

## **Analysis of water resources in the Yellow River basin in the last century**

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**Abstract** A statistical analysis on the precipitation and river discharge was carried out to explore annual and seasonal changes of water resources in the Yellow River basin in the last century. Together with a distributed hydrological model, this research examined the reason for river dry-up along the lower reaches of the Yellow River. In the upper basin up to the Lanzhou station, it was found that the observed runoff decreased by 23% from the 1950s to the 1990s; climate change contributed about 20% of this decrease, taking into account artificial water use. It was known that the river flow in the lower reaches downstream of the Huayuankou gauge during the dry season, was mainly supplied by the runoff generated from the upper basin above the Lanzhou gauge. The river dry-ups along the lower reaches were caused by both climate change and artificial water use.

**Key words** hydrological analysis; hydrological modelling; river dry-up; Yellow River basin

### **INTRODUCTION**

The Yellow River basin (Fig.1) is the second longest river basin in China, with a drainage area of 753 000 km<sup>2</sup>, population of about 100 million, and irrigated farmland of 6.3 million ha. Due to the dry climate in vast areas of the northern part and the loess plateau, it has very limited annual precipitation of 466 mm long-term mean. With the development of water resources in the past 50 years, the river flow has changed from natural to highly artificially controlled conditions and water shortage is becoming a serious problem. Many efforts of both research and management have been addressed to improve the river flow conditions. For better management of water resources in the Yellow River basin in the future, it is necessary to review the changes to water resources in the past century and understand this change from the mechanism of the water cycle. Statistical analysis is a useful tool for revealing the changing trend of hydrological quantities, but the processes of the water cycle can be explored in detail by physically-based hydrological modelling. In this paper, river flow and precipitation from 1950 to 2000 were analysed to reveal their changing annual and seasonal trends. A distributed hydrological model was employed to simulate 10 years (1980–1989) of

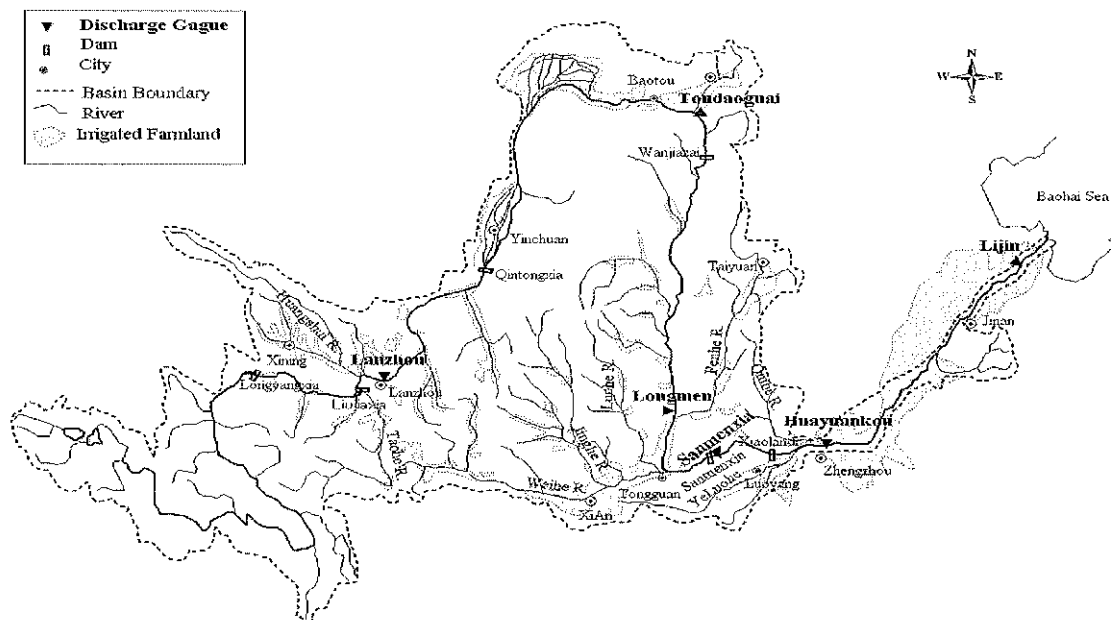


Fig. 1 The Yellow River basin.

the hydrological cycle to examine spatial and temporal characteristics of the water balance components. It is hoped that the results will explain river dry-up along the lower reaches in the last 20 years.

## STATISTICAL ANALYSIS

The Yellow River basin is divided into sections by six hydrological gauges, namely: Lanzhou, Toudaoguai, Longmen, Sanmenxia, Huayuankou and Lijin from the upper to lower reaches along the main river (Fig. 1). The upper basin up to Lanzhou is the Tibet plateau, which is one of the main water source areas. The section between Landzhou and Toudaoguai is the semiarid region. The loess plateau is mainly located between Toudaoguai and Longmen. The section between Longmen and Sanmenxia contains the main tributaries in the middle reaches. The section between Longmen and Huayuankou usually produces floods in the lower reaches during summer. In the last section downstream of the Huayuakou station, the Yellow River becomes the suspended river, there is a very small drainage area and the river dry-ups occurred in this section.

