Climatic Change
DOI 10.1007/s10584-008-9527-5

Coupling climate change with hydrological dynamic in Qinling Mountains, China

**Hongming He · Quanfa Zhang · Jie Zhou ·
Jie Fei · Xiuping Xie**

Received: 22 August 2006 / Accepted: 22 September 2008

Abstract This study intends to disclose orographic effects on climate and climatic impacts on hydrological regimes in Qinling Mountains under global change background. We integrate a meteorological model (MM5 model, PSU/NCAR, 2005) and a hydrological model (SWAT model, 2005) to couple hydrological dynamic with climate change in Qinling Mountains. Models are calibrated and validated based on the simulation of different combined schemes. Following findings were achieved. Firstly, Qinling Mountains dominantly influence climate, and hydrological process in Weihe River and upper Hanjiang River. Results show that Qinling Mountains lead to a strong north–south gradient precipitation distribution over Qinling Mountains due to orographic effects, and it reduces precipitation from 10–25 mm (December) to 55–80 mm (August) in Weihe River basin, and adds 25–50 mm (December) or 65–112 mm (August) in upper Hanjiang River basin; evapotranspiration (ET) decrease of 21% in Weihe River (August) and increase 10.5% in upper Hanjiang River (July). The Qinling Mountains reduce water yields of 23.5% in Weihe River, and decrease of 11.3% in upper Hanjiang River. Secondly, climate change is responsible for the changes of coupling effects of rainfall, land use and cover, river flow and water resources. It shows that average temperature significantly increased, and precipitation substantially reduced which leads to hydrological process changed greatly from 1950

H. He (✉) · Q. Zhang
Wuhan Botanical Garden, Chinese Academy of Sciences,
Moshan, Wuhan, 430074, China
e-mail: hehoming@yahoo.com

J. Zhou · X. Xie
State Key Laboratory of Loess and Quaternary Geology,
Institute of Earth Environment, Chinese Academy of Sciences,
P. O. Box 17, Xian, 710075, China

J. Fei
Department of History of Science and Technology and Archaeometr,
University of Science and Technology of China,
No. 96 Jinzai Road, Hefei, 230026, China

to 2005: temperature increased and precipitation decreased, climate became drier in the past two decades (1980–2005), high levels of precipitation exists in mid-1950, mid-1970, while other studied periods are in low level states. The inter-annual variation in water yield correlates with surface runoff with an R^2 value of 0.63 (Weihe River) and 0.87 (upper Hanjiang River). It shows that variation of annual precipitation was smaller than that of seasonal precipitation.

1 Introduction

Climate changes may have significant impacts on terrestrial hydrological dynamic. Variations of climate directly alter the hydrological processes, including precipitation, evaporation and land-surface hydrological cycle (Bhatti et al. 2000). Global change, whether generated from climate or other sources, has great impacts on water resources at different spatiotemporal scales, especially in geographical regions of the transition areas (Bootsma 1994; Wang et al. 1998; Najjar 1999; Menzel and Burger 2002; Raymond and Wolfgang 2005). Water storage in and flow through mountains are major features of mountain regions linking climate and its change to the hydrological cycle and human water use (Ren et al. 2002; Zhang et al. 2003). Understanding of the interactions between hydrological dynamic, climate, and land-use change is important for both real situation analyses and predicting the potential hydrological consequences of existing land-use practices and climate trends in the north and the south of the Qinling Mountains, China.

Studies show that orographic effects have great importance on hydrological regimes (Osborn and Lane 1969; Wood et al. 1988; Woolhiser 1996; Bi et al. 2005). Bindlish and Barros (2000) reviewed previous studies of orographic effects on rainfall, and concluded that rainfall a governing factor in the temporal and spatial variability of runoff production and soil moisture dynamic, and thus the entire hydrologic regime of a river basin (Barros and Lettenmaier 1994; Barros and Kuligowski 1998; Bindlish and Barros 2000). It is noted that orographic effects are characterized by an increase of precipitation amount and intensity with elevation up to 300%.on the upwind slopes of topographic barriers along the storm path, while the intensity and duration of storms were sharply reduced on the leeward side (Bindlish and Barros 2000). Topographic elevation and aspect, and wind speed and direction were also key factors in the orographic enhancement of precipitation, and associated spatial variability. Chen et al. (2005) simulated orographic influences on the development of two heavy rainfall events over southwestern Taiwan during the Mei-yu season, and found rain showers were enhanced or triggered in the coastal convergence zone due to island blocking and enhanced by the interaction between the decelerating incoming flow and the offshore flow in the early morning.

Modelling studies often provide more insights into the mechanisms of land surface process while field records and experiments can conclusively demonstrate the consequences of climate (Whitehead and Robinson 1993). Numerous climate models have been developed as an increasingly important tool to address scientific issues associated with climate variability, changes, and impacts at local-regional scales (Giorgi et al. 1992; Leung et al. 1999). The PSU/NCAR mesoscale model (MM5, the fifth-generation Pennsylvania State University, National Center for Atmospheric Research Mesoscale Model) has been broadly used to perform regional weather, climate, and water resources forecast and research (Wagner et al. 2006, 2008; Jimenez et al. 2006; Li et al. 2004). For the meteorological simulations, Bi et al. (2004, 2005) determined an adequate configuration of the available parameterizations for the Qingling-Daba Mountains. Hydrologic models were regarded as a powerful tool for predicting climate and land use and cover change impacts on watershed hydrology (Whitehead and Robinson 1993; He et al. 2008a). In spite of extensive research on specific impacts of climate change, research and information on the impacts of climate change to watershed systems remains in its infancy. Evaluation of climate change on the watershed system is important to develop alternative strategies and policies to mitigate the impacts of global warming (He et al. 2006, 2008b; Marshall and Randhir 2008). Watershed variables and inputs that may affect hydrologic responses may vary spatially, as well as temporally. Therefore, accounting for heterogeneity of environmental variables such as soil types, land uses, topographic features, and weather parameters is essential in order to properly simulate the effect of spatially varying properties (Muleta and Nicklow 2005). The SWAT (Arnold et al. 1998) was reported as a good tool for evaluating hydrologic regimes at daily/monthly/yearly time scales (Bouraoui et al. 2005; Marshall and Randhir 2008). The model is capable of describing this spatial and temporal variability though the number of parameters and variables in this distributed model makes calibration of such models far more complex (Refsgaard and Knudsen 1996; Refsgaard 1997; Arnold and Allen 1996; Arnold et al. 1998).

Previous efforts have focused on innovation of coupling simulation of meteorological–hydrological in field of hydrological research (Westrick et al. 2002; Jasper et al. 2006; Kunstmann and Stadler 2005). Various models were successfully applied to perform simulation hydrometeorological forecast system for mountainous watersheds using MM5 model and distributed hydrological models (Wigmosta et al. 1994; Bacchi and Ranzi 2000; Jasper et al. 2006). Several studies have compared climate model simulated runoff to observed river runoff in order to validate the model or to investigate the impact of global warming. Evans (2003) reviewed studies of integrating climate model and hydrological model to disclose the possibility and awareness of model applications (Hansen et al. 1983; Kuhl and Miller 1992; Miller and Russell 1992; Milliman and Meade 1983; Russell and Miller 1990), and pointed out that model performance is highly subject to the validity of the storage capacity distribution curve chosen in simulation of global warming impacts on river runoff.

This study aims at evaluating the role of climate change on watershed systems at a regional scale under global change. Abovementioned studies provide substantial ways in further research work. However, little work has been done to investigate interaction between meteorological and hydrological regimes at various spatial–temporal scales under global change. We assess this exemplary problem for Weihe River and upper Hanjiang River since seldom work has been completed with orographic effects in Weihe River and Hanjiang River in China. Compared to the studies mentioned above, our work focuses on the performance of coupled meteorological–hydrological simulations focus on various time scales (daily, monthly, and yearly), and apply the meteorological model for driving hydrological models. Based on the comprehensive hydrometeorological data and modeling, we target these issues as to provide a physical basis for assumption of topographic influence on climate, and global change impacts on prediction of hydrological parameters at different timescale. Firstly, we employ the PSU/NCAR mesoscale model (MM5) to simulate the topographic influences on climate based on the assumption of two different terrain combinations. Secondly, we use SWAT model to disclose climate impact on hydrologic regime using three different time periods of climate schemes (1954, 1982 and 2003).

