Impacts of climate change on hydrological processes and water resources in the headwater area of the Yellow River

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Abstract The headwater area upstream of the Tang-Nai-Hai hydrological gauge station is one of the main runoff generation areas of the Yellow River Basin. Climate change is one of the main reasons for water resources decrease and ecological deterioration in the headwater area in recent years, and analysing of future further change impact is important for water resources planning and management in the basin. In this article, we simulated the changes of both annual and monthly runoffs in the headstream of the Yellow River under air temperature and precipitation change by using the WEP model. WEP is a physically-based distributed model and can reflect the impact of air temperature change on water resources through evapotranspiration change, snow storage and melting change and infiltration capability change in the frozen soil layer. The model was validated using the observed daily discharge data from 1956 to 2000 at the Tang-Nai-Hai station. After validating the model, we assumed eight different schemes with temperature change of ±1, ±2°C and precipitation change by ±10%, ±20% on the basis of historical observed meteorological data. The results indicated that air temperature change had different impacts on annual and monthly runoffs. The temperature increase causes an annual runoff decrease, with an obvious decrease of monthly runoff from May to October because of the evapotranspiration increase, and an increase from November to the following April because of snow storage and melting, and frozen soil infiltration capability changes. The maximum increase is 63.7% in March, 1989, when assuming the air temperature increase of 2°C. Precipitation increase or decrease causes runoff increase or decrease to different extents, and the runoff has a larger change rate than precipitation.

Key words headwater area of the Yellow River; climate change; distributed model; Tang-Nai-Hai

INTRODUCTION

Due to a sharp increment of the world's population and quick economic development, a large quantity of greenhouse gases was released, and some climate conditions such as precipitation and temperature were changed, resulting in a change in the water resources situation and water resources and environmental problems. Although the United States National Research Association (USNA) held a conference to discuss the relationship between climate, climate change and water supply early in 1977, the research about how climate change influences water resources did not draw much attention from the international hydrology group until the mid-1980s. In China, special research has been carried out in the Seventh, Eighth, Ninth "Five-Years" programmes and the GAME programme since the 1980s (Jiang *et al.*, 2003).

There are several uncertainties in the research on climate change, which are caused by the amount of greenhouse gas discharged, the response of the climate system and the levity of nature (Metoffice, 2002). To study the impacts of climate change on water resources, researchers present different hydrology models, including statistical models, concept models, and distributed models. By analysing the climate factors (precipitation and temperature) and the hydrology factors (runoff and flood frequency), the statistical models were used to set up the statistical relationship between each variable with which we could analyse the influence of climate change on water resources. Stockton (1979) set up the experiential function among precipitation, air temperature and runoff, and analysed runoff change in main American rivers under different assumed scenarios. Lan *et al.* (2001) studied the response of runoff to climate change on the basis of the precipitation, air temperature, and runoff data in the Qilian Mountainous Area and the Hexi corridor area. Concept models were used to simulate the runoff under the assumed scenarios, study the influence of climate change on runoff, evaporation, flood peak and its occurrence time, and the spatial distribution of hydrological factors. Lettenmaier & Gan (1990) analysed the water process response to the climate warming using the Sacramento Model; Liu (1997) studied the slope runoff using the improved monthly runoff model (Schaake & Liu, 1989); Wang & Wang (2000) studied the impacts on the annual runoff at the upstream of the Yellow River. Distributed models could be used to study the influence of climate change on the runoff at a macroscopic scale by coupling the climate model and the distributed hydrology model, or making the output of the climate model the input of the hydrology model. Yuan *et al.* (2005) studied the trend of water resource change under the climate change by coupling the Variable Infiltration Capacity model and the Providing Regional Climate for Impacts Studies model. Chen & Gao (2003) discussed the impact of climate change on the runoff of the middle reach of the Yangtze River using a Two-parameter Monthly Water Balance Model under the climate scenarios provided by two global climate models. The coupling of distributed models and general circulation models (GCMs) is a new study direction of the impacts of climate change on the water cycle.

