mm); Rs , Rss , and Rg are the surface runoff, interflow, and baseflow (mm), respectively; In is the vegetation interception (mm); and i is the time step (day).

Table 2. Climate Models of CMIP5 Used in This Study

ID	GCMs	Modeling Group	Country
1	ACCESS1.0	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology	Australia
2	ACCESS1.3		
3	BCC-CSM1.1		China
4	BCC-CSM1.1-M	Beijing Normal University	China
5	BNU-ESM		
6	CanESM2		Canada
7	CCSM4	National Center for Atmospheric Research (NCAR)	USA
8	CESM1-BGC	Community Earth System Model Contributors National Science Foundation (NSF), the U.S. Department of Energy (DOE) and NCAR	USA
9	CESM1-CAM5	Centro Euro-Mediterraneo per I Cambiamenti Climatici	Italy
10	CESM1-WACCM		
11	CMCC-CESM		
12	CMCC-CM		
13	CMCC-CMS	Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	France
14	CNRM-CM5		
15	CSIRO-MK3.6.0	CSIRO in collaboration with Queensland Climate Change Centre of Excellence	Australia
16	EC-EARTH	European Centre-Earth (EC-EARTH) consortium	Europe
17	FGOALS-g2	State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Chinese Academy of Sciences and Center for Earth System Science (CESS), Tsinghua University	China
18	FGOALS-s2	LASG, Chinese Academy of Sciences	China
19	FIO-ESM	The First Institute of Oceanography, State Oceanic Administration (SOA), China	China
20	GFDL-CM3		USA
21	GFDL-ESM2G		
22	GFDL-ESM2M	NASA Goddard Institute for Space Studies	USA
23	GISS-E2-H		
24	GISS-E2-H-CC		
25	GISS-E2-R		
26	GISS-E2-R-CC	National Institute of Meteorological Research/Korea Meteorological Administration	Korea
27	HadGEM2-AO		
28	HadGEM2-CC		
29	HadGEM2-ES	Institute for Numerical Mathematics	Russia
30	INM-CM4		
31	IPSL-CM5A-LR	Institut Pierre-Simon Laplace	France
32	IPSL-CM5A-MR		
33	IPSL-CM5B-LR		
34	MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	Japan
35	MIROC-ESM		
36	MIROC-ESM-CHEM		
37	MPI-ESM-LR	Max Planck Institute for Meteorology	Germany
38	MPI-ESM-MR		
39	MRI-CGCM3	Meteorological Research Institute	Japan
40	NorESM1-M		
41	NorESM1-ME		Norway

The surface runoff (R_s , mm) yield was estimated by the time-variant gain model (TVGM). TVGM was deduced from the nonlinear Volterra function and exhibited a satisfactory performance, particularly in arid and semiarid regions [Xia *et al.*, 2005; Wang *et al.*, 2009]. The equation is expressed as follows:

$$R_s = g_1 (SW_u / W_{\text{sat}})^{g_2} \cdot (P - I_n) \quad (2)$$

where SW_u and W_{sat} are the surface soil moisture and saturation moisture (mm), respectively; g_1 and g_2 are the coefficients of basic runoff and soil moisture, respectively.

Glacial and snowmelt runoff was simulated using the degree-day factor method [Ohmura, 2001]. The interflow and baseflow were considered to have a linear storage-outflow relationship [Wang *et al.*, 2009]. Potential evapotranspiration was calculated using Hargreaves' method [Hargreaves and Samani, 1982], and the actual soil evaporation and plant transpiration were functions of potential evapotranspiration, leaf area index, and surface soil residues [Ritchie, 1972]. The Muskingum method was used in river flow routing. The

Figure 2. The structure of HEQM and the interactions among the major modules (1, hydrological part; 2, water environmental part; 3, ecological part; 4, dams regulation part; 5, the parameter analysis tool).

hydrological model considered the human activities by setting water withdrawal from reaches, adjusting the difference of several hydrological parameters for each subbasin (such as the parameters of runoff yields and evapotranspiration).

The Hexi Corridor is delineated by 238 subbasins with area ranges from 6.0 km² to 6197.0 km² according to DEM, land use, and the geographic positions of hydrological gauges. A total of 99 subbasins exist in SYRB, 89 subbasins in HRB, and 53 subbasins in SLRB. The minimum calculation cell for hydrological processes was divided according to land use types in each subbasin. In this study, 25 categories of cells were considered according to the land use classification standard of China (CNS 2007), including one category for paddy, one category for dry land, four categories for forest, three categories for grasslands, six categories for water area, three categories for urban area, and seven categories for unused land. The sizes of land use cells in the subbasins ranged from 1.0 km² to 3515.0 km².

The digital river network was continuous, which was extracted from DEM using ARC GIS platform. However, the most obvious feature of rivers in the arid and semiarid regions is that rivers disappear in the downstream zones because of the great evapotranspiration and scarce precipitation, as well as highly intensive water withdrawal. This actual feature would be considered in our model by forcing zero flows at the end points of the rivers that disappeared during the entire simulation period. The hydrological connection between these rivers and downstream subbasins were cut off.

The hydrological parameters of HEQM were calibrated individually from upstream to downstream for all regions controlled by the collected 20 gauges. In this study, relative bias (*bias*), correlation coefficient (*r*), and coefficient of efficiency (*NS*) were selected to evaluate model performance, i.e.,

$$bias = \sum_{i=1}^N (O_i - S_i) / \sum_{i=1}^N Q_i \quad (3)$$

$$r = \sum_{i=1}^N (O_i - \bar{O}) \cdot (S_i - \bar{S}) / \sqrt{\sum_{i=1}^N (O_i - \bar{O})^2 \cdot \sum_{i=1}^N (S_i - \bar{S})^2} \quad (4)$$

$$NS = 1 - \sum_{i=1}^N (O_i - S_i)^2 / \sum_{i=1}^N (O_i - \bar{O})^2 \quad (5)$$

where O_i and S_i are the i th observed and simulated values, respectively; $\bar{O}$ and $\bar{S}$ are the average observed and simulated values, respectively; and N is the length of the series.

The parameter sensitivity analysis and autocalibration of HEQM were performed using the parameter analysis tool of HEQM. Latin-hypercube one-factor-at-a-time (LH-OAT) [van Griensven *et al.*, 2006] was adopted to select the sensitive parameters of HEQM, which would be calibrated afterward by the shuffled complex evolution-University of Arizona autooptimization algorithm [Duan *et al.*, 1994]. Weighting method was a

traditional and simple way to comprehensively handle different objectives [Efstratiadis and Koutsoyiannis, 2010]. In the current study, the objective function (f_{obj}) for autocalibration was formed as the following equation by aggregating $bias$, r , and NS with equal weights. The optimal value of f_{obj} was zero.

$$f_{obj} = \min \left(\frac{|bias|}{3} + \frac{1-r}{3} + \frac{1-NS}{3} \right) \quad (6)$$

2.3.2. GCM Evaluation and Downscaling

Climate change projection is a difficult task with large uncertainties worldwide, particularly in arid and semiarid regions. Not all collected GCMs of CMIP5 were applicable in the study area. The score-based method proposed by Fu *et al.* [2013] was adopted to assess the projection performance of precipitation and temperature. The GCMs with worst performance would be excluded.

The eight aspects of projection performance were designed including the mean, standard deviation, temporal variation, monthly distribution, spatial distribution, trend and its magnitude, space-time variability, and probability density functions. The total rank score (RS) value of the j th GCM was calculated by summarizing the RS values of individual indices, i.e.,

$$RS_j = \sum_{i=1}^n \omega_i \cdot \frac{x_{i,j} - x_{i,\min}}{x_{i,\max} - x_{i,\min}} \times 9 \quad (7)$$

where i and j are the order numbers of the evaluated index and GCM, respectively; n is the total number of evaluated indices; $x_{i,j}$ is the relative error or relationship statistic between the GCM output and the observation of the i th index for the j th GCM; $x_{i,\max}$ and $x_{i,\min}$ are the maximum and minimum values of the i th index in all GCMs; and ω_i is the weight of the i th index. The equations of all indices and the detailed procedures of the GCM assessment were specified by Fu *et al.* [2013].

