Hydrological Studies of the Heihe River Basin in the Northwest Arid Regions of China

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Abstract: Because of the extremely continental dry climate, the Heihe River basin is characterized by less precipitation, rapid evaporation and low runoff ratio. The mountain watersheds of the Heihe River basin receive much more precipitation, and possess lower temperature and lower evaporation rate as compared with the basin area in front of the mountains, therefore are the runoff generation area of the Heihe River basin. A trend analysis indicates that, in the Heihe River basin during the 40 years from 1956 to 1996, air temperature increase is mainly in winter, next in autumn, while summer precipitation increases obviously. As a result, both yearly air temperature and precipitation show some increase trend. The runoff simulation is carried out with a model for simulating the response of monthly runoff from the mountain watersheds in the inland area of northwest China to climate change. Taken the mountain watershed of the Heihe River basin controlled by the Yingluoxia Hydrometric station as an example, the water balance and hydrological processes are simulated. The water balance simulation indicates that from the dry years to the wet years, precipitation, evaporation, runoff and runoff ratio all increase, while the alimentation ratio of glacier and snow melt water to the runoff decrease. The simulation of runoff change under the global warming indicates that, from 1990s to 2000s, as compared with the runoff during 1980s, along with the increase of air temperature, precipitation and glacier melt water increase in some amount. This compensates in some degree the runoff reduction caused by the increase of air temperature and evaporation. As a result, runoff shows slightly increase, and the increment range is within 3%. Then, to 2010s and 2040s, the increase of precipitation and glacial melt water is not enough to compensate the runoff reduction caused by air temperature increase, and the runoff will decrease in the aptitude within 10%.

Key words: Heihe River basin, hydrological characteristics, runoff simulation, water balance, runoff change projection

1. Introduction

The Heihe River basin is one of the relatively large inland river basins in the arid regions of northwest China. It is located at the middle of the north flank of the Qilian Mountains and the Hexi Corridor. The drainage area of the Heihe River basin ranges from 37°45′N to 42°40′N and from 96°42′E to 102°04′E, covering the area of 13×10^4 km^2 (Fig. 1). It originates from the Qilian Mountains in Qinghai province, and flows through the Hexi Corridor of Gansu province and enters the western part of Inner Mongolia Plateau (Gao et al., 1990).

As a representative of the inland river basins, the Heihe River basin can be divided into four altitude zones: high mountain ice, snow and permafrost zone, mountain vegetation zone, oases zone and desert zone. The former two zones constitute the mountain watersheds, which are the runoff generation area, while the latter two zones constitute the low land area where water resources are consumed and runoff is scattering and disappearing. The Heihe River basin is situated at the inland area of Eurasia, far from the oceans. The water vapor current comes mainly from the summer southeast monsoon from the Pacific Ocean and the summer southwest monsoon from the Indian Ocean (Zhou, 1983; Sun, 1977-1978), next from the wester air current (Yang, 1992a). In winter, it is extremely cold and dry because of the dominant control over the area by the Mongolia and Siberia High. Therefore, the Heihe River basin is dry in climate and short of water resources. Based on the data measured at the meteorological stations and hydrometric stations distributed in the Heihe River basin, this paper is intended to discuss the hydrological characteristics, runoff simulation and response of the mountain runoff to climate change in the Heihe River basin.