The headwater area of the Yellow River is the main water source of the basin. The environmental problems of glacier degradation, frozen soil degeneration, and lake drying up in the headwater area interact and aggravate each other, and have weakened the carrying-capacity of the water resources. The problem of water resources change will influence the socio-economies of the Yellow River Basin for a long time. It is necessary to simulate and analyse the runoff response to climate change in the headwater area of the Yellow River Basin, which is helpful for doing research and forecasting the change of water resources.

There is lots of research on the problem of water resources change in the headwater area and some conclusions have been obtained, e.g. the response to climate change in the headwater area is sensitive, if temperature falls and precipitation increases, the runoff will increase by different degrees. But these conclusions were discussed in the time scale of one year (Wang & Wang, 2000; Li *et al.*, 2004; Yang *et al.*, 2004), not including the seasonal and monthly responses. In this article, we analysed not only the change of annual runoff, but also the change of monthly runoff under climate change by assuming eight scenarios of precipitation, considering the contribution of glacier and thaw to the runoff and using the WEP model.

MODEL INTRODUCTION

WEP-L (Water and Energy transfer Processes in Large river basins) (Jia *et al.*, 2005, 2006), a distributed model, was developed in a National 973 Program of China entitled "Evolutionary Laws and Renewable Mechanism of Water Resources in the Yellow River Basin".

The horizontal structure of WEP model is shown in Fig. 1. Runoff routing on slopes is carried out based on elevation, gradient and Manning roughness by applying a one-dimensional (1-D) kinematic wave approach or dynamic wave approach to trace the overland flow from upstream to downstream. Numerical simulation is made for groundwater flows in mountain and plain areas separately, with consideration of the groundwater exchange with surface water, soil moisture and streamflow.

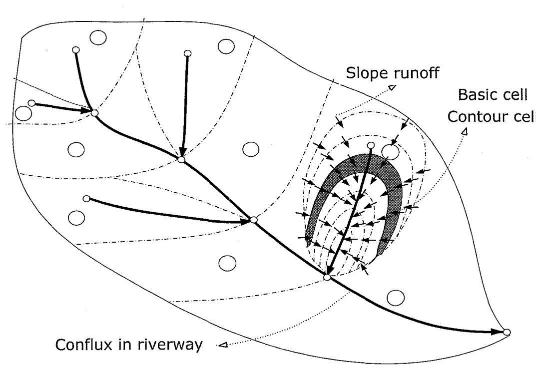

Fig. 1 Horizontal structure of the WEP-L model.

The vertical structure of the WEP model is shown in Fig. 2. From top to bottom, the vertical structure includes an interception layer of vegetation or buildings, a land surface depression layer, unsaturated soil layers, a transition zone, and unconfined and confined groundwater aquifers. State variables include interception by vegetation, storage in land surface depressions, temperature of land surface, soil moisture content, storage in transition zone, groundwater level and streamwater level. The main parameters are maximum interception, soil permeability, and characteristic curve parameters of soil moisture and suction, groundwater transmission coefficient, groundwater specific yield and storage coefficient, river bed permeability and Manning roughness. The "mosaic" method is applied to take unevenness of land use in the calculation unit into consideration by classifying the land into groups of bare land-vegetation, irrigated farmland, non-irrigated farmland, waters and impermeable areas for the calculation of water-heat flux through the land surface. The bare land-vegetation is further subdivided into bare land, grassland and woodland, and impermeable land into urban land and urban building. In addition, in order to reflect change in surface soil moisture content with depth and describe evaporation from soil and water uptake by root systems of grass, crops and trees, the top soils of permeable areas are divided into three layers.