The daily projections of GCMs contain huge uncertainties and gain poor performances, especially precipitation and the spatial-temporal variations [Fu *et al.*, 2013]. Thus, we adopted the coefficient adjustment method to produce the projected daily series of climate variables (precipitation and temperature) in different scenarios of all selected GCMs, instead of directly using the daily outputs generated by GCMs. The adjusting coefficient of each weather station was calculated by comparing the monthly series in future periods with those in the baseline period. The future daily series was projected by superposing the coefficients with the historically observed daily series of climate variables. Considering that the values of flow regime metrics tend to be stable when the record length was at least 15 years [Kennard *et al.*, 2010], the baseline period and three future periods were divided in this study: baseline (1986–2005), 2030s (2021–2040), 2050s (2041–2060), and 2070s (2061–2080). The adjusting coefficients of precipitation and temperature in different future periods were calculated as follows:

$$\begin{cases} P_{fc,i} = (PCP_{future,i} / PCP_{baseline,i} - 1) \times 100\% \\ T_{fc,i} = TMP_{future,i} - TMP_{baseline,i} \end{cases} \quad (8)$$

where $P_{fc,i}$ and $T_{fc,i}$ are the adjusting coefficients of precipitation (%) and temperature (°C) in the i th month, respectively. In the climate change study, $P_{fc,i}$ and $T_{fc,i}$ are usually expressed by increasing the ratio and range in the i th month, respectively. $PCP_{future,i}$ and $TMP_{future,i}$ are the average precipitation and temperature in the i th month of future periods, respectively. $PCP_{baseline,i}$ and $TMP_{baseline,i}$ are the average precipitation and temperature in the i th month of baseline period, respectively. Moreover, the future daily minimum and maximum temperatures were calculated on the basis of their respective relationships with the mean daily temperature, which were statistically obtained by using the historically observed daily temperature series (mean, minimum, and maximum).

2.3.3. Flow Regime Metrics

With the development of water sciences (e.g., environmental hydrology and eco-hydrology), the flow regime characteristics have been taken ever more seriously in water resource management. The evaluated indices of the impact of climate change on streamflow should be extended to all flow regime characteristics to adapt to current water resource studies and management. Ten representative metrics were selected to depict the dimensions of overall flow regimes (Table 3). They were the flow magnitude (MMF: average monthly flow; Lw75: low monthly flow; Hg25: high monthly flow), frequency (LwC75: low-flow spell count; HgC25: high-flow spell count), duration (LwS75: low-flow spell duration; HgS25: high-flow spell duration), and timing (TMinF:

Table 3. The Flow Regime Metrics Selected to Describe Overall Flow Paradigm^a

No.	Groups	Flow Regimes	Hydrological Metrics	Abbreviation	Units
1	Magnitude	average flow	Average monthly flow	MMF	mm d ⁻¹
2		low flow	Low monthly flow (5th percentile)	Lw75	-
3		high flow	High monthly flow (25th percentile)	Hg25	-
4	Frequency and Variability	average flow	Coefficient of variation of monthly flow	CVMF	-
5		low flow	Low-flow spell count (<75th percentile)	LwC75	-
6		high flow	High-flow spell count (>25th percentile)	HgC25	-
7	Duration	low flow	Low-flow spell duration (<75th percentile)	LwS75	months
8		high flow	High-flow spell duration (>25th percentile)	HgS25	months
9	Timing	low flow	Julian months of annual minimum	TMinF	-
10		high flow	Julian months of annual maximum	TMaxF	-

^aThe high and low flows were determined by flow duration curves. In this study, the flow was treated as high flow if its percentile was equal to 25%. The flow was treated as low flow if its percentile was equal to 75%.

julian months of annual minimum; TMaxF: julian months of annual maximum) of flow events and the variability (CVMF: coefficient of variation of monthly flow) of the overall flow regime [Poff *et al.*, 1997; Zhang *et al.*, 2012].

Restricted by the simulation performance of long-term daily flow regimes in our study area, it was impossible to describe the characteristics of daily flow regimes. Monthly flow metrics would be a valid alternative and have been widely used in the present water management and planning (e.g., water resources assessment, water withdrawal and allocation, and environmental improvement) in China and many other countries [The Ministry of Water Resources of China, 2002; Matondo, 2002; Cai *et al.*, 2003]. The monthly flow metrics still could capture several characteristics of daily flow regimes (e.g., flow magnitudes and coefficient of variation) [Poff *et al.*, 1997; Zhang *et al.*, 2012].

2.3.4. River Classification

River classification is an effective and efficient approach to deduce the similar spatial pattern from large numbers of metrics and stations for assessing complex patterns of flow regime variation across a broad range of spatial scales. This approach can capture the comprehensive variation of flow regimes at the regional scales, instead of individual metrics and stations. It has been widely used in environmental flow studies, physicochemical and ecosystem monitoring analysis, and flow alteration assessment as part of river condition assessment and management [Zhang *et al.*, 2012; Arthington, 2012]. In this study, the differences of flow regime metrics between the future and baseline periods were used to analyze the impact of climate change. The equation for the *j*th metric is expressed as follows:

$$M_{fc,j} = M_{\text{future},j} - M_{\text{baseline},j} \quad (9)$$

where M_{fc} denotes the differences of flow regime metrics; M_{future} and M_{baseline} are the values of flow regime metrics in future period and baseline, respectively. The negative value of M_{fc} means that the climate change decreases the flow regime characteristics. A value of zero means that the impact of climate change is not obvious. The positive value means that the climate change increases the flow regime characteristics.

Ward's [1963] method was adopted to cluster the differences of flow regime metrics to identify all classes of flow regime variation caused by climate change. The similarity of all stations was measured by Euclidean Distance on the basis of the standardized metrics (subtracting the mean of each factor and then dividing by the standard deviation) [Zhang *et al.*, 2012]. The evaluated indices of cluster performance were the Goodman-Kruskal index (GKI) [Goodman and Kruskal, 1954] and the C index (CI) [Hubert and Schultz, 1976]. High values of GKI and low values of CI indicated a good classification. In addition, the minimum size of each class should be no less than 2 in order to guarantee the representativeness of the class. All these statistical analyses were programmed using the R 3.0.1 software. The packages of amap [Antoine and Sylvain, 2006] and fpc [Hennig, 2007] were applied for hierarchical clustering and cluster performance assessment, respectively.

3. Results

3.1. Hydrological Simulation

Nine sensitive hydrological parameters were selected by LH-OAT. All of these parameters explained 96.3% of the flow variations, which were divided into four soil water parameters (48.47%) (WM: saturation moisture

Table 4. The Evaluation Criteria Results of Single-Objective Calibration

Basins	Stations	Calibration				Validation			
		<i>bias</i>	<i>r</i>	<i>NS</i>	<i>f_{obj}</i>	<i>bias</i>	<i>r</i>	<i>NS</i>	<i>f_{obj}</i>
<i>Shiyang River Basin</i>		<i>1988–1999</i>				<i>2000–2005</i>			
	Xiamt	−0.07	0.91	0.82	0.11	0.05	0.87	0.75	0.14
	Jiutl	0.02	0.93	0.85	0.08	0.02	0.88	0.77	0.12
	Zams	0.00	0.90	0.79	0.10	−0.01	0.89	0.79	0.11
	Dajx	−0.08	0.78	0.61	0.23	−0.05	0.81	0.65	0.20
	Caojh	−0.10	0.92	0.81	0.12	0.03	0.86	0.74	0.14
	Shibl	0.01	0.84	0.71	0.15	−0.02	0.82	0.67	0.18
	Gul	−0.09	0.63	0.37	0.36	−0.04	0.70	0.48	0.29
	Huangyh	−0.05	0.92	0.85	0.09	0.05	0.86	0.73	0.15
	Nany	−0.02	0.83	0.68	0.17	0.08	0.83	0.68	0.19
	Xidh	0.01	0.92	0.85	0.08	−0.01	0.89	0.80	0.11
<i>Hei River Basin</i>		<i>1990–1995</i>				<i>1996–2000</i>			
	Zamsk	0.10	0.93	0.84	0.11	−0.02	0.96	0.92	0.05
	Yinglx	0.02	0.97	0.95	0.03	−0.06	0.93	0.84	0.10
	Qil	−0.01	0.93	0.86	0.07	0.03	0.94	0.88	0.07
	Shuangss	−0.08	0.91	0.82	0.12	0.00	0.89	0.79	0.11
	Sun	0.06	0.89	0.79	0.13	−0.13	0.95	0.86	0.11
	Wafc	0.02	0.87	0.74	0.14	−0.01	0.89	0.78	0.11
	Gaoy	0.05	0.67	0.44	0.31	−0.02	0.72	0.50	0.27
	Bingg	−0.09	0.84	0.67	0.19	0.04	0.83	0.68	0.18
<i>Shule River Basin</i>		<i>1971–1979</i>				<i>1980–1987</i>			
	Changmb	−0.10	0.87	0.74	0.16	0.06	0.86	0.73	0.16
	Dangcw	0.14	0.53	−0.08	0.56	−0.10	0.68	0.22	0.40

capacity of soil; WMC : field capacity of soil; k_r : interflow yield coefficient; f_c : steady state infiltration rate), two surface runoff yield parameters (28.05%) (g_1 : basic surface runoff coefficient and g_2 : influence coefficient of soil moisture), two baseflow-related coefficients (1.29%) (T_g : delay time for aquifer recharge and k_{rg} : baseflow yield coefficient), and one evapotranspiration parameter (18.49%) ($KETp$: adjustment factor of evapotranspiration).