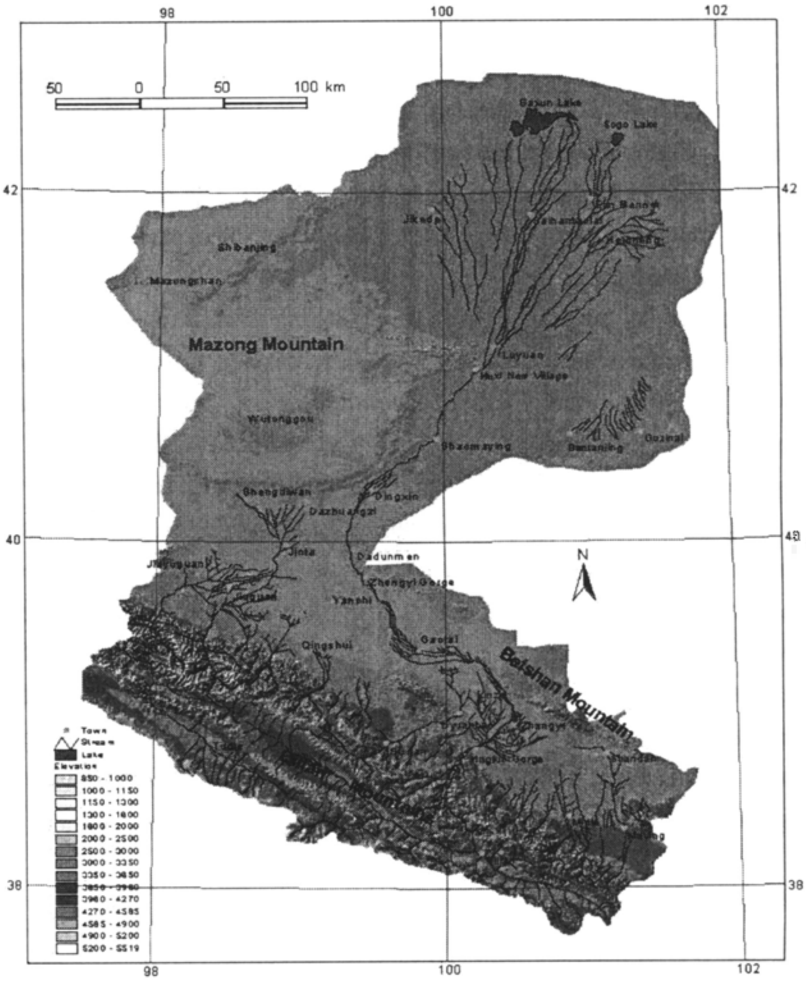

Fig. 1 A sketch map of the Heihe River basin

2 Hydrological characteristics

2.1 Drainage systems

The Heihe River drainage system consists of 35 rivers, which can be divided into three sub-drainage systems: the east sub-drainage system, the middle sub-drainage system and the west sub-drainage system (Fig. 1). Because of the increasing utilization of the water resources, the three sub-drainage systems have been separated from their surface water hydraulic connections, forming three relatively independent drainage systems. However, they may have some under surface hydraulic connections, but it still needs further investigation.

Because of the extremely continental dry climate, the Heihe River basin is characterized by less precipitation, rapid evaporation and low runoff ratio (Table 1).

Table 1 Precipitation and runoff in the Heihe River basin

	Drainege area (km^2)	Precipitation		Runoff		Runoff ratio
		10^8m^3	mm	10^8m^3	mm	
East drainage system	105602	122.6	116.1	29.28	27.7	0.24
Middle drainage system	5273	9.8	185.9	2.97	56.3	0.30
West drainage system	19125	33.5	175.2	9.61	50.2	0.29
Whole Heihe River basin	130000	165.9	127.6	41.85	32.2	0.25

According to the Glacier Inventory of China (Wang et al., 1981), there are 1078 glaciers covering 420.55km^2 in the Qilian Mountains of the Heihe River basin. The water storage of the glaciers accounts for $137.7 \times 10^8m^3$, and the annual glacial melt water accounts for $2.98 \times 10^8m^3$. The alimentary ratio of the glacial melt water to the total river runoff is averaged at 8% (Yang, 1991).

2.2 Runoff generation

The spatial distribution of annual air temperature and precipitation shows that, in the Heihe River basin, precipitation is more and air temperature is lower at the mountainous area than those at the low land area in front of the mountains (Yang, 1992b). Fig. 2 shows significant altitude dependency of annual air temperature, precipitation and pan evaporation measured at the standard meteorological stations distributed in the Heihe River basin. Along with the increase of altitude, precipitation increases, air temperature and evaporation decrease. As the regional characteristics, precipitation is closely related to altitude (Fig. 2). This indicates that the topographical lifting mechanisms play a very important role in the formation of precipitation in this area. This can be explained by the facts that the Qilian Mountains stretch from southeast to northwest, facing actually northeast. The controlling low pressure system over the Qilian Mountains and the subtropical high moving west during summer make the air current carrying water vapor from southeast move towards west (Yang, 1992a). Therefore, the lifting mechanisms are built up by the interaction between the air current, elevation and slope orientation of the Qilian Mountains. The precipitation is mostly concentrated during the summer season in a year (Yang, 1991), therefore, the annual precipitation shows obvious altitude dependency.

Fig.2 indicates that the mountain watersheds receive much more precipitation, and possess lower temperature and lower evaporation rate, and therefore are the runoff generation area.