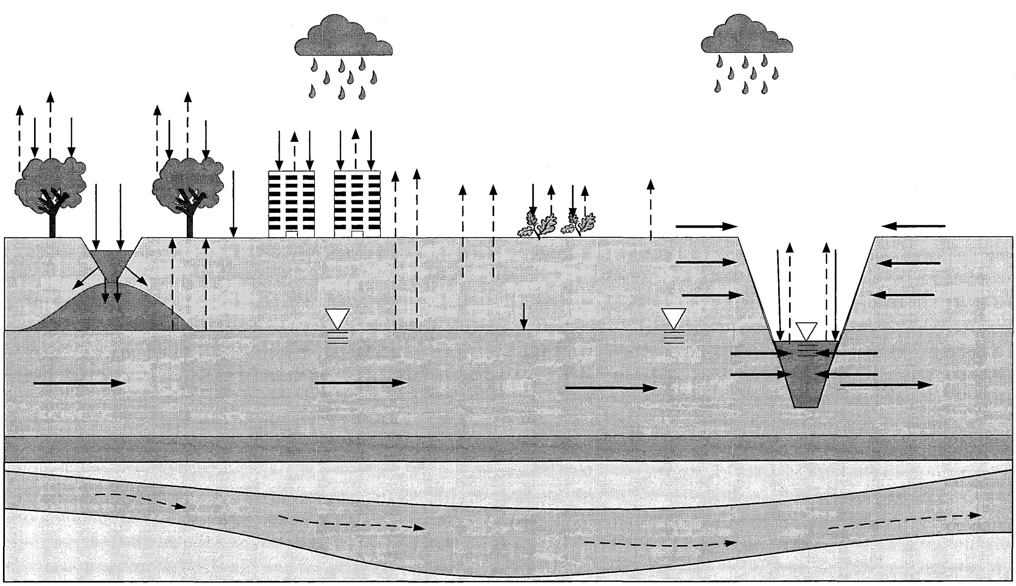

Fig. 2 Vertical structure of the WEP-L model.

The main characteristics of the WEP-L model are as follows:

(a) It integrates the merits of a distributed hydrological model and the SVATS model, couples the water cycle and energy processes, and calculates the vegetation canopy transpiration, surface evaporation, vegetation, soil and bare soil evaporation, water surface evaporation, and vegetation transpiration in each land-use area particularly.

(b) It generates the river system and divides sub-basins containing spatial topological information based on DEM and observed river vector graph, adopts "contour belt within sub-basin" as calculation unit, and considers diversity of land cover within the unit by means of a "mosaic" method, to avoid distortions of water balancing and runoff concentration route resulting from "coarse grids of large area" and to describe spatial variation of hydrological variables rationally.

(c) It performs simulations by adopting "varied time intervals" (such as 1 hour duration for the infiltration–runoff yield process of intensive rainfall, 6 hours duration for runoff concentration process on slopes and in the river course, and 1 day duration for groundwater flow) for each element of the hydrological cycle to ensure rational description of dynamic mechanisms, and efficient calculation.

(d) It incarnates the theory of variable source area (VSA) in the calculation, which can simulate the runoff yield under saturated storage, runoff yield under excess infiltration, and spring flow out, and calculate surface water, groundwater, and soil water dynamically.

(e) It has mutual-feedbacks with ROWAS (a lumped water allocation model) to realize close coupling of the natural hydrological cycle with the artificial water system.

(f) It has a quick calculation speed (11 minutes for simulation of the Yellow River Basin for one year duration), and functions of both flood forecasting and continuous calculation for the long-term.

The detailed content is referred to in Jia *et al.* (2005, 2006).

It should be mentioned that the temperature and precipitation changes, along with the topography, the snow and thaw simulation, and the moisture movement in frozen soil in the Yellow River Basin, are considered in the WEP-L model. The temperature and precipitation change along with the topography are interpolated based on the observations at gauge stations, DEM and the lapse rates to altitude. The snow and the thaw are computed by the degree-day index method, and the temperature influence to the hydraulic conductivity in frozen soil is computed as:

$$k_f = \begin{cases} k_0 & T_a \geq T_c \\ k_0 e^{a(T_a+b)} & T_a < T_c \end{cases} \tag{1}$$

where k_f is the hydraulic conduction coefficient; k_0 is the hydraulic conduction coefficient when frozen soils melt; T_a is the average daily temperature; T_c is the critical temperature of melting; and a, b are constants: $T_c = -5°C$, $a = 0.05$, $b = 0.25$ in the Yellow River Basin. It is found that the simulated hydrograph in dry seasons is difficult to match with the observed if the temperature influence on the hydraulic conduction coefficient is neglected.