The simulation of long-term streamflows showed good agreements with the observations at most stations according to the criteria recommended by *Moriasi et al.* [2007] (Table 4). The best performances were at Xidh in SYRB (f_{obj} values of 0.08 in the calibration period and 0.11 in the validation period), Yinglx in HRB (f_{obj} values of 0.03 in the calibration period and 0.10 in the validation period), and Changmb in SLRB (f_{obj} values of 0.16 in the calibration period and 0.16 in the validation period), respectively (Figures 3a–3c). The *bias* values of all the stations were within ± 0.15 . The median of *r* and *NS* were 0.90 and 0.79 in the calibration period, and 0.87 and 0.75 in the validation period, respectively.

However, the overall simulation performances at Gul in SYRB, Gaoy in HRB, and Dangcw in SLRB were not satisfactory. Gul and Dangcw were located at the downstream of Shibl and Cajh reservoirs in SYRB and Dangcw reservoir in SLRB, respectively. Thus, the regulations of the upstream reservoirs might weaken the simulation performances at these two stations. The simulation performance at Gaoy was also probably affected by the intensive human activities because this station was located in the middle reach of HRB. Nonetheless, the water balance (*bias*) and basic rainfall-runoff relationships (*r*) were still captured because all the values were within $\pm 10\%$ for *bias* and were over 0.60 for *r* (except for the calibration of Dangcw).

For the simulation of flow regime metrics, the *bias* values were within ± 0.10 , except Lw75 (−0.33), and the median values of *r* were over 0.75 (Figure 4). The best agreement between observation and simulation was MMF, while the simulation performances of LwS75, HgS25, TMinF, and TMaxF were not satisfactory because of the low *r* values. The calibrated model could well capture the flow regime characteristics including magnitude, frequency, and variability but was still deficient to simulate the characteristics of flow duration and timing. Therefore, the metrics of duration (LwS75 and HgS25) and timing (TMinF and TMaxF) were excluded from further analysis.

Figure 3. The simulated and observed flows at (a) Xidh station of Shiyang River Basin, (b) Yinglx station of Hei River Basin, and (c) Changmb station of Shule River Basin.

3.2. GCM Evaluation and Future Climate Variable Projection

For the model performance of historical precipitation simulation (Figure 5a), the *RS* values of 11 GCMs (i.e., FGOALS-g2, MIROC-ESM-CHEM, FIO-ESM, INM-CM4, CMCC-CESM, MIROC-ESM, GISS-E2-R, GISS-E2-H, GISS-E2-R-CC, GISS-E2-H-CC, and BNU-ESM) were evidently greater than those of the other GCMs. Thus, these 11 GCMs were considered unsuitable for the monthly precipitation simulation in the Hexi Corridor. For the model performance of historical temperature simulation, the *RS* values of five GCMs (i.e., CSIRO-MK3.6.0, FGOALS-g2, INM-CM4, GISS-E2-H, and MIROC-ESM) were evidently greater than those of the other GCMs (Figure 5b). Thus, these five GCMs were considered unsuitable for monthly temperature simulation in the Hexi Corridor. The detailed results are shown in Tables A1 and A2.

The unsuitable GCMs for the monthly precipitation and temperature simulations were excluded from the GCM ensemble. Thus, 29 GCMs were selected as the final GCM ensemble to predict the future precipitation and temperature series in the Hexi Corridor. Table 5 and Figure 6 show the possible changes

Figure 4. The simulations and observations of flow regime metrics of all the stations.

of projected precipitation and temperature in different future periods. In the RCP45 emission scenario, the change of precipitation will be -5.0% to 19.02% , with the median of 5.84% (GFDL-CM3) in the 2030s; -0.82% to 23.85% , with the median of 10.11% (GFDL-ESM2M) in the 2050s; and -3.15% to 31.34% , with the median of 13.56% (CNRM-CM5) in the 2070s. The change of temperature will be 0.86°C to 2.21°C with a median of 1.27°C (NorESM1-M) in the 2030s, 1.32°C to 3.16°C with a median of 1.88°C (CMCC-CMS) in the

Figure 5. The assessment results of GCMs' performance to simulate the historical (a) precipitation and (b) temperature at the Hexi Corridor.

Table 5. The Change of Projected Precipitation and Temperature of 29 Selected GCMs in the 2030s, 2050s, and 2070s in the RCP45 and RCP85 Scenarios^a

GCMs	RCP45						RCP85					
	2030s		2050s		2070s		2030s		2050s		2070s	
	pcp	tmp	pcp	tmp	pcp	tmp	pcp	tmp	pcp	tmp	pcp	tmp
ACCESS1.0	−5.00	1.75	9.68	2.24	27.43	2.99	9.93	1.63	17.39	2.99	19.74	4.59
ACCESS1.3	−3.25	1.33	6.38	2.24	11.60	2.89	2.29	1.56	10.28	2.96	14.62	4.29
BCC-CSM1.1	5.36	0.86	10.34	1.48	7.95	1.94	2.46	1.28	14.75	2.19	14.67	3.27
BCC-CSM1.1-M	9.89	1.19	12.61	1.86	13.67	2.01	4.74	1.59	13.09	2.49	24.61	3.53
CanESM2	8.36	1.58	15.92	2.48	20.29	2.96	10.90	1.89	15.90	3.15	23.23	4.79
CCSM4	7.83	1.15	8.78	1.76	2.84	2.14	5.31	1.28	6.21	2.56	12.96	3.70
CESM1-BGC	4.02	0.93	7.63	1.66	14.88	2.10	7.77	1.35	5.62	2.12	17.05	3.29
CESM1-CAM5	16.66	1.41	15.25	2.20	22.91	2.55	9.05	1.70	23.92	2.76	30.21	4.37
CESM1-WACCM	0.44	0.91	−0.82	1.40	4.25	1.69	1.67	1.05	0.91	1.98	11.55	2.87
CMCC-CM	0.22	1.28	10.64	2.07	11.31	2.64	−10.62	1.55	3.54	2.75	10.58	4.14
CMCC-CMS	12.04	1.31	23.81	1.88	11.06	2.74	9.37	1.57	9.60	2.98	21.61	4.21
CNRM-CM5	−2.05	1.03	7.80	1.76	13.56	2.21	−3.66	1.25	9.44	2.38	16.55	3.37
EC-EARTH	6.57	1.15	9.15	1.38	13.03	1.82	7.39	1.22	13.61	2.13	19.84	3.07
FGOALS-s2	19.02	1.47	15.18	2.47	19.88	2.49	12.60	2.24	26.90	3.49	18.61	5.38
GFDL-CM3	5.84	2.21	11.23	3.16	13.17	3.87	−0.27	2.41	12.83	3.86	8.30	5.79
GFDL-ESM2G	9.06	0.87	15.22	1.32	14.65	1.52	8.91	1.07	8.03	1.83	19.15	2.94
GFDL-ESM2M	3.28	1.02	10.11	1.53	17.55	1.73	12.04	1.18	20.68	1.92	12.23	2.95
HadGEM2-AO	4.59	1.57	12.54	2.52	22.53	3.05	8.57	1.05	13.10	2.54	18.28	4.39
HadGEM2-CC	4.93	1.61	10.41	2.24	15.23	2.73	0.16	2.00	24.02	3.20	31.66	4.89
HadGEM2-ES	5.78	1.39	7.67	2.17	22.07	3.11	5.97	1.68	13.51	2.98	17.71	4.79
IPSL-CM5A-LR	8.06	1.26	5.19	1.92	5.00	2.70	2.36	1.61	6.35	2.83	16.85	4.38
IPSL-CM5A-MR	1.38	1.48	3.86	2.30	−3.15	2.93	0.41	1.48	−3.22	2.98	−8.34	5.13
IPSL-CM5B-LR	14.72	1.02	8.72	1.58	10.90	1.99	6.49	1.30	12.58	2.12	29.34	3.54
MIROC5	6.29	1.46	9.53	2.21	7.36	2.89	4.15	1.78	7.60	3.01	7.23	4.14
MPI-ESM-LR	2.69	1.13	2.45	1.88	5.35	2.04	14.36	1.14	12.12	2.41	17.65	3.47
MPI-ESM-MR	3.53	1.10	14.78	1.65	4.85	2.19	5.05	1.35	11.78	2.19	12.90	3.58
MRI-CGCM3	17.82	0.95	23.85	1.41	31.34	1.81	15.98	0.99	29.31	1.96	34.89	3.73
NorESM1-M	13.08	1.27	9.45	1.74	17.04	2.27	15.27	1.24	17.85	2.39	23.50	3.69
NorESM1-ME	10.58	1.38	11.47	2.15	16.38	2.76	5.70	1.70	17.09	2.82	23.25	4.43

^aThe “pcp” means the change ratio of precipitation comparing with the baseline (%), and “tmp” means the increase temperature comparing with the baseline (°C). The bold GCMs provide estimates (in bold) that are close to the median change of all the climate change models, which are used to analyze the impact of climate change on flow regime metrics and classes.