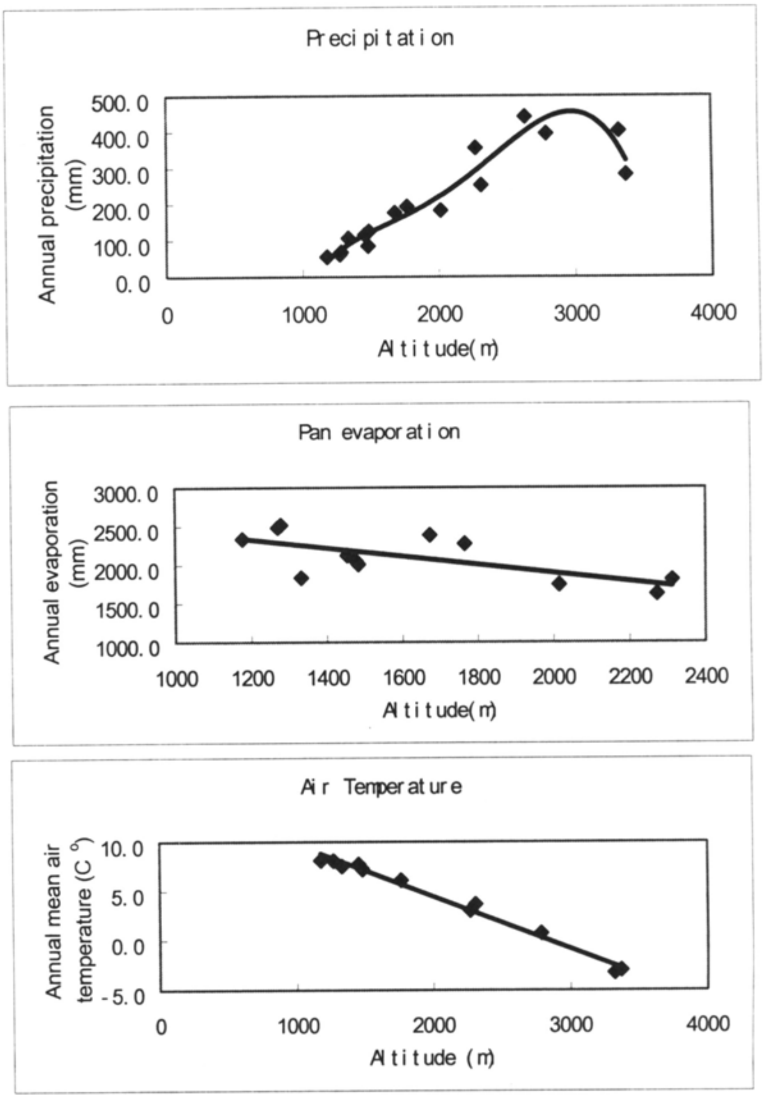

Fig. 2 Altitude dependency of yearly mean air temperature, total precipitation and pan evaporation in the Heihe River basin (averaged values at the standard meteorological stations during 1956 to 1998)

2.3 Monthly runoff distribution

Figure 3 shows the mean monthly runoff depth at the hydrometric stations of four sub basins of the Heihe River basin. The hydrometric stations Yingluoxia, Qilian and Zhamask control the three mountainous watersheds of the north flank of the Qilian Mountains, which represent the runoff generation area of the mountains. The Zhengyixia hydrometric station is located at the north side of the Hexi Corridor, at the north Beishan Mountains, which is much lower than the Qilian Mountains. The catchment area controlled by the Zhengyixia station consists of the mountainous part in the Qilian Mountains and the low land part of the Hexi Corridor. Therefore, runoff at the Zhengyixia station represents the surplus of the mountain runoff after utilization of water resources in the Hexi corridor, and is much smaller than the runoff at the other three hydrometric stations. Figure 3 indicates that runoff is generated from the mountain watershed and consumed at the low land Hexi corridor area. Runoff from the mountains is mostly concentrated during the months from May to September, and the largest runoff occurs during the summer months from June to August. The three mountain watersheds can be divided into the high mountain ice, snow and permafrost zone and mountain vegetation zone by the altitude line 3600m(Gao et al., 1991). The high mountain zone accounts for 55%, 40% and 83% in the hydrometric basins of Yinglouxia, Qilian and Zhamask respectively. The hydrographs of the three mountain watersheds show the similar characteristics. The monthly runoff distribution is the same, and the runoff generation is also close to each other. At the high mountain zone, the runoff coefficient is large because of the more precipitation, less evaporation, and the existence of glaciers and permafrost (Yang, 1991). At the mountain vegetation zone, the water restraining forests have strong ability to conserve water, and therefore to promote the runoff generation (Che et al., 1996). Therefore, both the high mountain zone and the mountain vegetation zone are important to contribute the runoff generation.