MODEL APPLICATION

The headwater area is defined as the region upstream of the Tang-Nai-Hai station, with an area of 122 000 km^2, which is mainly located in Qinghai province.

It is a typical continental climate in the headwater area of the Yellow River: cold, dry and windy. The annual average temperature is –4°C, only being above 0°C in May to September. The annual average evaporation from the water surface is 1400 mm, and the annual average precipitation is 300 mm. It freezes from November to April every year, >160 days.

We selected the daily precipitation data of 14 rainfall stations, the daily weather data of 10 weather stations, and daily runoff data at 7 hydrology stations. The Earth surface data consists of 1:100 000 land use data in three periods of time (1986, 1996, 2000), 1:250 000 DEM terrain data, and soil data. Figure 3 shows the area upstream of Tang-Nai-Hai, Level-3 sub-basins and the distribution of weather and rainfall stations.

The calculation units of this simulation are contour belts of sub-basins divided on the base of DEM of the Yellow River Basin. According to the direction of flow, the whole basin is divided into several sub-basins, and then according to the elevation, each sub-basin is divided into several contour belts. Spatially, the precipitation data interpolated into sub-basins is enough. The detailed calculation steps are as follows: calculate the related coefficient of data between every two stations and fix a threshold of these coefficients. If the related coefficient of two stations is larger than the threshold, the two stations can be supposed to be related and can be reference stations for each other. Otherwise, if the related coefficients of a station to all the other stations are smaller than the threshold, interpolation with the Thiessen polygon method is needed.

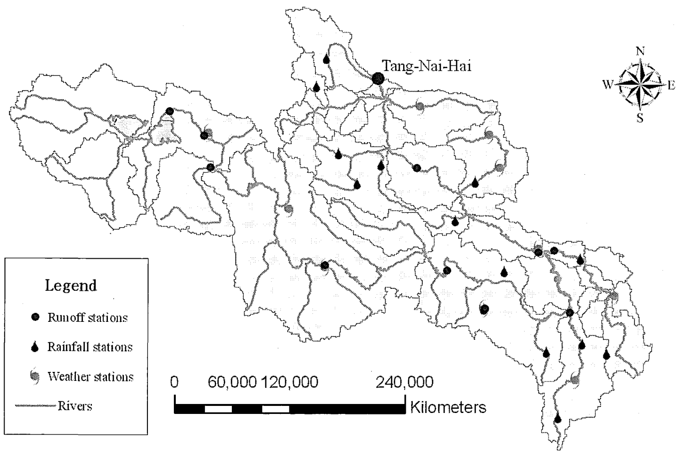

Fig. 3 Headwater area of the Yellow River and distribution of weather and rainfall stations.

Model calibration

In this article, we calibrated the model by the runoff in 1956–1979 with a time step of day. Then we validated the parameters by the runoff in 1980–2000 and got a good result, the relative error is not more than 4%, and the Nash coefficient is larger than 0.8 (see Table 1), which proved that the model fitted for the headwater area. Figure 4 shows the comparison between the simulated runoff and the observed ones.

Table 1 Comparison of the observed runoffs and calculated ones.

year	Observed runoff (10^8m^3)	Calculated runoff (10^8m^3)	Relatively error (%)	Nash coefficient
1956–2000	203.963	198.037	–2.90	0.821
1956–1979	202.145	197.609	–2.20	0.829
1980–2000	206.042	198.526	–3.60	0.814