1.1 Study area

Our study area is focused on two representative river basins (Weihe River and Hanjiang River, 31°–38°N, 104°–112°E, Fig. 1) around the Qinling Mountains. The west–east Qinling Mountains reach as high as 3,900 m in central China (Liu 1983), and form an important geographical boundary between Weihe River (the largest tributary of the Yellow River) and Hanjiang River (the largest tributary of the Yangtze River).

Weihe River lies in the north of Qinling Mountains, and is dominated by semi-arid hydrologic characteristics. Weihe River has main channel length of 818 km, and its basin covers 135000 km^2. The whole basin can be divided into three types, the north subbasins (upper Weihe River, Jinghe River, and Beiluohe River), the middle subbasins (Qishuihe River and Shichuanhe River), and the south subbasins (Shitohe

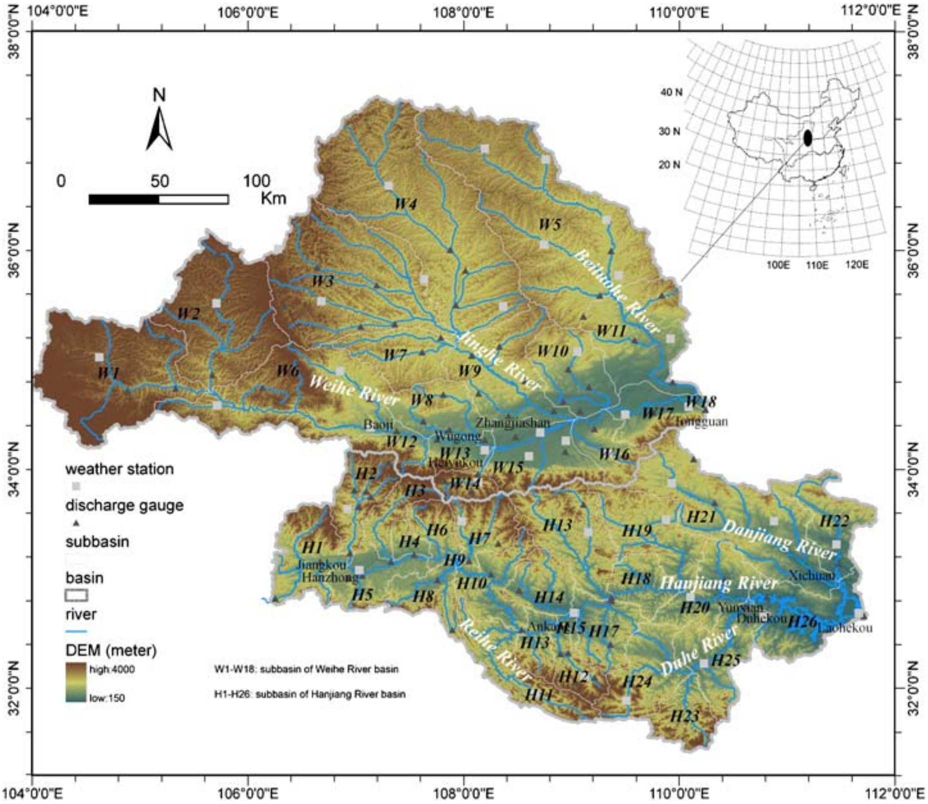


Fig. 1 Location of study area in the middle Qinling Mountains

River, Heihe River, Fenghe River and Bahe River). Weihe River basin locates in temperate continental monsoon climate region, and both precipitation and runoff vary greatly at inter-annual and intra-annual timescales. The average temperature is 7.8–13.5°C (decrease from the main channel toward the north and south tributaries), and annual precipitation of 400 mm–800 mm (decrease from the south to the north). The average runoff is 195 m^3/s, and runoff coefficient of variation falls within 0.1–0.2. About 80% precipitations happen during July to September, and 65–80% river flow falls within July to September. The long tributaries in the north run through the arid Loess Plateau, accounting for 80% basin area with only 30–40% runoff. The south tributaries originate from the Qinling Mountains, contributing to 60–70% runoff with 20% basin area (Liu 1983).

The Hanjiang River is in the south of the Qinling Mountains, and is controlled by humid hydrologic characteristics. The river's length is 1,570 km and the basin area is 170,400 km^2. Our study area focuses on upper Hanjiang River (channel length is 925 km, basin area is 95,000 km^2). From the northwest to the southeast, the basin can be divided into the north alpine subbasins (55% of the whole basin area), the middle hilly subbasins (21% of the whole), and the south plain subbasins (24% of the whole). Hanjiang River basin is in subtropical monsoon climate region, and both climate and runoff have strong inter-annual and intra-annual variabilities. It has an average temperature of 13.6–18.3°C (decrease from upper north to the lower south), and annual precipitation of 800–1,200 mm (increase from upper north to the lower south). About 80% precipitations happen during May and October, and 65% river flow concentrate between July and October. The average runoff is 585 m^3/s, and runoff coefficient of variation falls within 0.3–0.6 (Liu 1983).

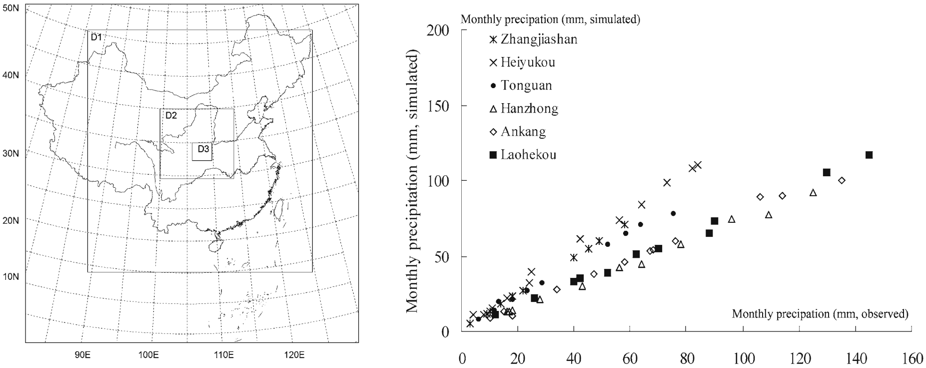
2 Materials and methods

2.1 Data collection

In this study, to address climate change impacts on hydrologic dynamic regimes, we employ various data for model simulation purpose, such data including Digital Elevation Model (DEM), meteorological, hydraulic, and hydrometric data, land use cover data and soil data. To describe the climate situation, meteorological data, such as precipitation, temperature, wind velocity, and net radiation were used. Meteorological data from 1953 to 2003 are acquired 54 stations (Fig. 1) from the National Climatic Centre of China. Hydrometric data includes daily runoff depth, runoff velocity and river water level from 1950 to 2005. We collected data from 117 hydrological gauges covering the whole watershed (Fig. 1) from Yellow River Conservancy Commission and Changjiang River Water Resources Commission (YRCC-MWR 2005, Yellow River Conservancy Commission, Ministry of Water Resources; CRWRC-MWR 2005, Changjiang River Water Resources Commission). Topographic data, such as river channel roughness, river bed slope, and distance between particular cross-sections, are extracted from the 90-m digital elevation model (DEM, from IRSA-CAS 2007, Institute of Remote Sensing Application, Chinese Academy of Sciences). To identify land use cover changes occurred between 1950 and 2005, we determine vegetation dynamic from land cover maps (IGSNRR-CAS, 1980, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences) and remote-sensing satellite images (LANDSAT5 TM, June 29th 2003), and combine this information with a land use map at scale of 1:100,000. Soil map (at scale of 1:100,000) is employed (from IGSNRR-CAS, 2005, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences). These variables reflect environmental change of two different time periods, and we used these data sets to deal with rainfall-runoff and water balance simulation.