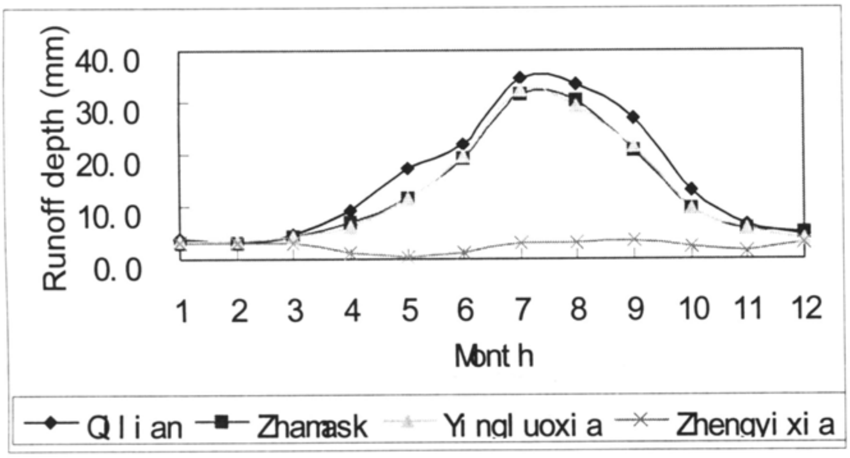

Fig. 3 Mean monthly runoff distribution at the hydrometric stations of Heihe River (Averaged from 1967 to 1995)

Station	Altitude(m)	Catchment area(km^2)
Qilian	2590	2452
Zhamask	2635	4589
Yingluoxia	1674	10009
Zhengyixia	1995	35634

3 Runoff simulation

3.1 Model structure

The basic structure of the model for simulating the response of monthly runoff from the mountainous watersheds in the inland area of northwest China to climate changes is presented in Fig. 4 (Kang et al., 1999).

The basic inputs to the model are precipitation *P* and air temperature *T* at a standard meteorological station, outputs are evapotranspiration *ET* and runoff *R* from the mountainous watersheds (Fig. 4), and the time step is a month. In the model, the mountain watersheds are divided into two basic altitude zones, the high mountain ice, snow and permafrost zone (expressed as high mountain zone in Fig. 4) and the mountain vegetation zone.

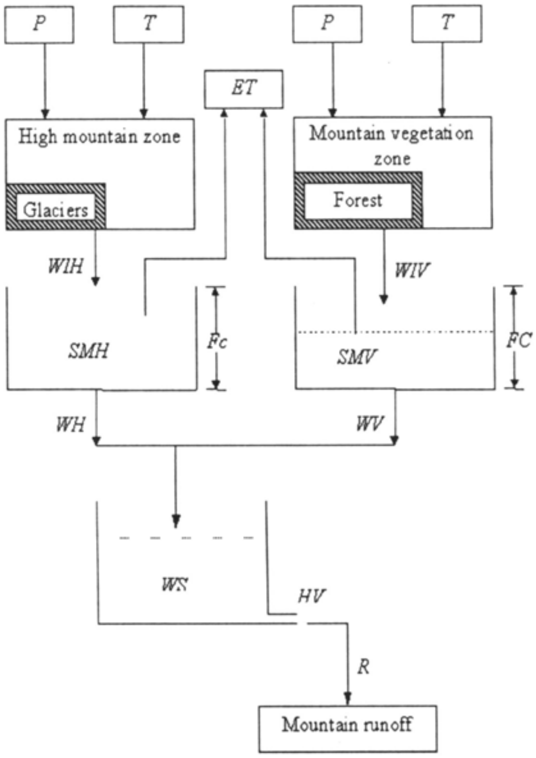

Fig. 4 Diagrammatic sketch of the model for simulating the from the mountainous watersheds in the inland area of northwest China (designed based on HBV runoff model (Bergstrom, 1976), and the symbols are interpreted in the text.) (from Kang Ersi et al., 1999)

The procedure of runoff simulation expressed in Fig. 4 is interpreted as follows.