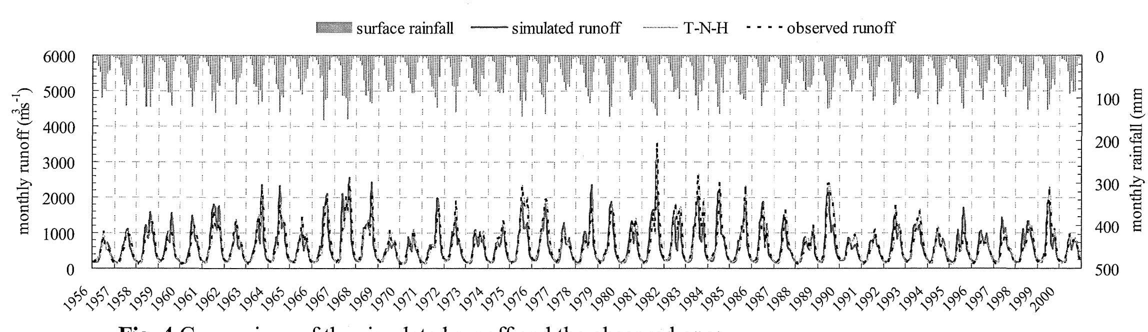

Fig. 4 Comparison of the simulated runoff and the observed ones.

Scenarios enactment

Considering the further trend of climate change and to analyse the runoff response clearly, we supposed that precipitation and temperature changed independently. In this research, we assumed eight different schemes with temperature change by ±1, ±2°C and precipitation change by ±10%,

±20% on the basis of historical observed meteorological data. Table 2 shows the results of these eight schemes' simulation.

Table 2 Simulation results of eight scenarios.

	Temperature change (°C)				Proportion of precipitation change (%)			
Climate change	–2	–1	+1	+2	–20	–10	+10	+20
Proportion of yearly runoff change (%)	+22.59	+10.43	–8.68	–15.77	–30.43	–15.96	+17.26	+35.64

Table 3 Comparison of simulation results with temperature changes.

Year		Actual case		Scenario case	
	Precipitation difference (mm)	Temperature difference (°C)	Runoff change (%)	Temperature difference (°C)	Runoff change (%)
1965 *vs* 1956	4.2	–1.94	20.30	–2.0	22.59
1977 *vs* 1969	–6.0	–1.22	11.30	–1.0	10.43
1989 *vs* 1967	–12.38	0.68	–15.74	1.0	–8.68

Table 4 Comparison of simulation results with precipitation changes.

year		Actual case		Scenario case	
	Temperature change (°C)	Precipitation difference (%)	Runoff change (%)	Precipitation difference (%)	Runoff change (%)
1983 *vs* 1965	0.01	–22.0	–31.4	–20.0	–30.43
1962 *vs* 1963	0.00	22.0	28.0	20.0	35.64
1966 *vs* 1980	0.01	–11.0	–20.8	–10.0	–15.96

Table 3 and Table 4 are comparisons of simulation results with temperature and precipitation changes. It is obvious that annual runoff changes with different rates when temperature and precipitation change. Annual runoff increases along with temperature decreasing. Precipitation change also affects the annual runoff. When precipitation increases, the annual runoff increases at a greater rate than precipitation does. The response of runoff to precipitation is more obvious than that to temperature. The maximal change rate is 35.64% when the precipitation increases by 20%.

Analysis of rationality of scenarios simulation results

In order to qualitatively validate the rationality of the simulation results, we analysed the response to temperature and precipitation separately. We chose the two years in which annual average precipitation was close and the average temperature discrepancy was about 1 or 2°C, from the data series, and then compared the annual runoff. For convenience, it was called "actual case" and the assumed scenario was called "scenario case".

In the actual case, the runoff change rates in every set of two years in which the annual average precipitation was very close and average temperature discrepancy was about 1°C or 2°C, were consistent with the runoff change rates of the scenario case. It proved that the scenario analysis results of temperature change were rational.

Similarly, we chose the two years in which annual average temperatures were close and average precipitation discrepancy was about 10% or 20% from the data series, and compared the annual runoff.

In the actual case, runoff in the two-years in which annual average temperatures were close and the average precipitation discrepancy was about 10% or 20% was uniform in the simulation result. It proved that the simulation result of precipitation change was rational.

Scenarios analysis

(a) Analysis of annual runoff change The proportions of runoff change in 45-year series were simulated based on the scenarios supposition. The results are shown in Figs 5 and 6, and the black line is the state without runoff change.