2.2 MM5 model for numerical simulation on precipitation schemes

The PSU/NCAR mesoscale model (MM5) has been broadly used to perform regional weather, climate, and water resources forecast and research. For climate simulation in Qinling Mountains, we propose an adequate configuration of the available parameterizations on basin of previous research work implemented by Bi et al. (2004, 2005) and Wagner et al. (2006, 2008). Cloud cover, precipitation and sunshine are the major parameters of model simulation. For this study, MM5 is applied in non-hydrostatic mode to dynamically downscale the global atmospheric fields stepwise using three domains with horizontal resolutions of 45×45 km^2 (95×61 gridpoints), 15×15 km^2 (82×91 gridpoints) and 5×5 km^2 (82×91 gridpoints; Fig. 2). For the vertical resolution, 24 layers from the surface up to an atmospheric pressure of 30 mbar were chosen. The required global analysis fields are obtained from the National Centers for Environmental Prediction (NCEP, USA), and used to construct the initial and boundary conditions with a temporal resolution of 6 h. Later the simulation uses the remote sensing for model initialization and run. The simulation period was the rainy season (summer, August) and drought season (winter, December) in 1954, 1982 and 2003. A sensitivity experiment (TER) is designed which lowers Qinling Mountains to 1,000 m above sea level (a.s.l.). By comparing with controlled experiment (CTRL), we can readily identify orographic effects of Qinling Mountains on precipitation in Weihe River basin and upper Hanjiang River basin.



Computational domain schemes of MM5 (D1, Domain 1 with 45 km grid spacing; D2, Domain 2 with 15 km grid spacing; D3, Domain 3 with 5 km grid spacing)

Monthly precipitation corelation between simulated and observed

Fig. 2 Simulation on monthly precipitations (average of 1954, 1982 and 2003) for schemes of MM5 model

2.3 SWAT model for rainfall–runoff process

SWAT (Arnold et al. 1998) is a spatially distributed, physically based hydrological model, which can operate from a daily time step to annual steps for long-term simulations. The model is physically based, uses readily available inputs, is computationally efficient for use in large watersheds, and is capable of simulating long-term yields for determining the impact of land management practices (Arnold and Allen 1996). Components of SWAT include: hydrology, weather, sedimentation/erosion, soil temperature, plant growth, nutrients, pesticides, and agricultural management. In this model, potential evapotranspiration is estimated using either the Priestley–Taylor or Penman–Monteith methods. The soil profile is represented by up to ten soil layers, a shallow aquifer and a deep aquifer. When the field capacity in one layer is exceeded, the water is routed to the lower soil layer. If this layer is already saturated, a lateral flow occurs from the bottom soil layer, percolation goes into the shallow and deep aquifers. Water reaching the deep aquifer is lost, but a return flow from the shallow aquifer due to deep aquifer saturation is added directly to the subbasin channel. Surface runoff is computed by the SCS curve number method (Arnold et al. 1998), and is therefore a non-linear function of precipitation and a retention coefficient. Spatially distributed input parameters datasets such as elevation, soil and land use data were implemented in the SWAT model. Relational databases such as soil, weather and original crop databases were replaced with regional datasets. The SWAT model was calibrated and validated by adjusting the SCS curve numbers that were realistic for the watershed, and was evaluated through the statistical analysis methods of the root mean square error (RMSE), and Nash–Sutcliffe coefficient (Nash and Sutcliffe 1970).

3 Results

3.1 Simulation of orographic effects on climate in middle Qinling Mountains

For the comparison it has to be considered that a point measurement (observation) is compared here with a result of the meteorological model which is only able to simulate precipitation averages on a scale that is two to four times the model resolution. This is especially relevant for regions with a high spatial variability.

Precipitation shows a strong north–south gradient distribution and reduction in Weihe River basin, and augment in upper Hanjiang River basin due to orographic effects of Qinling Mountains. Figures 2 and 3 are simulated average values of precipitation in 1954, 1982 and 2003 using MM5 model. Figure 2 is a comparison of the available observed and simulated monthly precipitation sums for the average values of 1954, 1982, and 2003. The differences in slopes (around 1.0) of both simulated and measured curves indicate that the lowering Qinling Mountains will increase precipitation in the north (slopes are above 1.0 of Zhangjiashan, Heiyukou and Tongguan), and reduce in the south (slopes are below 1.0 of Hanzhong, Ankang and Laohekou). Figure 3 shows comparison of the spatial distribution of the simulated precipitation for domain2 (15×15 km^2). Values range from 40 mm (north) to 150 mm (south) in August (wet summer), and vary from 400 mm (north) to 1500 mm

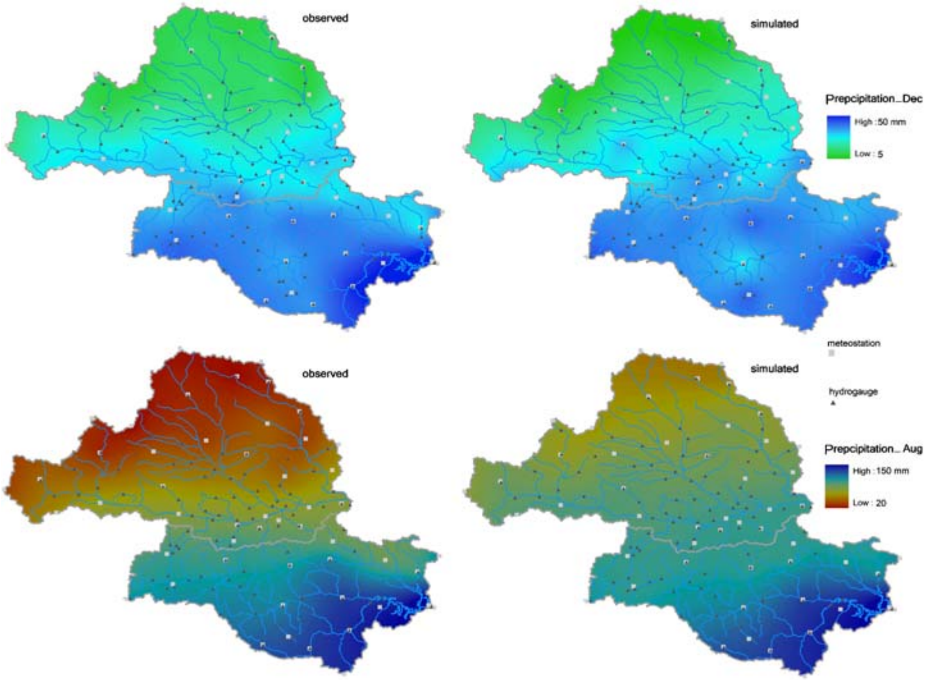


Fig. 3 Simulation of orographic effects on precipitations in (wet) and droughty seasons (December) (Values of precipitation distribution are average of 1954, 1982 and 2003)

(south) for the whole year. The coefficient of variation of the intra 15×15 km^2-scale rainfall variability ranges between 0.38 and 0.47. The coefficient of determination R^2 varies between 0.78 and 0.87. Precipitation reduces from 10–25 mm (December) to 55–80 mm (August) in the north slope of Qinling Mountains and north Weihe River basin, and adds 25–50 mm (December) or 65–112 mm (August) in the south slope of Qinling Mountains and valleys of upper Hanjiang River basin.

Simulation results indicate that Qinling Mountains have great orographic effects on climate situations. Firstly, it shows that mesoscale climate situations depends mainly on the topography and the macro-scale conditions, positive perturbation of potential vorticity in the lower layers is one of the important factors for the formation and development of torrential rain, and the cold masses invade into the middle level of the eastern part of northwest area and result in strong instability which is favorable for convective rainfall. Secondly, orographic effects on precipitation of Qinling Mountains have different behaviors. Qinling Mountains increase precipitation in the area of Hajiang River valley and the southern slope of Qinling Mountains, and decrease in itself and the northern part of Shaanxi Province. The effect is result of vertical circulation from orographic mechanism and thermal forcing. The overall orographic effects on precipitation of Qinling Mountains result in the southern Shaanxi as the center of extremely heavy rainfall, and dried Weihe River basin.