2050s, and 1.52°C to 3.87°C with a median of 2.49°C (FGOALS-s2) in the 2070s. In the RCP85 emission scenario, the change of precipitation will be −10.62% to 15.98% with a median of 5.97% (HadGEM2-ES) in the 2030s, −3.22% to 29.31% with a median of 12.83% (GFDL-CM3) in the 2050s, and −8.34% to 34.89% with a median of 17.71% (HadGEM2-ES) in the 2070s. The change of temperature will be 0.99°C to 2.41°C with a median of 1.48°C (IPSL-CM5A-MR) in the 2030s, 1.83°C to 3.86°C with a median of 2.56°C (CCSM4) in the 2050s, and 2.87°C to 5.79°C with a median of 4.14°C (MIROC5) in the 2070s. Thus, both precipitation and temperature will increase steadily in the future. The shift from warm-dry to warm-wet climate will be further evident in the Hexi Corridor. The increase in the ratio of the RCP85 scenario will be greater than that of the RCP45 scenario.

3.3. Impact Assessment of Individual Metrics

Figures 7 and 8 show that the metric changes in the RCP45 scenario will be similar to those in the RCP85 scenario. The changes of all the metrics will be more evident in the RCP85 scenario than those in the RCP45 scenario. However, the changes in Dajx, Caojh, Shibl, and Gul were quite different between these two scenarios, especially for MMF, Lw75, and CVMF.

For flow magnitude, the MMF and Lw75 in the future three periods will increase continuously at most stations because precipitation will increase evidently. However, there are still four exceptions (i.e., Dajx, Caojh, Shibl, and Gul) in the RCP85 scenario. The decrease of flow magnitude at these stations is probably caused by more evident increase of evapotranspiration due to the remarkable increase of temperature, although the increase of precipitation will increase the flow magnitude slightly. The increase ranges of these stations are the lowest for precipitation (2.58~3.17% in the 2030s, 4.68~5.13% in the 2050s, and 9.24~9.72% in the

Figure 6. The variations of (a) precipitation and (b) temperature in the 2030s, 2050s, and 2070s. Each box plot illustrates the 25th, 50th, and 75th percentile values, and the vertical bars (whiskers) define the 10th and 90th percentile values. The small circle defines the average value, and the red dashed line represents no difference (0.0) between the baseline and future periods.

2070s) but are the highest for temperature (1.4~1.5°C in the 2030s, 2.4~2.6°C in the 2050s, and 4.1~4.2°C in the 2070s) (Figures 9b, 9d, 9f, 11b, 11d, and 11f).

For MMF, in the RCP45 scenario, the variations will range from 0.0% to 5.0% in the 2030s, from 10.9% to 19.5% in the 2050s, and from 13.4% to 26.0% in the 2070s. In the RCP85 scenario, the variations will range from −5.5% to 24.4% in the 2030s, from −20.1% to 13.1% in the 2050s, and from −22.8% to 32.9% in the 2070s. The increase in ranges will be the largest in SLRB, followed by HRB and SYRB, particularly in the RCP85 scenario. The most evident change will be observed at Dangcw. For Lw75, in the RCP45 scenario, the variations will range from −2.0% to 33.6% in the 2030s, from −6.5% to 38.4% in the 2050s, and from −0.6% to 40.6% in the 2070s. In the RCP85 scenario, the variations will range

Figure 7. The variations of flow regime metric at individual stations in the 2030s, 2050s, and 2070s of the RCP45 scenario.

Figure 8. The flow regime metric variations at individual stations in the 2030s, 2050s, and 2070s of the RCP85 scenario.

from -2.7% to 26.8% in the 2030s, from -19.1% to 37.7% in the 2050s, and from -18.9% to 114.1% in the 2070s. The increase in ranges will be the largest in HRB, followed by SYRB and SLRB. The most evident change will be at Wafc in the RCP45 scenario and at Sun in the RCP85 scenario. In addition, Hg25 will change inconsistently among the stations. That is, Hg25 will increase slightly at Xiamt, Caojh, Shibl, Gul, Zamsk, and Yinglx but decrease slightly at the other stations. In the RCP45 scenario, the variations will range from -4.3% to 7.7% in the 2030s, from -8.9% to 9.4% in the 2050s, and from -5.3% to 4.3% in the 2070s. In the RCP85 scenario, the variations will range from -12.7% to 6.1% in the 2030s, from -7.6% to 11.4% in the 2050s, and from -7.6% to 11.7% in the 2070s.

Therefore, the general impact pattern of climate change on flow magnitudes will result in more stable flow regimes, and CVMF will decrease. In the RCP45 scenario, the variations will range from -6.5% to -0.8% in the 2030s, from -6.4% to 6.1% in the 2050s, and from -6.2% to -0.3% in the 2070s. In the RCP85 scenario, the variations will range from -2.1% to 5.0% in the 2030s, from -10.1% to 1.8% in the 2050s, and from -9.9% to 5.3% in the 2070s. The variation ranges will also be the largest in HRB, followed by SYRB and SLRB. The most evident change will be at Wafc.

For the flow frequency, climate change will evidently increase LwC75 but slightly increase HgC25. For LwC75, in the RCP45 scenario, the variations will range from -5.0% to 25.0% in the 2030s, from -17.4% to 18.5% in the 2050s, and from -11.8% to 31.3% in the 2070s. In the RCP85 scenario, the variations will range from -20.0% to 12.5% in the 2030s, from -8.7% to 25.0% in the 2050s, and from -11.8% to 50.0% in the 2070s. The ranges will also be the largest in HRB, followed by SYRB and SLRB. The station most affected by climate change will be Yinglx. For HgC25, in the RCP45 scenario, the variations will range from 0.0% to 20.8% in the 2030s, from -7.1% to 9.5% in the 2050s, and from -9.1% to 19.2% in the 2070s. In the RCP85 scenario, the variations will range from -12.5% to 7.7% in the 2030s, from 0.0% to 30.0% in the 2050s, and from 0.0% to 25.0% in the 2070s. The ranges will be the largest in SYRB, followed by HRB and SLRB. The station most affected by climate change will be Nany.

The projected climate change will sensibly increase the magnitudes of the average and low flows (MMF and Lw75), and frequencies of low and high-flow events (LwC75 and HgC25), but decrease the flow variability

Figure 9. (a, c, e) The cluster dendrograms of flow variation and (b, d, f) the spatial distributions of flow variation classes and climate variables in the median change of the RCP45 scenario.

(CVMF). However, it will not change the magnitude of high flow sensibly. The most affected metrics were HgC25 in SYRB, Lw75, CVMF and LwC75 in HRB, and MMF in SLRB. However, the analysis of the individual metrics and stations cannot easily represent the overall impact of the projected climate change on the flow regime characteristics in the entire region.

3.4. Regional Impact Assessment

All the 20 stations could be divided into two, three, and four main classes in the future individual periods (2030s, 2050s, and 2070s) of the RCP45 and RCP85 scenarios, respectively. Table 6 illustrates the evaluation

Table 6. The Evaluation of the Flow Regime Clusters

Classes	Indices	RCP45			RCP85		
		2030s	2050s	2070s	2030s	2050s	2070s
2	GKI	0.72	0.66	0.66	0.63	0.47	0.50
	CI	0.15	0.16	0.16	0.17	0.25	0.20
	minimum size	6	6	6	8	5	7
3	GKI	0.77	0.74	0.74	0.62	0.81	0.74
	CI	0.11	0.12	0.12	0.15	0.07	0.11
	minimum size	6	2	2	4	5	6
4	GKI	0.85	0.82	0.82	0.75	0.79	0.84
	CI	0.07	0.07	0.07	0.09	0.08	0.06
	minimum size	2	1	1	2	2	3

results of different classifications. The four classes were excluded because the minimum size of classes was only one station. Compared with the results of the other two classifications, the values of GKI for the three classes were greater and the values of CI were smaller. Thus, the classifications for the three classes were the most robust. The impact of projected climate changes on flow regime metrics would be summarized into the three main classes.

3.4.1. RCP45 Scenario

The 2030s period. Class 1 has six stations (i.e., Gul, Xiamt, and Jiutl in SYRB; and Wafc, Yinglx, and Gul in HRB), Class 2 has six stations (i.e., Nany and Zams in SYRB; Shuangss, Zamsk, and Sun in HRB; and Changmb in SLRB), and Class 3 has eight stations (i.e., Dajx, Caojh, Shiblb, Xidh, and Huangyh in SYRB; Qil and Bingg in HRB; and Dangcw in SLRB) (Figures 9a and 9b). In Class 1, most stations are located in the middle stream and downstream with moderate-sized catchment areas (median: 1115 km²). The land use types are various, and the major type is desert. In Class 2, most stations are located in the middle streams with large-sized catchment areas (median: 1374 km²). The major land use types are desert and forest. In Class 3, most stations are located in the source and upper streams with relatively small catchment areas (median: 745 km²). The main land use types are farm land and forest.