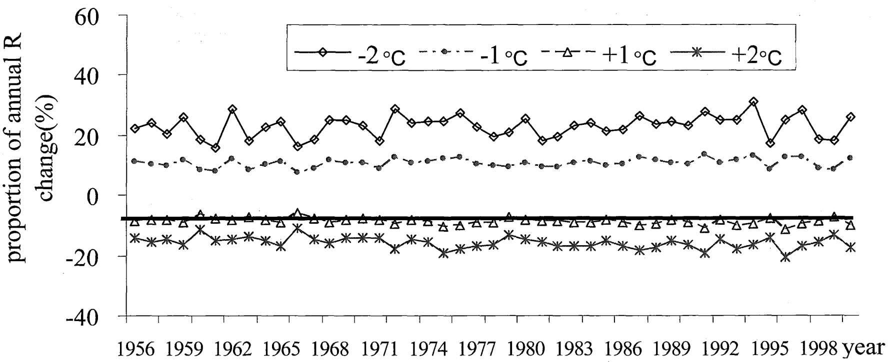

Fig. 5 Response of annual runoff to the temperature change in 45-year series.

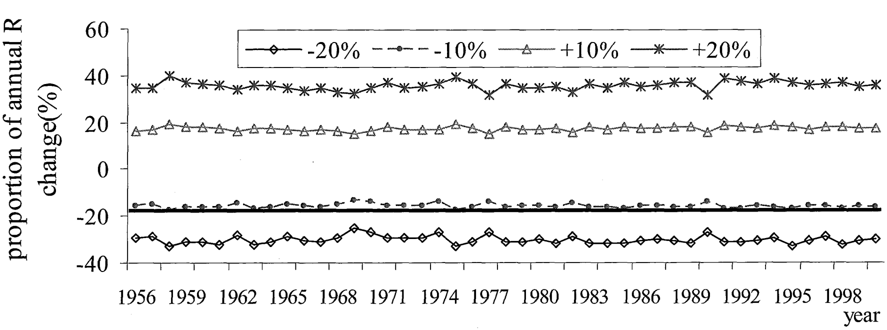

Fig. 6 Response of annual runoff to the precipitation change in 45-year series.

It can be seen that the response of runoff in the 45-year series to temperature change is accordant. Runoff decreases if the temperature increases. It is clear that in the same scenario the proportion of runoff change is at the same level, without obvious relation to precipitation.

The response of annual runoff to the precipitation is larger than that to the temperature changes. The runoff increases when the precipitation increases and in the same scenario the proportion of runoff change is at the same level.

(b) Analysis of monthly runoff change On the basis of the annual runoff analysis, the runoff change was simulated at a smaller time step. Figure 7 shows the average of monthly runoff in a 45-year series under temperature change, which is different from annual runoff.

The monthly runoff in 45-year series under temperature change is different from annual runoff. The curves in Fig. 7 intersect, which is mainly represented in the spring season every year because the headwater area is located at altiplano where there is perennial snow. When the

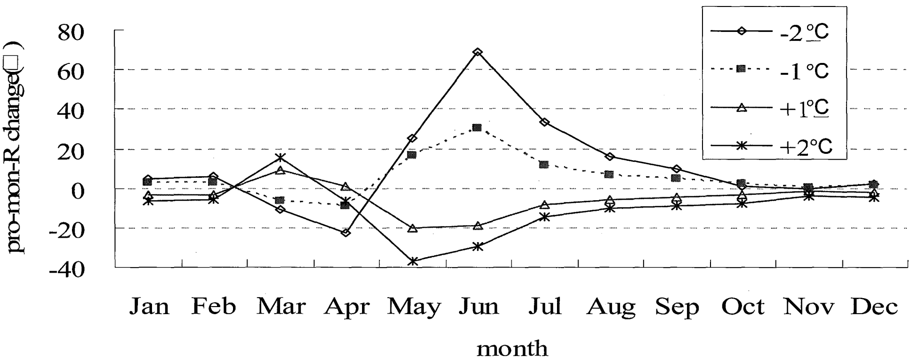

Fig. 7 Average monthly runoff under temperature change.