3.2 Simulation of hydrological process in Weihe River and the Hanjinag River

3.2.1 Hydrological model setup

Presumably, the designed orographic scheme (lowering Qinling Mountains to 1,000 m) would likely lead to changes in hydrologic dynamic according to MM5 simulation. For study purposes, we need to describe relationships between the decreased Qinling Mountains and the possibly changed hydrology processes. The SWAT model is adapted for the application in rainfall–runoff simulations at time scales of daily (August of 1954, 1982 and 2003) monthly (1954, 1982 and 2003), and yearly (1950–2005) to disclose climatic change impacts on hydrologic dynamic in basins of Weihe River and upper Hanjiang River. The study area is divided into 44 subbasins (18 of Weihe River basin, and 26 of upper Hanjiang River basin). The SWAT model is calibrated and validated (with datasets of 1978) by adjusting the SCS curve numbers that are realistic for the basins, and is evaluated through the statistical analysis methods of the root mean square error (RMSE), and Nash–Sutcliffe coefficient (Table 1). It can be seen that the general discharge hydrograph could be simulated fairly well with Nash–Sutcliff model efficiencies of 0.67 (average for Weihe River) and 0.71 (average for upper Hanjiang River) for daily discharges in August 1–31 of 1954, 1982, 2003.

3.2.2 Evapotranspiration

Orographic effects on evapotranspiration (ET) caused by Qinling Mountains result in increased values in Weihe River and decreased values in upper Hanjiang River. Simulation under designed scheme (lowering Qinling Mountains to 1000 m) shows that changes in average ET rates under designed scheme range from a decrease of 21% (August in Weihe River) to an increase of 10.5% (July in upper Hanjiang River) compared with conditions of observation (Fig. 4). Evapotranspiration is a major source of loss in the water balance for the study watershed. An examination of changes in monthly evapotranspiration rates provides an insight into hydrologic changes in river basin system under two climate change scenarios. Simulation based on observation show that the actual evapotranspiration (AET) and potential evapotranspiration (PET) vary monthly through complete year. The highest simulated AET occurs in March, June to September in Weihe River, and May to September

Table 1 Model efficiency analysis of surface rainfall–runoff simulation

Timescale	Year	Nash–Sutcliffe coefficient		RMSE (m^3/s)	
		Weihe River	Upper Hanjiang River	Weihe River	Upper Hanjiang River
Daily	August 1–31, 1954	0.62	0.74	14	23
	August 1–31, 1982	0.68	0.70	25	29
	August 1–31, 2003	0.71	0.69	15	27
Monthly	August, 1954	0.81	0.72	33	23
	August, 1982	0.77	0.87	37	39
	August, 2003	0.67	0.77	28	37
Yearly	1950–2005	0.81	0.71	45	58

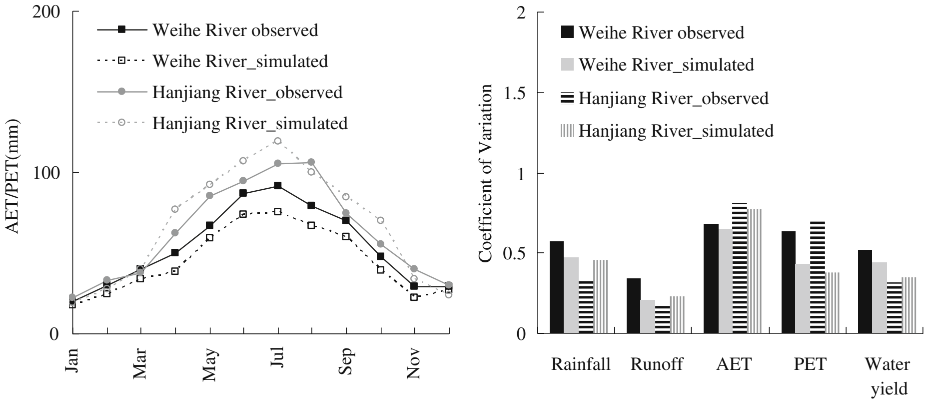


Fig. 4 Simulated evapotranspiration (actual evapotranspiration and potential evapotranspiration) in Weihe River and upper Hanjiang River basins

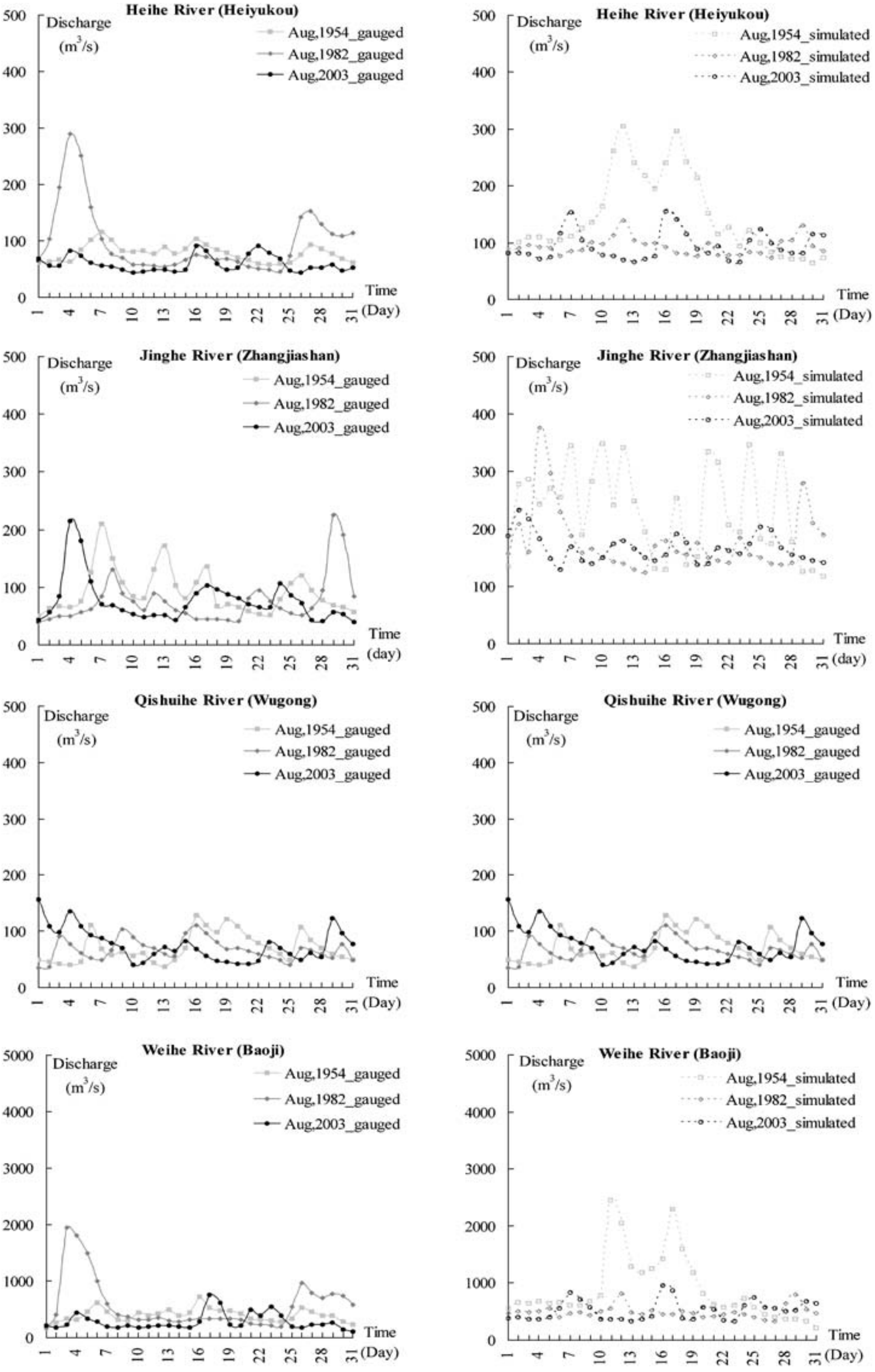
in upper Hanjiang River. The PET averages 600 mm/year (Weihe River) and 720 mm/year (upper Hanjiang River) with the highest values in June and July (Weihe River), and July and August (upper Hanjiang River). Average AET values are 35 mm/month (Weihe River) and 87 mm/month (upper Hanjiang River) less than PET values. From September to April, it exhibits low variation in monthly PET and AET. The coefficients of variation (defined as the variability of model output data series around the mean) for PET are 0.68 (Weihe River) and 0.74 (upper Hanjiang River), AET are 0.72 (Weihe River) and 0.82 (upper Hanjiang River) respectively. Average annual PET rates increase 17%(in Weihe River) and 11.3% (in upper Hanjinag River) from 1950 to 2005. Simulation shows that changes in average ET rates between observation and designed scheme (lowering Qinling Mountains to 1000 m) range from a decrease of 21% (August in Weihe River) to an increase of 10.5% (July in upper Hanjiang River). Changes in evapotranspiration rates under different schemes were driven by temperature.