Compared with the baseline period, MMF and Lw75 will increase evidently, whereas the changes of Hg25 will not be consistent among the three classes (Figure 10a and Table 7). The median variations of MMF are in the following order: 0.016 mm d⁻¹ (Class 1), 0.014 mm d⁻¹ (Class 2), and 0.009 mm d⁻¹ (Class 3). The variations of Lw75 are in the following order: 2.8×10^{-2} (Class 2), 2.1×10^{-2} (Class 1), and 1.1×10^{-2} (Class 3). For the flow variability, CVMF will decrease in all the three classes, and the median variations will be -0.053 (Class 2), -0.039 (Class 1), and -0.029 (Class 3) from the smallest to the largest. Thus, climate change will cause the flow regime more stable. For the flow frequency, both LwC75 and HgC25 will increase in Classes 1 and 3 due to the increase of precipitation but will not change homogeneously in Class 2. The median variations will be 3.0 (Class 1), 1.125 (Class 3), and 0.0 (Class 2) for LwC75 and will be 3.0 (Class 2), 2.0 (Class 1), and 0.875 (Class 3) for HgC25.

Figure 10. The flow regime metric variations among different classes in the RCP45 scenario in (a) SYRB, (b) HRB and (c) SLRB. Each box plot illustrates the 25th, 50th, and 75th percentile values, and the vertical bars (whiskers) define the 10th and 90th percentile values. The black dot defines the average value, and the red dashed line represents no difference (0.0) between the baseline and future periods.

Table 7. The Variation of Flow Metrics and Climate Variables in the Typical Classes in the 2030s, 2050s, and 2070s in the RCP45 and RCP85 Scenarios

Scenarios	Periods	Classes	MMF (mm d ⁻¹)	Lw75	Hg25	CVMF	LwC75	HgC25	Precipitation (%)	Temperature (°C)
RCP45	2030s	Class 1	0.016	0.021	0.036	-0.04	3.00	2.00	3.87	1.2
		Class 2	0.014	0.028	-0.017	-0.05	0.00	3.00	4.70	1.3
		Class 3	0.009	0.011	0.027	-0.03	1.13	0.88	4.77	1.3
	2050s	Class 1	0.050	0.019	0.025	-0.01	3.00	0.00	10.40	1.9
		Class 2	0.043	0.008	-0.045	-0.01	0.00	-1.00	10.96	1.8
		Class 3	0.028	0.012	0.033	-0.03	0.00	1.00	10.75	1.9
	2070s	Class 1	0.086	0.036	0.020	-0.04	3.50	1.50	16.42	2.5
		Class 2	0.069	0.011	-0.004	-0.01	-1.50	-2.00	11.95	2.4
		Class 3	0.055	0.021	-0.011	-0.03	1.00	0.00	13.82	2.4
RCP85	2030s	Class 1	0.028	0.015	-0.075	0.01	-1.00	0.00	6.69	1.5
		Class 2	0.024	0.009	-0.005	0.02	1.50	0.00	7.47	1.5
		Class 3	0.010	0.000	-0.003	0.02	1.00	-1.00	3.68	1.5
	2050s	Class 1	0.028	0.003	0.013	-0.03	0.50	4.50	7.42	2.5
		Class 2	0.026	0.025	0.036	-0.04	3.00	6.00	8.08	2.4
		Class 3	0.009	0.026	-0.031	-0.08	0.00	1.00	9.26	2.4
	2070s	Class 1	0.070	0.052	-0.035	-0.06	1.00	4.00	13.29	4.1
		Class 2	0.039	0.021	0.018	-0.03	5.00	5.00	14.06	4.1
		Class 3	0.016	0.022	0.022	-0.06	2.50	1.00	12.63	4.1

Therefore, climate change will have an evident impact on the average magnitude and variability of the entire flow regimes, and the frequency of low-flow events, but have heterogeneous impact on the high-flow events. Most metrics will be changed most evidently in Class 1 (especially for MMF, LwC75, and HgC25), followed by Classes 2 and 3. However, the flow will become most stable in Class 2, followed by Classes 1 and 3. The variation characteristic of Class 1 will be called the highly increased discharge with moderately stable variability and more flow spells (Class 1: HD-MV-MF). The variation characteristic of Class 2 will be called the moderately increased discharge with stable variability and no evident variation of flow frequencies (Class 2: MD-LV-NF). The variation characteristic of Class 3 will be called the slightly increased discharge with highly stable variability and more low-flow spells (Class 3: SD-HV-MLF).

Compared with the baseline period, the mean annual precipitation will increase by 1.8%–5.4%, and the increase range will be the largest in the SLRB, followed by SYRB and HRB. The mean annual temperature will increase by 1.20–1.40°C, but the spatial difference will not be distinct in these three basins. The increase of precipitation will increase the average flow magnitudes in all the classes. The spatial heterogeneities of precipitation and underlying surface conditions will result in the different classes of flow regime variations. For example, most stations in Classes 1 and 2 are located in the large-sized and semidesert catchments, whose water conservation capacities are very weak. Thus, the variations of flow regimes are very sensitive to climate change. In Class 3, most stations are in the upstream catchments, which have good vegetation covers and provide stable flows for the downstreams. The geographic characteristics are similar to the montane vegetation zone named by Kang *et al.* [1999]. Because of the strong capacity of water conservation, the flow regimes will change slightly. Furthermore, the increase of temperature will cause the melting of snow covers and glaciers and subsequently increase the magnitude and frequency of low-flow events.

The 2050s period. Class 1 has eight stations (i.e., Jiutl, Huangyh, and Shiblb in SYRB; and Zamsk, Gul, Wafc, Yinglx, and Gaoy in HRB), Class 2 has five stations (i.e., Caojh and Zams in SYRB; and Gul, Shuangss, and Sun in HRB), and Class 3 has seven stations (i.e., Nany, Dajx, Xidh, and Xiamt in SYRB; Bingg in HRB; and Changmb and Dangcw in SLRB) (Figures 9c and 9d). The geographic features of each class are approximately similar to those in the 2030s. In Class 1, most stations are also located in the downstreams except Qil and Shiblb. The catchment areas range from 270 km² to 16,080 km² with the median of 1120 km², and the major land use type is desert. In Class 2, most stations are located in the middle stream and downstream with large catchment areas (median: 3740 km²), especially for Bingg, Changmb, and Dangcw. The major land use types are desert, grass, and forest. In Class 3, the stations are located in the upper streams except Sun. The catchment areas range from 312 km² to 1899 km² with the median of 848 km². The major land use types are farm land and forest.

The variations of the flow regimes among these three classes will also be discrepant and similar to those of the 2030s. In addition, the variations will be further strengthened, particularly for the average flow magnitudes, because precipitation will increase continuously with the range of 10.40%–10.96% (Figure 10b). The increase in ranges of MMF will be from 0.016 mm d^{-1} in the 2030s to 0.050 mm d^{-1} in the 2050s in Class 1, from 0.014 mm d^{-1} in the 2030s to 0.043 mm d^{-1} in the 2050s in Class 2, and from 0.009 mm d^{-1} in the 2030s to 0.028 mm d^{-1} in the 2050s in Class 3. The flow regimes will become even more stable because CVMF values of these classes will decrease by -0.011 , -0.011 , and -0.026 in Classes 1, 2, and 3, respectively.

The 2070s period. Class 1 has six stations (i.e., Qil, Zamsk, Wafc, Yinglx, and Gaoy in HRB; and Changmb in SLRB), Class 2 has two stations (i.e., Shiblb and Xiamt in SYRB); and Class 3 has 12 stations (i.e., Dajx, Caojh, Nany, Jiutl, Zams, Huangyh, Gul, and Xidh in SYRB; Shuanss, Bingg, and Sun in HRB; and Dangcw in SLRB) (Figures 9e and 9f). The geographic futures of Classes 1 and 3 are similar to those of the 2030s and 2050s. That is, the stations in Class 1 are located in the large-sized and semidesert catchments (median of areas: 6187 km^2), and those in Class 3 are located in the relatively small and montane vegetation catchments (median of areas: 847 km^2). However, the stations in Class 2 are in the upstream of SYRB, whose catchment areas are smaller than 500 km^2 . The major land use types are forest and farm land. The features are different from those Class 2 in the 2030s and 2050s.