1) Computation of water inputs

The glacial melt, separation of solid and liquid precipitation, and snow accumulation and melt are computed. The water inputs to the mountainous watersheds are composed of glacier meltwater, snow meltwater and liquid precipitation. The water inputs are symbolized as *WIH* in the high mountain ice, snow and permafrost zone, and as *WIV* in the mountain vegetation zone.

2) Computation of water content in the soil moisture layer

The concept of soil moisture layer of HBV runoff model is used (Bergstrom, 1976). The ground surface and subsurface layer including the active layer of permafrost and the layer above the groundwater level constitute the soil moisture layer. The water storage of soil moisture layer in the high mountain ice, snow and permafrost zone is symbolized as *SMH*, and that in the mountain vegetation zone as *SMV*. The output of the water storage in the soil moisture zone is evapotranspiration *ET*. The critical water content of the soil moisture layer for runoff generation is symbolized as *Fc* in the high mountain ice, snow and permafrost zone, and as *FC* in the mountain vegetation zone.

3) Computation of runoff

Taking the soil moisture layer as a reservoir, then when its water storage reaches to *Fc* or *FC*, there will be runoff generation *WH* or *WV*. *WH* of the high mountain ice, snow and permafrost zone and *WV* of the mountain vegetation zone form together the water storage WS of the mountainous watershed. Then, through a lumped watershed response function with a drainage coefficient *HV*, the runoff *R* out of the outlet of the mountainous watershed is simulated.

4) Model test

Model test is carried out by the model evaluation criteria R^2 (Bergstrom, 1976) and a relative error expressed with the ratio of simulated value minus measured value to the measured value.

3.2 Water balance simulation of the mountain watershed

3.2.1 The mountain watershed

Taken the mountain watershed of the Heihe River basin controlled by Yingluoxia Hydrometric station (38°48'N, 100°11'E) (Table 2) as an example, the water balance and hydrological processes are simulated.

Table 2 The Heihe mountain watershed controlled by Yingluoxia hydrometric station at the Qilian Mountains [1)]

Hydrometric station	Altitude (m)	Drainage area (km^2)	Glacier covered area (km^2)	Glacier water storage (10^8m^3)	Glacier covered ratio (%)	Annual runoff (10^8m^3)	Glacier melt runoff (10^8m^3)	Alimentation ratio of glacier melt (%)
Yingluoxia	1674	10009	59	13.808	0.59	16.05	0.72	4.5

1) The years for statistics are from 1959 to 1993

The underlying surface of the high mountain glacier, snow and permafrost zone consists mainly of glaciers, snow cover, permafrost and alpine meadow, while that of the mountain vegetation zone consists of grass land, shrub and forests. In the mountain watershed controlled by Yingluoxia hydrometric station, the area of the high mountain zone accounts for 59% of the mountain watershed, and its mean altitude is 3993.1m. The mean altitude of the mountain vegetation zone is 3142.3m, and the mean altitude of the mountain watershed is 3737.7m.

3.2.2 Runoff variation

Figure 5 shows the yearly runoff departure time series of the Yingluoxia hydrometric station.

Suppose the yearly runoff departure is Q_d (%), according to the variation range of Figure 5, the yearly runoff is divided into the following groups.

Dry years:	$Q_d \leq -15.0\%$
Partial dry years:	$-15.0 < Q_d < -5.0\%$
Normal years:	$-5.0\% \leq Q_d \leq +5.0\%$
Partial wet years:	$5.0\% < Q_d < 15.0\%$
Wet years:	$Q_d \geq 15.0\%$

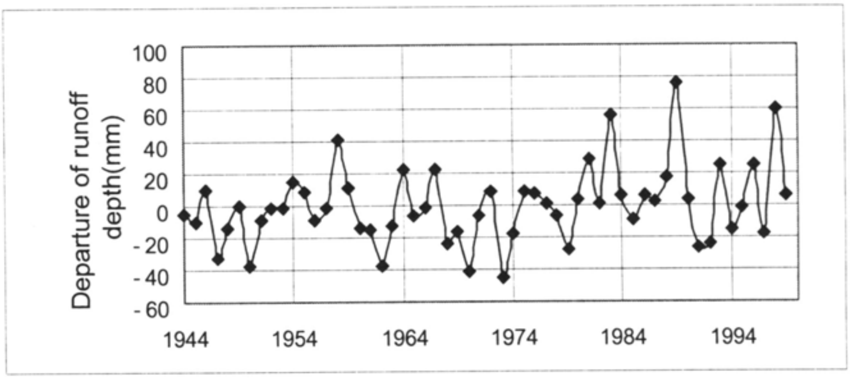

Fig. 5 Departure of the yearly runoff depth at the Yingluoxia hydrometric station (the years from 1944 to 1999)