3.2.3 Rainfall–runoff process

Analysis of rainfall–runoff process discloses that flow discharge in valleys watersheds of Qinling Mountains correspond to high values. Figures 5 and 6 are simulations on daily runoff discharge in August (1954, 1982, and 2003) in Weihe River and upper Hanjiang River. We investigate different types of watersheds for further analysis in Weihe River basin (Jinghe River–Zhangjiashan of north tributaries, Qishuihe River–Wugong of middle tributaries, Heihe River–Heiyukou of south tributary, and Baoji and Tongguan of the main channel) and upper Hanjiang River basin (Baohe River–Jiangkou of north tributary, Duhe River–Duhekou of southwest tributary, Danjiang River–Xichuan of northeast tributary, and Hanzhong, Ankang, and Laohekou of main channel).

Fig. 5 Simulation on daily runoff discharge in August (1954, 1982, and 2003) in Weihe River (Jinghe River and Qishuihe River of north tributaries; Heihe River of south tributary; Baoji and Tongguan of the main channel in Weihe River basin)

▶


Heihe River (Heiyukou)
Discharge (m^3/s)
Aug,1954_gauged
Aug,1982_gauged
Aug,2003_gauged
Time (Day)
Heihe River (Heiyukou)
Discharge (m^3/s)
Aug,1954_simulated
Aug,1982_simulated
Aug,2003_simulated
Time (Day)
Jinghe River (Zhangjiashan)
Discharge (m^3/s)
Aug,1954_gauged
Aug,1982_gauged
Aug,2003_gauged
Time (day)
Jinghe River (Zhangjiashan)
Discharge (m^3/s)
Aug,1954_simulated
Aug,1982_simulated
Aug,2003_simulated
Time (day)
Qishuihe River (Wugong)
Discharge (m^3/s)
Aug,1954_gauged
Aug,1982_gauged
Aug,2003_gauged
Time (Day)
Qishuihe River (Wugong)
Discharge (m^3/s)
Aug,1954_gauged
Aug,1982_gauged
Aug,2003_gauged
Time (Day)
Weihe River (Baoji)
Discharge (m^3/s)
Aug,1954_gauged
Aug,1982_gauged
Aug,2003_gauged
Time (Day)
Weihe River (Baoji)
Discharge (m^3/s)
Aug,1954_simulated
Aug,1982_simulated
Aug,2003_simulated
Time (Day)
0 100 200 300 400 500
0 1000 2000 3000 4000 5000
1 4 7 10 13 16 19 22 25 28 31

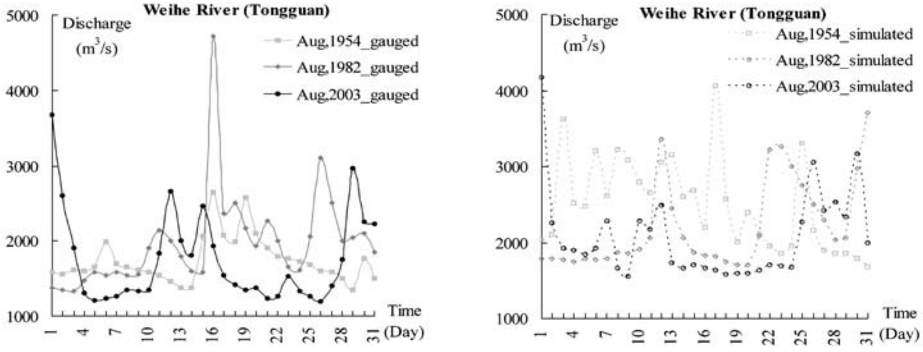


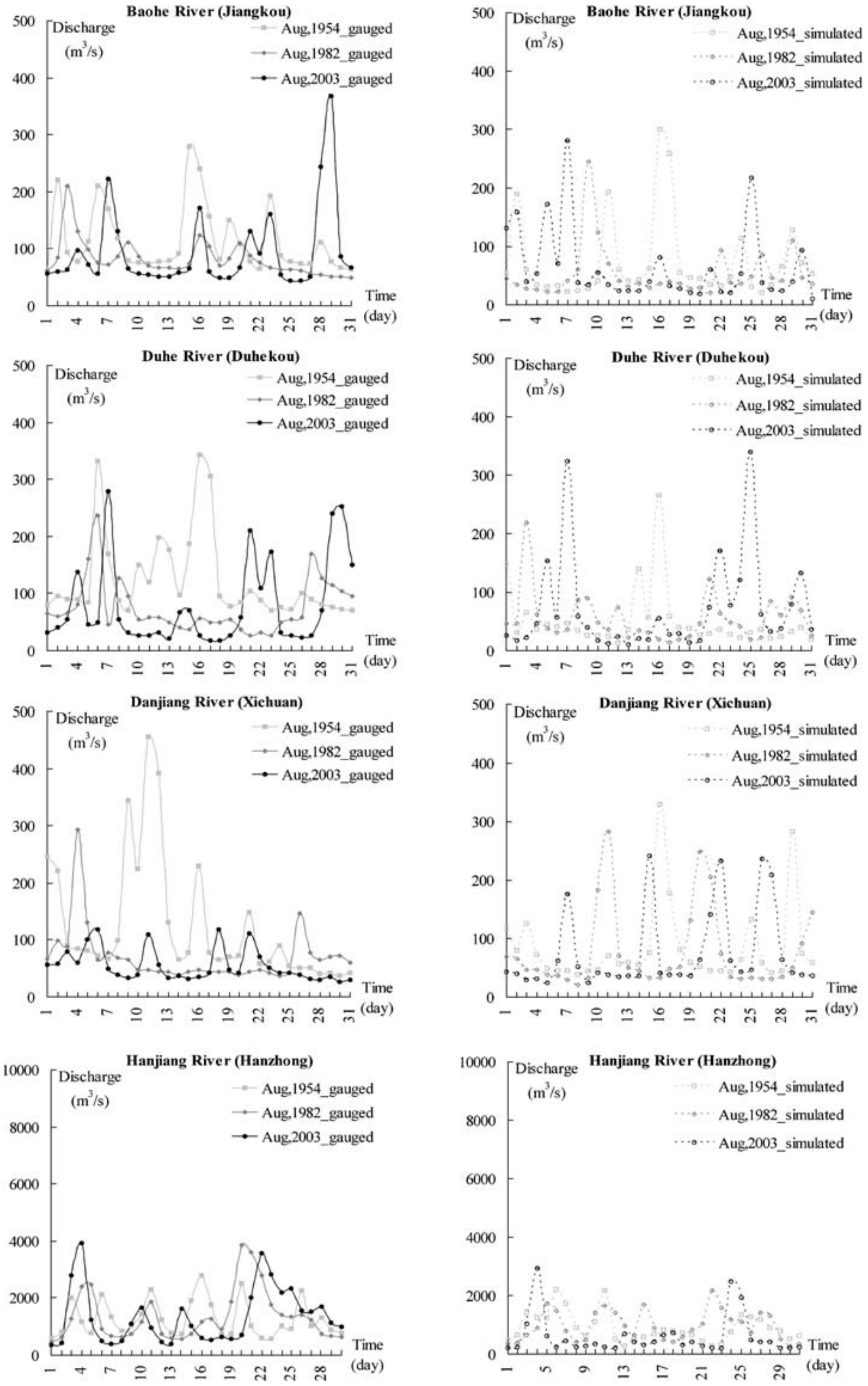
Fig. 5 (continued)