The variations of flow regime metrics will also be divided into the same three classes with those of the 2030s and 2050s (Figure 10c). For example, the increase ranges of MMF will be from 0.050 mm d^{-1} in the 2050s to 0.086 mm d^{-1} in the 2070s (Class 1), from 0.043 mm d^{-1} in the 2050s to 0.069 mm d^{-1} in the 2070s (Class 2), and from 0.028 mm d^{-1} in the 2050s to 0.055 mm d^{-1} in the 2070s (Class 3). The decrease ranges of CVMF will be from 0.011 in the 2050s to 0.043 in the 2070s (Class 1) and from 0.026 in the 2050s to 0.030 in the 2070s (Class 3). However, the CVMF will not evidently change in Class 2. Furthermore, Hg25 will gradually decrease and the variations will be from 0.025 in the 2050s to 0.020 in the 2070s (Class 1) and from 0.033 in the 2050s to -0.011 in the 2070s (Class 3). The further increase of precipitation and temperature will result in a gradual increase of average flow magnitude, more stable flow regimes, and more frequencies of low-flow events. In Class 2, the moderate increase of flow magnitude will be probably caused by the increase of precipitation (12.0%) and glacier melt (due to 2.4°C increase of temperature) in the source regions. The influence of climate change will be so evident that it may be the main interpretation of flow regime variation in this Class rather than the geographic features.

3.4.2. RCP85 Scenario

The 2030s period. Class 1 has eight stations (i.e., Zams, Xiamt, and Xidh in SYRB; Shuangss, Qil, and Sun in HRB; and Changmb and Dangcw in SLRB), Class 2 has four stations (i.e., Gul in SYRB; and Wafc, Yinglx, and Gaoy in HRB), and Class 3 has eight stations (i.e., Nany, Caojh, Jiutl, Huangyh, Shiblb, and Dajx in SYRB; and Zams and Bingg in HRB) (Figures 11a and 11b). In Class 1, most stations are located in the moderate-sized and semidesert catchments (median of areas: 1375 km^2). In Class 2, most stations are located in the middle stream and downstream with large catchment areas (median: 2433 km^2). The major land use types are desert and forest. In Class 3, the controlled catchments of most stations own relatively small areas with the median of 844 km^2 and various land use types (farm land, grass, forest, and desert). The basic geographic disparity among these classes is also similar to that of the classification in the RCP45 scenario.

Therefore, the variations of all metrics will also be approximately consistent with the RCP45 scenario. Climate change will increase MMF and Lw75 but will not change Hg25 evidently (Figure 12a). The variations of MMF in Classes 1, 2, and 3 will be 0.028 mm d^{-1} , 0.024 mm d^{-1} , and 0.010 mm d^{-1} , respectively, and of Lw75 in Classes 1, 2, and 3 will be 0.015 , 0.009 , and 0.000 , respectively. For the flow variability, CVMF will increase slightly, and the variations will be 0.015 (Class 1), 0.019 (Class 2), and 0.024 (Class 3). The main reason is that the magnitude of extremely high flow will increase by climate change. For example, the maximum flow will increase by 0.11 mm d^{-1} (Class 1), 0.09 mm d^{-1} (Class 2), and 0.05 mm d^{-1} (Class 3), respectively, although Hg25 will not change. For the flow frequency, climate change will increase the frequencies of low-flow events in Classes 2 and 3 but decrease those in Class 1. The variations of LwC75 will be -1.0 (Class 1), 1.5 (Class 2), and 1.0 (Class 3). Climate change will not change the frequencies of high-flow events evidently.

The 2050s Period. Class 1 has 10 stations (i.e., Nany, Caojh, Zams, Gul, Dajx, and Xidh in SYRB; Zamsk, Sun, and Bingg in HRB; and Changmb in SLRB), Class 2 has five stations (i.e., Jiutl and Shiblb in SYRB; and Qil, Yinglx,

Figure 11. (a, c, e) The cluster dendrograms of flow variation and (b, d, f) the spatial distributions of flow variation classes and climate variables in the median change of the RCP85 scenario.

and Gaoy in HRB), and Class 3 has five stations (i.e., Huangyh and Xiamt in SYRB; Shuangss and Wafc in HRB; and Dangow in SLRB) (Figures 11c and 11d). In Class 1, the catchment areas range from 312 km² to 13,779 km² with the median of 979 km². The major land use types are desert and grass. In Class 2, the catchment areas range from 446 km² to 16,080 km² with the median of 2450 km². The major land use types are desert and grass. In Class 3, the median of catchment areas is only 617 km² and the major land use types are farm land, forest, and desert.

Compared with the variations in the 2030s, the average magnitude will not change evidently because of the slight increase of precipitation and temperature. However, the magnitudes of low flow and the flow frequencies will increase, but the flow variability will decrease (Figure 12b). For example, the variation ranges

Figure 12. The flow regime metric variations among different classes in the RCP85 scenario, in (a) SYRB, (b) HRB and (c) SLRB. Each box plot illustrates the 25th, 50th, and 75th percentile values, and the vertical bars (whiskers) define the 10th and 90th percentile values. The black dot defines the average value, and the red dashed line represents no difference between the baseline and future periods.

of CVMF will be from 0.015 in the 2030s to -0.030 in the 2050s (Class 1), from 0.019 in the 2030s to -0.043 in the 2050s (Class 2), and from 0.024 in the 2030s to -0.082 in the 2050s (Class 3). Thus, climate change will cause the flow regime to be more stable and increase the frequencies of flow events in this period.

The 2070s period. Class 1 has seven stations (i.e., Jiutl, Zams, Shiblb, and Xidh in SYRB; Zamsk and Sun in HRB; and Changmb in SLRB). Class 2 has seven stations (i.e., Nany, Caojh, and Gul in SYRB; and Qil, Yinglx, Gaoy, and Bingg in HRB), and Class 3 has six stations (i.e., Huangyh, Dajx, and Xiamt in SYRB; Shuangss and Wafc in HRB; and Dangcw in SLRB) (Figures 11e and 11f). The geographic features among these classes also show significant differences and are similar to the classifications of other periods. In Class 1, most stations are located in the middle stream and downstream, except Shiblb and Xiamt. The catchment areas range from 446 km^2 to $13,779 \text{ km}^2$ with the median of 1120 km^2 . The major land use types are desert and grass. In Class 2, most stations are located in the middle stream and downstream of SYRB and HRB, except Caojh and Gul. The median of catchment areas is 2450 km^2 , and major land use types are desert, grass, and forest. In Class 3, the stations are in the upper and middle streams. The median of catchment areas is only 505 km^2 , and the major land use types are farm land, forest, and desert.

The variations of the flow regime metrics will also be similar to those of the 2030s and 2050s, but all of the variations will be strengthened by climate change (e.g., MMF, Lw75, LwC75, and HgC25) because of the evident increase of precipitation (9.2%–24.9%) and temperature (4.1–4.2°C) (Figure 12c). For example, the increase in ranges of MMF will be from 0.028 mm d^{-1} in the 2050s to 0.070 mm d^{-1} in the 2070s (Class 1), from 0.026 mm d^{-1} in the 2050s to 0.039 mm d^{-1} in the 2070s (Class 2), and from 0.009 mm d^{-1} in the 2050s to 0.016 mm d^{-1} in the 2070s (Class 3).

3.4.3. Comparison Between the RCP45 and RCP85 Scenarios

In the RCP45 and RCP85 scenarios, the impacts of climate change on flow regime metrics are detected to have some similar patterns in the different periods across a broad range of spatial scales, especially for MMF, CVMF, and LwC75. The patterns are divided into three main classes based on the homogeneous variations of some critical metrics, namely, Class 1: HD-MV-MF, Class 2: MD-LV-NF, and Class 3: SD-HV-MLF. The main impact rules of all the classes are that climate change will evidently increase the magnitudes of average and low flow (MMF and Lw75), and the low-flow frequencies (LwC75), decrease the flow variability (CVMF), but will not homogeneously change the high-flow events (Hg25 and HgC25). The variation ranges of the classes will also be basically consistent between the RCP45 and RCP85 scenarios, although both precipitation and temperature in the RCP85 scenario will increase greater than those in the RCP45. The probable explanations are that, on the one hand, flow will increase even more in the RCP85 scenarios caused by precipitation; on the other hand, the larger increase of temperature will increase evapotranspiration more and thus decrease flow.

The geographic features of three classes are also quite different. The highly and moderately impacted stations will be categorized into Class 1 (HD-MV-MF) and Class 2 (MD-LV-NF), which are located in the middle stream and downstream with the large-sized and semidesert catchments. The variations of flow

regime at these stations are sensitive to climate change because of the weak capacities of water conservation. Most stations in Class 3 (SD-HV-MLF) are located in the upper and middle streams. These catchments belong to the montane vegetation zone owning relatively small areas, good vegetation covers, and strong capacity of water conservation. Moreover, the spatial heterogeneities of climate variable variations will result in the frequent shift of flow regime classes of most stations in the 2030s, 2050s, and 2070s. For example, in the RCP85 scenario, the variation of flow regimes at Jiutl belong to Class 3 in the 2030s because of the slight increase of precipitation (4.6%) and temperature (1.4°C). The class will shift to Class 2 in the 2050s and even Class 3 in the 2070s because both precipitation and temperature will increase evidently. The increase ranges are 6.6% in the 2050s and 11.5% in the 2070s for precipitation, and 2.4°C in the 2050s and 4.1°C in the 2070s for temperature, respectively. The flow regimes at only 4 out of 20 stations (20%) will not change in the RCP45 scenario (i.e., Wafu, Yinglx, and Gaoy in HRB; and Caojh in SYRB), whereas the percent will be 35% (7 out of 20 stations) in the RCP85 scenario (i.e., Zams, Huangyh, and Xidh in SYRB; Yinglx, Gaoy, and Sun in HRB; and Dangcw in SLRB).