Then the runoff simulation is carried our for the different yearly runoff groups. Each group has tow parts, one for model calibration and another for model test. The simulation processes is as mentioned by Kang (Kang et al., 1999)

Table 5 Water balance composition of the different degree of wet and dry years in the Heihe mountain watershed controlled by the Yingluoxia hydrometric station

Sample years	Precipitation (mm)	Evaporation (mm)	Glacier melt water (%)	Snow melt water (%)	Runoff (mm)	Runoff ratio (%)
Dry	364.8	250.8	10.7	35.8	114.0	31.3
Partial dry	405.8	265.2	8.1	35.7	140.6	34.6
Normal	412.7	259.9	7.7	34.2	152.8	37.0
Partial wet	483.0	311.4	6.7	34.3	171.6	35.5
wet	534.4	328.8	5.6	30.6	205.6	38.5

3.2.3 Water balance simulation

With the runoff simulation, the water balance of the mountainous watershed is then simulated. Table 3 indicates that from the dry years to the wet years, precipitation, evaporation, runoff and runoff ratio all increase, while the alimentation ratio of glacier and snow melt water to the runoff decrease. This shows the regulation role of the glacier and snow melt water to the runoff. Because in the dry years, the more glacier and snow melt water compensates the runoff reduction, while in the wet years, less melt water makes the glaciers increase their ice storage. The water balance composition of Table 3 indicates that, the runoff ratio of the mountain watershed, that is the ratio of annual runoff to annual precipitation, is larger than the average value 16.5% of the inland dry regions of northwest China, but it is less than the average value 42.0% of the whole country. Therefore, although the mountain area of the inland river basins is the runoff generation area, because of the dry climate background, the water resources are still limited.

4 Response of the mountain runoff to climate change

The runoff model shown in Figure 4 is employed to simulate the response of mountain runoff to climate change (Kang et al., 1999).

4.1 Scenarios of climate change

According to the trend analyses of air temperature and precipitation at the hydrological and meteorological stations distributed in the Heihe River basin, which have the altitude ranges from 1178.6m to 3368.0m, the trend aptitudes are obtained from 1956 to 1996 (Table 6). During the years from 1956 to 1996, the glacier covered area of the Heihe River basin was reduced by 7% (Liu et al.,1999), while the annual runoff of the mountain watershed controlled by the Yingluoxia hydrometric station increased by 11%.

Table 6 Change of air temperature and precipitation in the Heihe River basin during the years from 1956 to 1996

Time interval	Air temperature (°C)	Precipitation (mm)
Spring (March to May)	-0.1	-9.8
Summer (June to Aug.)	-0.2	+25.1
Autumn (Sep. to Nov.)	+0.8	+0.9
Winter (Dec. to Jan.)	+2.1	-0.5
Yearly	+0.7	+15.6

Table 6 indicates that, in the Heihe River basin during the 40 years from 1956 to 1996, in terms of the change trend, air temperature increase is mainly in winter, next in autumn, while summer precipitation increases obviously. As a result, both yearly air temperature and precipitation show some increase trend.

In order to get the climate change scenarios in a decade time interval in future 50 years, the simulation results of HadCM2Gsa climate model (Viner, 1996) is used. The climate model made a climate prediction by the yearly increase of 1% both for CO_2 and for sulphate aerosol. After a comparison between HadCM2Gsa results and the measured results at the Hexi Corridor area during the years from 1956 to 1996, it is found that in the area, HadCM2Gsa results over estimate the air temperature increase and underestimate the precipitation increase. Thus a regional correction factor is added to the HadCM2Gsa results, for air temperature, it is −0.3°C, and for precipitation, it is +25%, to get then the climate scenarios for the mountain watershed during the future 50 years (Table 7).