For Weihe River basin, simulation based on observation shows that daily hydrographs of peak flow at Tongguar are much more similar with to that of Heiyukou (Heihe River) than that of others. This can be explained that average flow discharge of south tributaries of Weihe River in north Qinling Mountains accounts for 60–80% for the whole Weihe River basin, and flow discharge of the upper Weihe River (300 m^3/s at Baoji) possesses less than 18% of Tongguan (1,300 m^3/s). Although the basin area of Jinghe River is 30 times of Heihe River, average base flow discharges are almost the same (80 m^3/s). Velocity of flood wave propagation in south tributary is faster than the north. Considering ground situations (land use cover, soil and terrain), tributaries can generate the highest flow discharge in the south (Heiyukou), followed by the middle (Wugong) and the north (Zhangjiashang) under the same precipitation. Simulation under designed scheme (lowering Qinling Mountains to 1,000 m), flow discharge increases of twice (150 m^3/s at Zhangjiashang) of the north tributaries, and 21% (92 m^3/s at Wugong) of the middle, and 16% (110 m^3/s at Heiyukou). However, daily base flow of the observed and the simulated decrease from 1954 to 2003.

As to upper Hanjiang River basin, simulation based on observation shows that spatial distribution flow discharge varies greatly. Average base flow discharge of north tributary (85 m^3/s at Jiangkou) is higher than southwest tributary (63 m^3/s at Duhekou) and northeast tributary (76 m^3/s at Xichuan), and the upper reach (discharge at Ankang accounts for 38% discharge of the total basin) contribute much more than the lower reaches). Also, velocity of flood wave propagation in upper tributaries is faster than the lower reaches. Simulation under designed scheme (lowering Qinling Mountains to 1,000 m), flow discharge decreases by 83% at Jiangkou in the north, 87% at Ankang in the middle, 89% at Xichuna in northeast, and 93% at Duhekou in southeast. However, daily base flow of the observed and the simulated decrease from 1954 to 2003.

Fig. 6 Simulation on daily runoff discharge in August (1954, 1982, and 2003) in Hanjiang River (Baohe River of northwestern tributary; Duhe River of southwestern tributary; Danjiang River River of northeastern tributaries; Hanzhong, Ankang, and Laohekou of the main channel in Hanjiang River basin)

▶


Baohe River (Jiangkou)
Discharge (m³/s)
Aug,1954_gauged
Aug,1982_gauged
Aug,2003_gauged
Aug,1954_simulated
Aug,1982_simulated
Aug,2003_simulated
Time (day)
Duhe River (Duhekou)
Danjiang River (Xichuan)
Hanjiang River (Hanzhong)
0
100
200
300
400
500
2000
4000
6000
8000
10000
1
4
7
10
13
16
19
22
25
28
31
5
9
17
21
29

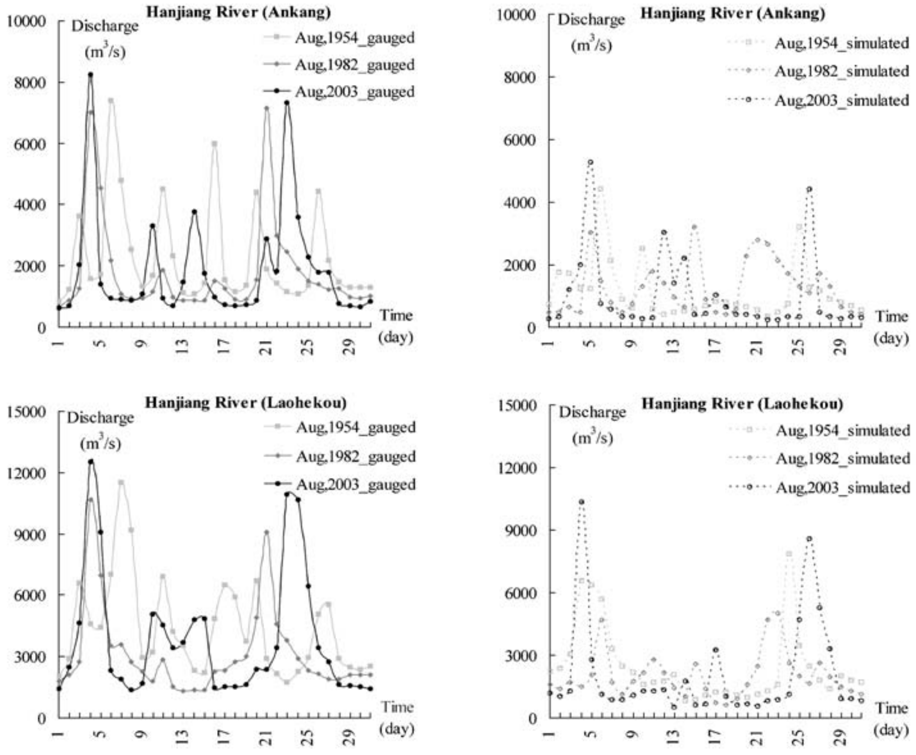


Fig. 6 (continued)

Monthly rainfall–runoff process shows strong seasonal variation in a complete year (Fig. 7). Simulation results based on observation shows that seasonal cycle of flow discharge is obvious both in Weihe River (Tongguan) and upper Hanjiang River (Laohekou). Peak discharge at Tongguan (August) and Laohekou (May, July and September) is caused by summer monsoon activity which brings large vapours though it shows different behaviours in 1954 1982 and 2003. Simulation under designed scheme (lowering Qinling Mountains to 1,000 m) shows that flow discharge in Weihe River (Tongguan) increases 72% in summer (June to September), 43% in winter (December to February) and 27% in spring and autumn. On the contrary, flow discharge in upper Hanjinag River (Laohekou) decreases 12% in summer (June to September), 27% in winter (December to February) and 21% in spring and autumn. Overall monthly flow discharge decreases from 1954 to 2003.