4. Discussion and Conclusions

The impact assessment of climate change on streamflow was extended to the simulation and assessment of the overall flow regime characteristics instead of the traditional magnitude-oriented assessment. The spatial impacts of projected climate change were further determined by river classification in the entire Hexi Corridor. This study would be comprehensive for the regional impact assessment of climate change.

The developed water system model well simulated the historical long-term streamflows at most stations in these three basins of the arid Hexi Corridor. The overall performances of monthly flow simulations were more satisfactory than those of the existing studies [Wang *et al.*, 2008 and Wang *et al.*, 2012 in SYRB; Kang *et al.*, 1999 and Yang *et al.*, 2015 in HRB]. However, the daily runoff simulations were still not acceptable, especially in the middle stream and downstream, due to the human activities (e.g., the regulation of upstream reservoirs or the intensive agricultural irrigation in the middle streams), the impact of glacier and permafrost melt, and the complex interchange mechanism of surface water-groundwater in our study area [Kang *et al.*, 1999; Wang *et al.*, 2007; Yang *et al.*, 2015]. These causes might also weaken the monthly runoff simulation performances at several stations (Shiblb, Gul, and Dangcw). Nonetheless, the basic rainfall-runoff relationships and water balance were still well captured, as well as the intra-annual distribution and the flow regime metrics including flow magnitude, frequency, and variability. The model could be used to predict the flow regime characteristics in the arid Hexi Corridor under different future scenarios.

The GCM still had large uncertainties in the reproduction and projection of climate variables, particularly in the arid and semiarid regions [Lioubimtseva, 2004; Fu *et al.*, 2013]. Thus, it was unreasonable to assess the future impact of climate change using only a single GCM. Evaluating the simulation performance of the GCM ensemble to exclude the unsuitable GCMs was a necessary procedure, which would eliminate the impact of large uncertainties of GCM output on the climate change analysis. The projection of the GCM ensemble showed that precipitation and temperature increased steadily and that the climate change from warm-dry to warm-wet was further evident in the Hexi Corridor.

The projected climate change will evidently increase the average and low-flow magnitudes and the low-flow frequencies and decrease the flow variability. However, it will not evidently change the high-flow events. The reasons are that the increase of temperature will increase the snowmelt in the low-flow season in the source regions, whereas the increase of precipitation will increase MMF but will not change the high-flow events because of the high-flow magnitude and the limited impact of climate change. These similar variations of the average and low-flow magnitudes in our study region were reported at global scale analysis [Arnell [1999a, 1999b]; Bates *et al.* [2008]; Döll and Schmied [2012]] and at the site scale [Wang *et al.*, 2012] and were also close to those of other arid basins (e.g., Tarim basin in Peng and Xu [2010]), but the variations of other flow indices were not illustrated.

All of the variations of the flow regime metrics were clustered into the highly, moderately, and slightly impacted classes by climate change in the entire Hexi Corridor. The different classes of the nearby stations were basically consistent with the spatial heterogeneity of the underlying surface conditions and climate variables. The stations of the highly and moderately impacted classes were located in the middle stream and downstream with the large-sized and semidesert catchments. The slightly impacted classes usually

Table A1. The Model Performance of 41 GCMs for Monthly Precipitation^a

GCMs	Mean	St_Dev	RMSE _N	r_t	r_s	M-K test		EOF		PDF		RS
						Z	β	EOF1	EOF2	BS	S _{score}	
GCM0	132.2	21.90				0.99	0.0007	41.6	18.4			
MRI-CGCM3	133.5	24.09	1.35	0.88	0.86	1.05	0.0007	56.9	22.3	0.001	95.2	6.6
CNRM-CM5	232.2	40.15	2.74	0.96	0.90	1.87	0.0025	65.1	18.3	0.004	92.9	12.6
CMCC-CM	217.7	39.06	2.42	0.81	0.93	1.57	0.0016	64.1	16.6	0.006	93.3	14.9
IPSL-CM5B-LR	222.7	34.31	2.95	0.87	0.83	0.66	0.0009	64.1	24.9	0.007	93.1	15.5
IPSL-CM5A-MR	284.3	31.76	4.94	0.97	0.75	1.12	0.0012	55.1	29.6	0.013	91.4	16.1
EC-EARTH	251.9	46.36	2.81	0.94	0.88	−0.79	−0.0012	69.9	17.9	0.006	92.3	17.4
FGOALS-s2	301.1	52.93	3.32	0.86	0.84	0.89	0.0014	68.5	21.0	0.011	90.9	19.7
IPSL-CM5A-LR	274.2	42.71	3.50	0.91	0.78	−0.15	−0.0002	76.0	16.6	0.013	91.7	19.7
GFDL-ESM2G	353.5	51.47	4.42	0.96	0.87	1.30	0.0023	71.5	18.1	0.019	89.4	19.8
HadGEM2-CC	342.5	52.56	4.14	0.94	0.88	0.13	0.0003	62.0	23.6	0.015	89.8	19.8
CSIRO-MK3.6.0	321.8	35.41	5.45	0.99	0.91	2.55	0.0027	47.1	34.1	0.013	90.3	20.2
CMCC-CMS	334.0	62.78	3.40	0.94	0.88	0.11	0.0002	72.4	18.1	0.017	90.0	20.8
GFDL-ESM2M	346.7	52.56	4.23	0.95	0.87	−0.13	−0.0002	69.7	20.7	0.019	89.6	20.9
CCSM4	414.2	55.85	5.16	0.97	0.87	0.28	0.0007	60.3	19.4	0.025	87.7	21.1
MPI-ESM-MR	359.6	62.42	3.78	0.97	0.87	0.07	0.0001	65.2	22.4	0.018	89.3	21.2
HadGEM2-ES	344.8	47.09	4.64	0.90	0.88	0.07	0.0002	73.4	15.4	0.016	89.7	21.8
ACCESS1.3	275.9	44.90	3.43	0.77	0.88	−0.26	−0.0005	71.7	16.7	0.012	91.6	21.8
BCC-CSM1.1-M	340.4	39.42	5.43	0.93	0.87	−0.79	−0.0008	68.6	18.0	0.022	89.8	21.9
CESM1-CAM5	401.9	55.48	4.96	0.97	0.90	0.01	0.0000	59.4	22.9	0.022	88.1	21.9
MPI-ESM-LR	354.4	58.77	3.93	0.97	0.88	−0.48	−0.0008	69.1	20.5	0.017	89.4	23.6
HadGEM2-AO	364.5	65.70	3.67	0.91	0.87	0.3	0.0006	76.3	14.6	0.018	89.1	24.1
MIROC5	453.2	47.82	6.80	0.92	0.89	0.21	0.0003	67.9	18.9	0.033	86.6	25.3
NorESM1-M	428.0	56.94	5.30	0.96	0.82	−0.22	−0.0005	70.8	19.6	0.026	87.3	25.7
CESM1-WACCM	453.8	59.86	5.47	0.96	0.85	−0.01	0.0000	68.7	21.3	0.030	86.6	26.2
ACCESS1.0	356.8	51.83	4.49	0.86	0.88	−1.24	−0.0022	68.6	20.5	0.018	89.3	26.5
CESM1-BGC	414.6	53.66	5.38	0.96	0.87	−1.01	−0.0018	57.0	25.9	0.024	87.7	27.5
CanESM2	456.0	65.34	5.09	0.98	0.83	−0.03	−0.0001	52.6	34.6	0.026	86.5	27.7
NorESM1-ME	430.0	55.85	5.42	0.95	0.82	−1.28	−0.0020	71.6	20.3	0.026	87.2	29.2
BCC-CSM1.1	476.4	69.35	5.07	0.93	0.84	0.21	0.0007	80.3	14.9	0.040	85.9	29.9
GFDL-CM3	408.7	54.75	5.15	0.94	0.87	−1.56	−0.0031	68.8	23.4	0.026	87.9	30.0
FGOALS-g2	421.8	30.66	9.52	0.72	0.85	0.54	0.0007	58.2	29.5	0.037	87.5	32.9
INM-CM4	520.3	70.81	5.58	0.74	0.88	1.56	0.0032	72.8	17.7	0.047	84.7	35.2
MIROC-ESM-CHEM	578.3	58.77	7.67	0.96	0.83	−0.28	−0.0006	58.9	33.7	0.046	83.0	37.5
FIO-ESM	546.4	72.64	5.78	0.84	0.85	1.52	0.0033	79.5	16.7	0.060	83.9	37.5
CMCC-CESM	532.3	64.61	6.28	0.88	0.81	−0.26	−0.0004	85.2	10.1	0.052	84.3	37.8
MIROC-ESM	598.6	71.54	6.60	0.98	0.82	−1.42	−0.0035	72.4	19.2	0.047	82.4	38.0
GISS-E2-R	584.1	52.20	8.73	0.83	0.06	1.28	0.0021	65.9	18.0	0.068	82.8	43.8
GISS-E2-H	739.9	79.94	7.66	0.85	0.63	0.34	0.0009	63.9	16.7	0.083	78.4	44.5
GISS-E2-R-CC	586.9	50.74	9.02	0.82	0.07	1.87	0.0033	63.0	22.1	0.069	82.8	46.7
GISS-E2-H-CC	706.6	78.48	7.39	0.84	0.52	0.42	0.0011	73.4	12.7	0.082	79.4	46.7
BNU-ESM	751.4	76.29	8.17	0.83	0.85	2.61	0.0068	66.0	27.7	0.098	78.1	52.3