Table 7 Estimation of climate change scenarios of decade mean in the mountainous watersheds of the Heihe River (a regional correction is carried out on the prediction by the HadCM2 climate model (Viner, 1996)) 1)

Watersaed	1990s versus 1980s		2000s versus 1980s		2010s versus 1980s		2020s versus 1980s		2030s versus 1980s		2040s versus 1980s	
	t (oC)	p (%)	t (oC)	p (%)	t (oC)	p (%)	t (oC)	p (%)	t (oC)	p (%)	t (oC)	p (%)
Heihe mountain watersheds	+0.09	+14.8	+0.28	+16.6	+0.63	+23.2	+0.87	+18.3	+1.37	+20.4	+1.20	+23.4

1) In the table, t and p represents the yearly mean air temperature and precipitation separately.

4.2 Runoff change projection

Based on the climate scenarios and the model shown in Figure 4, the runoff change of the Heihe mountain watershed controlled by the Yingluoxia hydrometric station is simulated and compared with the measured yearly mean runoff value during 1980s for the future decades (Table 8). During the simulation, the glacier- covered area is reduced by the ratio of –0.2%/year (Liu et al., 1999). The simulation indicates that, from 1990s to 2000s, along with the increase of air temperature, precipitation and glacier melt water increase in some amount. This compensates in some degree the runoff reduction caused by the increase of air temperature and evaporation. As a result, runoff shows slightly increase, and the increment range is within 3%. Then, to 2010s and 2040s, the increase of precipitation is not enough to compensate the runoff reduction caused by air temperature increase, and the runoff will decrease in the aptitude within 10%. Along with the air temperature increase, evaporation will increase, but precipitation also has some increase, and glacier melt water will also increase its alimentation to the rivers. On the other hand, the alimentation of snow melt water to the rivers would decrease in some degree because of the reduction of the solid precipitation caused by the air temperature increase.

Table 8 Simulation of the decade mean runoff composition and change of the mountainous watershed of the Heihe river controlled by the Yingluoxia hydrometric station in the future 50 years1)

Decades	Runoff (mm)	Runoff change versus 1980s %)	P (mm)	E (mm)	Glacier melt alimentation(%)	Snow melt alimentation(%)
1980s measured	173.3	100.0	463.2	287.6	5.7	34.8
1990s simulated	178.3	+2.9	526.7	309.0	5.4	35.6
2000s simulated	176.1	+1.6	531.0	320.8	5.7	35.5
2010s simulated	167.6	-3.3	560.9	337.8	6.8	30.3
2020s simulated	170.2	-1.8	540.1	334.0	6.6	29.3
2030s simulated	155.5	-10.3	545.4	343.6	7.7	27.7
2040s simulated	158.4	-8.6	555.9	344.7	7.2	30.5

1) In the table, P and E represent yearly mean precipitation and evaporation separately.

5 Conclusion

Because of the less precipitation, rapid evaporation and low runoff ratio of the Heihe River basin, it is extremely lack of water resources. The human activities are concentrated in the oases area in front of the mountains and the ecological environment is extremely vulnerable. Although the mountainous watersheds receive more precipitation and have less evaporation rate, forming the runoff generation area, the runoff is still limited because of the dry continental climate background. The water balance composition is different from the dry years to the wet years. The glacier covered area is relatively small in the Heihe River basin, therefore the glacier melt water contribution to the river runoff is limited, but the glaciers still play some regulation role to the mountain runoff.

Under the global worming conditions, the change trend of air temperature shows increase mainly in winter, next in autumn, and the precipitation change trend shows increase in summer. As a result, the yearly air temperature and precipitation both show some increase trend, and the mountain runoff shows slight increase trend.

The response of monthly runoff from the mountain watershed of the Heihe River basin is simulated. It is projected that, under the climatic warming, precipitation and evaporation would increase in some degree, and the alimentation of glacial meltwater runoff to the Heihe river would be increasing in some amount. The mountain snow melt runoff would have a reducing trend. In the future decades to 2040s, as compared to the mean yearly runoff during 1980s, the decade mean runoff from the mountain watershed would increase by the amount within 3% first to 2000s, then along with the continuous climatic warming, the runoff could be reduced by the amount within 10%.

Therefore, during the future 50 years, the global worming impact to the mountain water resources of the Heihe River basin is not very serious. If we can achieve a rational utilization and exploitation of water resources, then we can get the sustainable ecological and social development of the Heihe River basin.

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