Yearly water yields of Qinling Mountains reduce in Weihe River, and increase in upper Hanjiang River for a long run (1950–2005). Duration of yearly hydrographs quantifies the water balance during the past 50 years (1950 to 2005, Fig. 8). Simulation based on observation shows that average water yield varies from 420 mm/year (Weihe River) to 850 mm/year (upper Hanjiang River), and both river basins present drought trends from 1950 to 2005. The inter-annual variation in water yield correlates with surface runoff with an R^2 value of 0.63 (Weihe River) and 0.87 (upper Hanjiang River). Analysis from climate data showed that variation of annual precipitation was smaller than that of seasonal precipitation, drier years corresponded to lower

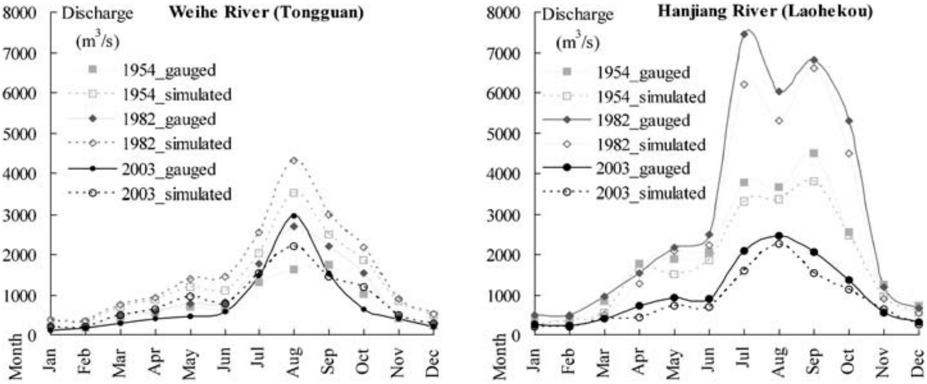


Fig. 7 Simulation on monthly runoff discharge in Weihe River (Tongguan) and Hanjiang River (Laohekou)

precipitation years but not to higher temperature years, higher temperature and stronger wind velocity corresponded to higher evapotranspiration, the interactive effect between temperature and precipitation resulted in increasing arid in the Weihe River and upper Hanjiang River. The phenomenon that drier year corresponded to lower precipitation year could be explained by duration of summer monsoon current in this region: summer monsoon air current brought more precipitation when it stayed for long time, and brought less precipitation when it stayed for a short time. Simulation results of hydrologic process showed that total water resource decreased 12.7% (upper Hanjiang River) and 21.3% (Weihe River) in 2003 compared to that of 1954. Simulation under designed scheme (lowering Qinling Mountains to 1,000 m) shows that water yields increase 23.5% in Weihe River, and decrease 11.3% in upper Hanjiang River during 1950–2005.

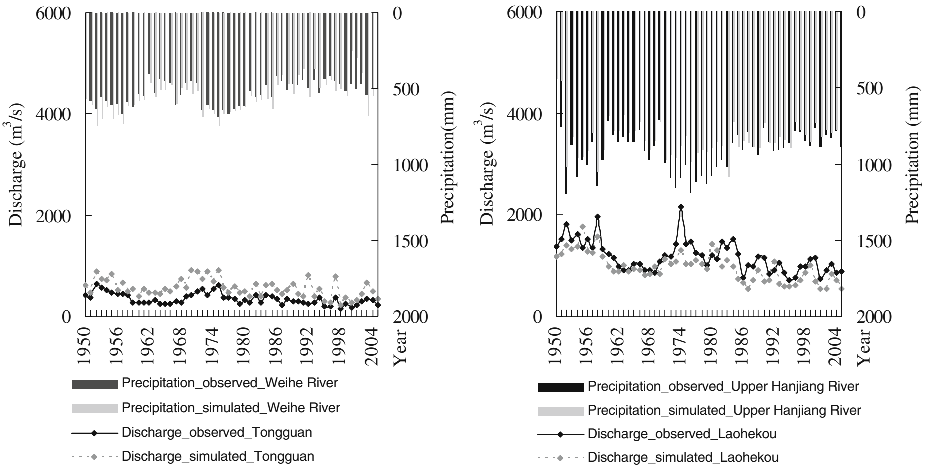


Fig. 8 Simulation on annual runoff discharge in Weihe River (Tongguan) and Hanjiang River (Laohekou)

3.3 Decoupling water balance response to environmental changes

Analysis reveals that climate change leads to the changes of coupling effects of rainfall, land use and cover, river flow and water resources on basis of computational results of model simulations. Observed data shows that the annual temperature changes from 1954 to 2005 in Weihe River and upper Hanjiang River cause changes in the annual evapotranspiration, precipitation reduced the coupling of river flow on seasonal time scales, and river flow was monotonically related to water storage. Figure 4 shows that variation of annual evapotranspiration was much smaller than variation in precipitation and river flow and had strong positive correlation with annual mean temperature in accordance with potential evapotranspiration formulae. River flow was monotonically related to diagnosed storage of water in Weihe River and upper Hanjiang River from June through September. The flow in Weihe River has a strong mean annual cycle with a peak near the middle of August and a minimum near early March, and with peak value in July and September in upper Hanjiang River. Precipitation also had a strong mean annual cycle with higher values in the middle of the summer and lower in the winter for both Weihe River and upper Hajiang River.

It shows that high levels of precipitation exist in mid-1950, mid-1970, while other studied periods are in low level states (Fig. 8). The temperatures generally decrease from 1956 to the 1960s followed by a decrease in mid-1970 and mid-1980, after which there was a long-term increase from early in1990 to the end of the record. Strong negative correlation (−9.1 of Weihe River and −8.7 in upper Hanjiang River) exists between annual precipitation and temperature. We computed annual average values (January–December, February–May, June–September, and October–February) to determine the relationship between river flow discharge and precipitation. Twelve least-squares linear regressions were performed, one for each 12-month period ($n=51$, from 1950 to 2005). It revealed that river flow was highly correlated with annual precipitation ($r^2 = 0.93$ in Weihe River, and 0.83 in Hanjiang River) and changes in annual river flow were about 1.6 times (Weihe River) and 1.3 times (upper Hanjiang River) greater than changes in annual precipitation. The highest correlation between river flow discharge and precipitation was in summer time (July to September), $r^2 = 0.97$ (Weihe River) and 0.91 (upper Hanjiang River). A significantly lower correlation existed in springtime (from February to May), $r^2 = 0.57$ (Weihe river) and 0.52 (upper Hanjiang River). Two possible causes could be explained for these behaviours. Firstly, vegetation plant and soils may normally be saturated during summer time. While in spring time, vegetation was in great need of water, and soils could not be saturated or even became completely dry. Temporal evapotranspiration showed strong variability as temperature, humidity, solar radiation, and wind speed were factors that affect evapotranspiration. Secondly, vegetation was sensitive to soil moisture and evapotranspiration. Analysis revealed that water storage and evapotranspiration were responsible for the decoupling of precipitation and river flow. This can be explained by two causes. Firstly, in spite of strong seasonal cycle of maximum potential evapotranspiration, maximum precipitation caused maximal river flow in summer. Secondly, water storage as snow during winter and melting during the spring helped to contribute to the river flow, when precipitation was near the minimum.

4 Conclusions and discussions

The overall investigation of this study provides several important insights into disclosing the dynamic relationship between environment change and hydrologic regimes at different time scales in the Wei River and upper Hanjiang River.

Firstly, Qinling Mountains dominantly influence climate, and hydrological process in Weihe River and upper Hanjiang River. Simulation results indicate that mesoscale meteorological situations depends mainly on the topography and the macro-scale conditions, positive perturbation of potential vorticity in the lower layers is one of the important factors for the formation and development of torrential rain, and the cold masses invade into the middle level of the eastern part of the northwest district and result in strong instability which is favorable for convective rainfall. The Qinling Mountains increase precipitation in valleys of the upper Hanjiang River and the southern slopes of Qinling Mountains, and decrease in itself and the northern part of Shaanxi Province. Mountainous effect on precipitation is realized by vertical circulation caused by mechanical topography and thermal forcing. The overall topographic effects on precipitation of Qinling Mountains result in the southern Shaanxi as the center of extremely heavy rainfall.

Secondly, climate change is responsible for the changes of coupling effects of rainfall, land use and cover, river flow and water resources. Results show that the average temperature significantly increased, and precipitation substantially decreased from 1950 to 2005 in Weihe River and upper Hanjiang River, and climate became drier in the past two decades (1980–2005). Meanwhile, retrogressed land cover made it more difficult for water storage. As human activities intensify, more water supplies will be needed, thus aggravating the water shortage situation in this area. Therefore, it is necessary to become more aware of water-based ecological protection.

Acknowledgements The study was supported by grants of China National Key Technology R&D Program (2006BAC10B020), the Hundred-talent Project of the Chinese Academy of Sciences (O629221C01), Wuhan Botanical Garden, Chinese Academy of Sciences (754511C03),and the China Postdoctoral Science Foundation (Grant No.20060400732), Chinese Academy of Sciences (KZCX3-SW-146).