^aThe bold values were the best simulation of individual evaluation indices.

appeared in the upper and middle streams, which belonged to the montane vegetation zone owning relatively small areas, good vegetation covers, and strong capacity of water conservation. However, the climate change would be the determinant factor on the variation of flow regimes [Yang *et al.*, 2015]. The magnitudes of climate variables would directly affect the flow magnitude, while their intra-annual distribution would affect the flow variability, frequency, duration, and timing. The spatial differences of climate change would evidently vary the impacted classes at most stations because their classes would be shifted to another class in different future periods.

In this study, all analyses were conducted at the monthly scale because of the poor model performance of daily streamflow and climate variables, as well as the data availability. Although some characteristics of the flow regimes were missed at the monthly scale (e.g., change rate of flow events), most monthly metrics of the flow regimes were highly correlated with the daily metrics [Zhang *et al.*, 2012]. The simulation and classification of the variation of monthly flow regime would provide the foundation and reference for

further study at the daily scale and would also be suitable and helpful to support the present water resources planning and management. Some works should be taken seriously, including the hydrological model calibration, the improvement of simulation performance on daily streamflow and flow regime metrics, and uncertainties impact analysis of GCMs on river classification. Moreover, further physical interpretations about the classification will be performed.

Appendix A

Tables A1 and A2 provide the results of model performance of 41 GCMs for monthly precipitation and temperature.

Table A2. The Model Performance of 41 GCMs for Monthly Temperature^a

GCMs	Mean	St_Dev	RMSE _N	r_t	r_s	M-K test		EOF		PDF		RS
						Z	β	EOF1	EOF2	BS	S _{score}	
GCM0	6.9	0.62				4.37	0.0313	93.3	1.8			
CMCC-CM	5.7	0.60	2.34	1.000	0.71	3.82	0.0270	94.5	3.5	0.0013	39.7	5.0
CESM1-BGC	5.4	0.62	2.71	0.996	0.49	4.12	0.0306	93.7	3.6	0.0019	39.6	8.6
CESM1-CAM5	5.8	0.61	2.16	0.999	0.46	3.22	0.0239	88.8	6.6	0.0012	39.6	10.1
CCSM4	5.2	0.66	2.78	0.995	0.49	4.27	0.0322	94.6	3.0	0.0023	39.6	10.3
CESM1-WACCM	8.2	0.68	2.10	1.000	0.56	3.96	0.0277	95.3	2.3	0.0015	37.0	11.0
MPI-ESM-MR	5.7	0.66	2.04	0.999	0.13	4.63	0.0347	95.8	3.3	0.0021	39.4	12.3
MIROC5	6.7	0.53	1.19	0.997	0.19	3.67	0.0217	94.2	3.5	0.0003	39.3	13.5
GFDL-ESM2M	4.9	0.55	3.79	0.997	0.57	3.47	0.0205	91.9	5.2	0.0036	39.6	14.5
CMCC-CMS	5.5	0.70	2.31	0.999	0.09	3.90	0.0332	96.7	2.3	0.0027	39.6	14.5
MPI-ESM-LR	6.0	0.52	2.22	0.999	0.14	4.14	0.0225	94.8	3.3	0.0018	39.4	14.7
NorESM1-M	3.8	0.55	5.82	1.000	0.56	3.96	0.0244	93.4	4.1	0.0064	39.7	14.7
NorESM1-ME	3.6	0.58	5.87	0.999	0.61	3.39	0.0204	93.6	3.8	0.0072	39.7	15.1
FIO-ESM	4.4	0.64	4.03	0.998	0.35	2.83	0.0231	97.3	2.1	0.0057	39.7	15.5
GFDL-ESM2G	4.6	0.51	4.70	0.997	0.58	4.57	0.0236	91.7	5.8	0.0045	39.6	15.7
IPSL-CM5A-MR	3.7	0.66	5.00	0.992	0.45	3.96	0.0291	95.9	2.2	0.0077	39.7	18.0
BCC-CSM1.1-M	4.2	0.71	4.00	0.995	0.35	3.02	0.0269	95.2	3.4	0.0054	39.7	18.4
BNU-ESM	2.8	0.65	6.44	0.996	0.37	4.33	0.0286	96.8	2.1	0.0106	39.7	19.0
GFDL-CM3	3.0	0.64	6.16	0.997	0.33	3.16	0.0253	92.8	4.3	0.0097	39.7	19.5
CMCC-CESM	4.6	0.69	3.51	0.999	−0.06	3.41	0.0244	97.3	2.1	0.0044	39.7	19.8
EC-EARTH	4.0	0.52	5.82	0.996	0.31	3.92	0.0246	92.1	4.2	0.0059	39.7	20.4
HadGEM2-ES	3.3	0.60	6.12	0.998	0.13	5.12	0.0344	92.0	4.3	0.0081	39.6	20.6
FGOALS-s2	6.3	0.93	1.10	0.997	0.43	5.10	0.0528	97.9	1.6	0.0012	39.0	20.7
MRI-CGCM3	3.8	0.54	6.06	0.997	0.38	2.83	0.0177	96.3	2.3	0.0066	39.7	21.6
ACCESS1.0	3.6	0.63	5.38	0.998	0.05	2.85	0.0207	88.5	5.5	0.0068	39.7	22.8
CanESM2	2.5	0.68	6.55	0.996	0.23	4.98	0.0392	90.3	5.7	0.0115	39.7	24.1
HadGEM2-CC	2.7	0.59	7.28	0.998	0.09	2.73	0.0213	89.4	5.2	0.0107	39.7	25.9
BCC-CSM1.1	2.4	0.49	9.32	0.999	0.38	3.73	0.0200	94.9	4.2	0.0133	39.7	26.1
HadGEM2-AO	3.1	0.78	4.99	0.998	0.04	4.78	0.0432	88.8	7.0	0.0090	39.7	26.7
ACCESS1.3	4.1	0.44	6.47	0.995	0.09	3.63	0.0171	95.8	2.7	0.0051	39.7	27.6
IPSL-CM5A-LR	1.9	0.71	7.19	0.990	0.30	3.63	0.0290	95.4	3.0	0.0162	39.7	28.3
MIROC-ESM-CHEM	4.4	0.65	4.18	0.984	0.35	2.51	0.0197	84.5	13.7	0.0054	39.5	28.5
GISS-E2-H-CC	5.1	0.51	3.78	0.993	−0.03	3.12	0.0184	93.6	4.0	0.0117	37.8	28.5
GISS-E2-R-CC	6.2	0.45	2.02	0.991	−0.01	4.26	0.0196	92.6	4.7	0.0109	36.7	28.7
IPSL-CM5B-LR	0.6	0.70	9.08	0.997	0.30	3.28	0.0287	94.9	3.4	0.0226	39.7	29.0
GISS-E2-R	6.3	0.46	1.94	0.992	0.00	2.89	0.0173	93.2	3.2	0.0107	36.7	29.1
CNRM-CM5	2.4	0.51	8.98	0.997	0.50	2.14	0.0117	88.0	6.7	0.0121	39.7	29.1
CSIRO-MK3.6.0	2.5	0.51	8.77	0.997	0.01	2.79	0.0191	95.1	3.0	0.0117	39.7	31.0
FGOALS-g2	0.7	0.67	9.41	0.989	0.21	3.75	0.0262	96.4	2.3	0.0220	39.7	33.5
INM-CM4	−0.1	0.61	11.61	0.999	0.16	2.91	0.0201	82.9	9.4	0.0294	39.7	36.4
GISS-E2-H	5.1	0.41	4.72	0.990	−0.03	0.44	0.0024	92.9	3.5	0.0112	37.8	39.6
MIROC-ESM	4.4	0.37	7.04	0.986	0.36	0.63	0.0030	70.9	24.7	0.0053	39.5	46.3

^aThe bold values were the best simulation of individual evaluation indices.

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