temperature rises to above 0°C in March or April every year, the snow melts into water, which causes spring floods. Thaw, the main part of the runoff in that season, is sensitive to temperature change, so monthly runoff increases when temperature increases in this season. The maximal proportion of change is 63.67% when temperature increased by 2°C in March, 1989. From November or December, to January or February of the next year, when the temperature is so low that the snow may not melt even under increasing temperature, the runoff response to the temperature is insensitive. In May to October every year when the actual temperature is above 0°C, temperature change deeply affects the evaporation, so monthly runoff decreases when temperature increases as the main part of runoff is surface flow.

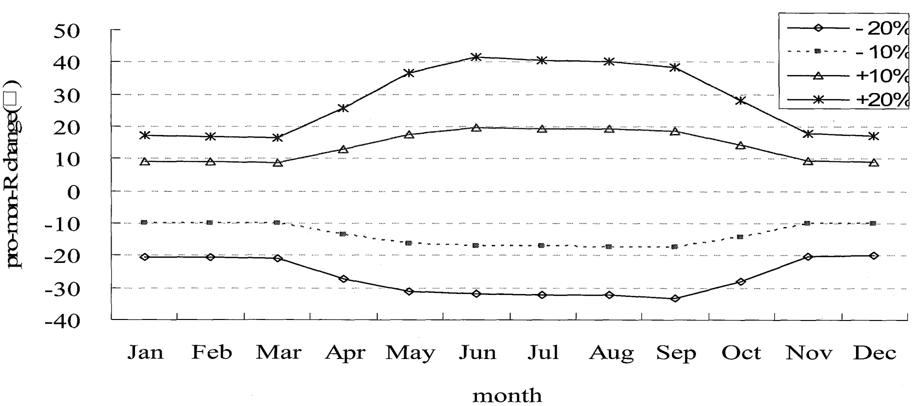

Fig. 8 Average monthly runoff under precipitation change (1956–2000).

Figure 8 shows average monthly runoff under precipitation change. We could see that the proportion of monthly runoff change in different months is different. The response to precipitation could be divided into three phases of dry season, wet season, and transitionary season. In the first phase, from November to the next March, because of the small amount of rainfall, the proportion of runoff change is maintained at the same lower level, which is close to the precipitation change proportion. During the wet season, from June to September, the change proportion is at an upper level, which is about 1.5 to 2.0 times that of the lower proportion in dry season. During three transitionary months, April, May, and October, the change proportion is between the other two.

CONCLUSIONS

In this paper, we simulated the changes of both annual runoffs and monthly ones in the headstream of the Yellow River under air temperature and precipitation changes using the WEP-L model. After calibrating the model by the runoff in 1956–1979 with a time step of day, we validated the parameters by the runoff in 1980–2000 and received good results that the relative error is not more than 4%, and the Nash coefficient is larger than 0.8. Eight different scenarios are assumed on the basis of historical observed meteorological data. The main findings are as follows:

(a) The annual runoff changes by different proportions under the temperature change. When the temperature increases, the annual runoff decreases. However, the precipitation change affects the annual runoff to different extents. When the rainfall increases, the annual runoff increases. The proportion of annual runoff change is larger than that of the precipitation change, but all of 45 years are almost at the same level under a climate change.

(b) Under temperature change, the changes of monthly runoff in different months are different during a year. In every spring season, monthly runoff increases when temperature increases. From November or December to January or February of the next year, the monthly runoff response to the temperature is insensitive. From May to October every year, monthly runoff obviously decreases with temperature increase because of the evapotranspiration increase.

(c) The monthly runoff response to precipitation change could be divided into three phases, the dry season phases, the wet season phases, and the transitionary season phases. In the first phase, from November to the next March, the proportion of runoff change is maintained at a similar lower level, which is close to the precipitation change proportion. During the wet season, from June to September, the change proportion is at an upper level, which is about 1.5 to 2.0 times of the lower proportion in the dry season. During three transitionary months, April, May, and October, the change proportion is between the other two phases.

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