References

Arnold JG, Allen PM (1996) Estimating hydrologic budgets for three Illinois watersheds. J Hydrol 176:55–77

Arnold JG, Srinivasan R, Muttah RS, Williams JR (1998) Large area hydrologic modeling and assessment part I: model development. J Am Water Resour Assoc 34(1):73–89

Bacchi B, Ranzi R (eds) (2000) RAPHAEL—runoff and atmospheric processes for flood hazard forecasting and control. Final report to the EC, directorate general XII, Programme Environment and Climate, 1994–1998

Barros AP, Kuligowski RJ (1998) Orographic effects during a severe wintertime rainstorm in the Appalachian mountains. Mon Weather Rev 126:2648–2672

Barros AP, Lettenmaier DP (1994) Dynamic modeling of orographically-induced precipitation. Rev Geophys 32:265–284

Bhatti JS, Fleming RL, Foster NW, Meng FR, Bourque CPA, Arp P (2000) Simulations of pre- and post-harvest soil temperature, soil moisture, and snowpack for jack pine: comparison with field observations. For Ecol Manag 138(1–3):413–426

Bi B, Liu Y, Li Z (2004) Numerical simulations of extremely heavy rain in the southern Shaanxi Province during 8 and 9 June 2002. Chin J Atmos Sci 28(5):747–761 (in Chinese)

Bi B, Liu Y, Li Z (2005) Mesoscale system analysis of extremely heavy rainfall in the southern part of Shaanxi Province during 8 and 9 June 2002. Chin J Atmos Sci 29(5):814–826 (in Chinese)

Bindlish R, Barros AP (2000) Disaggregation of rainfall for one-way coupling of atmospheric and hydrological models in regions of complex terrain. Glob Planet Change 25:111–132

Bootsma A (1994) Long-term (100 YR) climatic trends for agriculture at selected locations in Canada. Clim Change 26:65–88

Bouraoui F, Benabdallah S, Jrad A, Bidoglio G (2005) Application of the SWAT model on the Medjerda river basin (Tunisia). Phys Chem Earth 30:497–507

Chen CS, Chena WC, Chen YL, Lina PL, Laic HC (2005) Investigation of orographic effects on two heavy rainfall events over southwestern Taiwan during the Mei-yu season. Atmos Res 73: 101–130

Evans JP (2003) Improving the characteristics of streamflow modelled by regional climate models. J Hydrol 284:211–227

Giorgi F, Marinucci MR, Visconti G (1992) A $2\times CO_2$ climate change scenario over Europe generated using a limited area model nested in a general circulation model: 2. Climate change scenario. J Geophys Res 97(D9):9989–10009

Hansen J, Lacis A, Rind D, Russell G, Stone P, Fung I, Ruedy R, Lerner J (1983) Climate sensitivity: analysis of feedback mechanisms in climate processes and climate sensitivity. Geophys Monogr 29:130

He H, Yu Q, Zhou J, Tian YQ (2008a) Modelling complex flood flow evolution in the Middle Yellow River China. J Hydrol 353:76–92

He H, Zhou J, Zhang W (2008b) Modelling the impacts of environmental changes on hydrological regimes in the Hei River Watershed, China. Glob Planet Change 61:175–193

He H, Zhou J, Yu Q, Tian YQ, Chen RF (2006) Flood frequency and routing processes at a confluence of the middle Yellow River in China. River Res Appl 22:1–21

Jasper K, Calanca P, Fuhrer J (2006) Changes in summertime soil water patterns in complex terrain due to climatic change. J Hydrol 327:550–563

Jimenez P, Jorba O, Parra R, Baldasano JM (2006) Evaluation of MM5-EMICAT2000-CMAQ performance and sensitivity in complex terrain: high-resolution application to the northeastern Iberian Peninsula. Atmos Environ 40(26):5056–5072

Kuhl SC, Miller JR (1992) Seasonal river runoff calculated from global atmospheric model. Water Resour Res 28(8):2029–2039

Kunstmann H, Stadler C (2005) High resolution distributed atmospheric-hydrological modelling for Alpine catchments. J Hydrol 314:105–124

Leung LR, Ghan SJ, Zhao ZC, Luo Y, Wang WC, Wei HL (1999) Intercomparison of regional climate simulations of the 1991 summer monsoon in eastern Asia. J Geophys Res 104(D6):6425–6454

Li J, Lu HC, Wang HJ, Zhu M, Zheng K (2004) A mesoscale analysis of heavy rain caused by frontal and topographical heterogeneities on Taiwan Island. Adv Atmos Sci 21(6):909–922

Liu YH (1983) Hydrography of Qinling Mountains (in Chinese). Shaanxi People's Press, Xi'an

Marshall E, Randhir T (2008) Effect of climate change on watershed system: a regional analysis. Clim Change 89:263–280. doi:10.1007/s10584-007-9389-2

Menzel L, Burger G (2002) Climate change scenarios and runoff response in the Mulde. J Hydrol 267:53–64

Miller JR, Russell GL (1992) The impact of global warming on river runoff. J Geophys Res 97(D3):2757–2764

Milliman JD, Meade RH (1983) World-wide delivery of river sediment to the oceans. J Geol 91:1–21

Muleta MK, Nicklow JW (2005) Sensitivity and uncertainty analysis coupled with automatic calibration for a distributed watershed model. J Hydrol 306:127–145

Najjar RG (1999) The water balance of the Susquehanna River Basin and its response to climate change. J Hydrol 219:7–19

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models, part 1—a discussion of principles. J Hydrol 10(3):282–290

Osborn HB, Lane LJ (1969) Precipitation–runoff relationships for small semi-arid rangeland watersheds. Water Resour Res 5(2):419–425

Raymond PM, Wolfgang B (2005) Impacts of present and future climate change and climate variability on agriculture in the temperate regions: North America. Clim Change 70:137–164

Refsgaard JC (1997) Parameterization, calibration and validation of distributed hydrologic models. J Hydrol 198:69–97

Refsgaard JC, Knudsen J (1996) Operational validation and intercomparison of different types of hydrologic models. Water Resour Res 32(7):2189–2202

Ren LL,Wang MR, Li CH (2002) Impacts of human activity on river runoff in the northern area of China. J Hydrol 261:204–217

Russell G, Miller J (1990) Global river runoff calculated from a global atmospheric general circulation model. J Hydrol 117:241–254

Wagner S, Kunstmann H, B'ardossy A (2006) Model based distributed water balance monitoring of the White Volta catchment in West Africa through coupled meteorological–hydrological simulations. ADGEO 9:39–44

Wagner S, Kunstmann H, Bárdossy A, Conrad C, Colditz R (2008) Water balance estimation of a poorly gauged catchment in West Africa using dynamically downscaled meteorological fields and remote sensing information. Phys Chem Earth (in press). doi:10.1016/j.pce.2008.04.002

Wang Y, Wang G, Wang C (1998) Study on recent 10 years climate and surface river flow of Weihe River Basin. Yellow River (in Chinese) 20(10):4–7

Westrick K, Storck P, Mass C (2002) Description and evaluation of a hydrometeorological forecast system for mountainous watersheds. Weather Forecast 17:250–262

Whitehead PG, Robinson M (1993) Experimental basin studies—an international and historical perspective of forest impacts. J Hydrol 145:217–230

Wigmosta MS, Vail LW, Lettenmaier DP (1994) A distributed hydrology–soil–vegetation model for complex terrain. Water Resour Res 30:1665–1679

Wood EF, Sivaplan M, Beven K, Band L (1988) Effects of spatial variability and scale with implications to hydrologic modeling. J Hydrol 102:29–47

Woolhiser DA (1996) Search for physically based runoff model—a hydrologic El Dorado. J Hydraul Eng 3:122–129

Zhang N, Yu G, Yu Z (2003) Simulation of temporal–spatial variation characteristics of surface runoff in Changbai Mountain based on process model for landscape scale. J Appl Ecol (in Chinese) 14(5):653–658