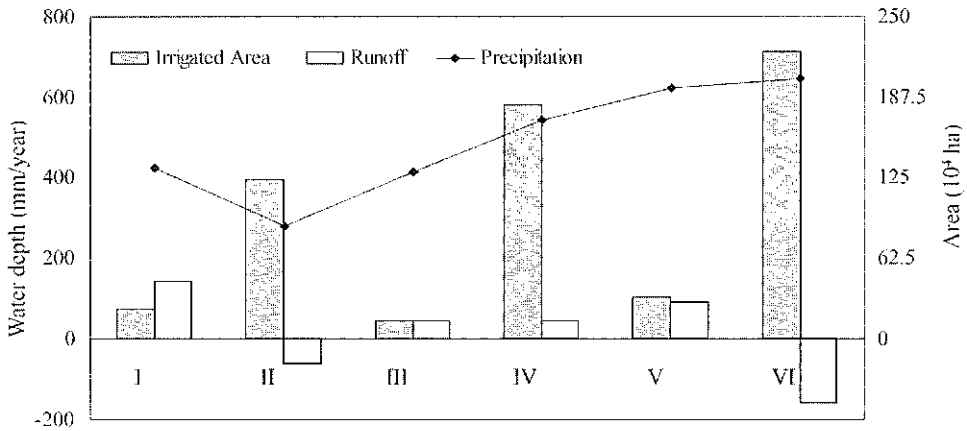
A 50-year monthly discharge data set at the six gauges was collected. A global data set of historical climate of the twentieth century, which contains monthly gridded precipitation at  $0.5^\circ$  spatial resolution developed from surface measurements (New *et al.*, 1999, 2000), was used in this research. Annual and seasonal averages of the 50-year data for discharge and precipitation were calculated and are shown in Table 1. This gives a comparison of the basic hydrological characteristics in different sections from the upper to lower streams. Precipitation increases from west to east, and from north to south. About 60% of annual precipitation is concentrated in 4 months

**Table 1** Annual and seasonal comparison of river discharge at different locations and precipitation in different regions for the 50-years (1951-2000) mean.

Gauge name	Drainage area* (km <sup>2</sup> )	Discharge <sup>†</sup> (mm year <sup>-1</sup> )			Precipitation <sup>‡</sup> (mm year <sup>-1</sup> )		
		Annual	Jul.-Oct.	Nov.-Jun.	Annual	Jul.-Oct.	Nov.-Jun.
Lanzhou	222 551	142.1	76.0	66.2	426.4	268.8	157.6
Toudaoguai	367 898 (145 347)	61.1 (-61.3)	32.7 (-29.0)	28.4 (-32.3)	338.3 (278.6)	214.4 (192.1)	123.9 (86.5)
Longmen	497 752 (129 654)	57.3 (46.7)	31.3 (27.5)	26.0 (19.2)	357.0 (413.8)	230.6 (279.9)	126.4 (133.9)
Sanmenxia	688 421 (190 869)	53.8 (44.7)	30.0 (25.3)	23.8 (18.3)	406.7 (546.4)	260.2 (343.6)	146.5 (202.8)
Huayuankou	730 036 (41 615)	55.9 (90.3)	31.7 (59.9)	24.2 (30.4)	419.3 (631.5)	267.2 (384.6)	152.1 (246.9)
Lijin	751 869 (21 833)	45.8 (-289.7)	28.5 (-78.5)	17.4 (-211.2)	419.3	267.2	152.1

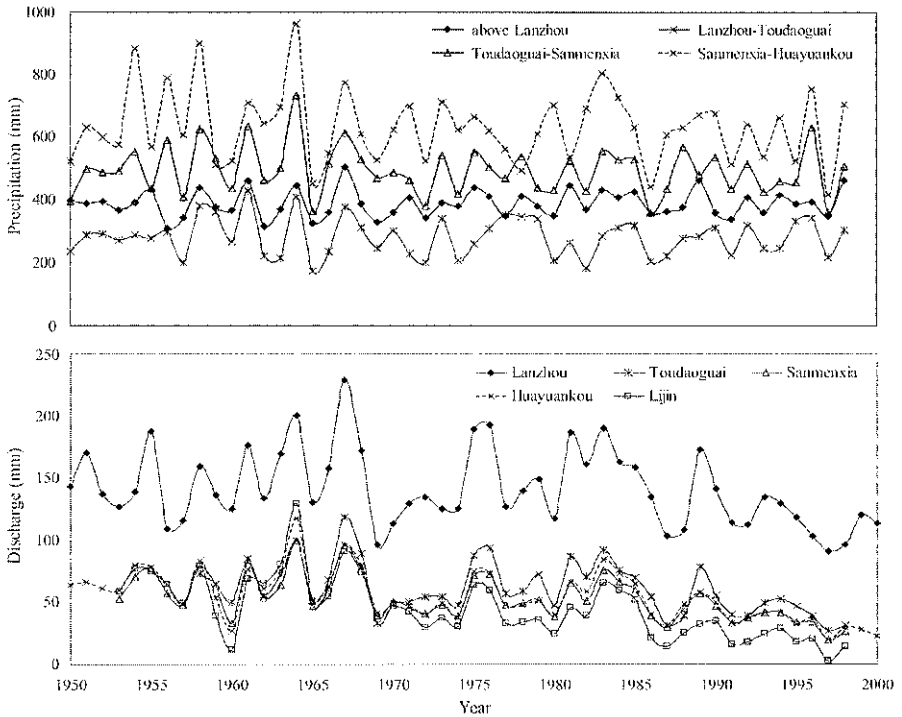
\* This drainage area is calculated for both the whole drainage area up to this gauge point and the area between the upper and this gauge (in the bracket).

†,‡ The same method is used for calculating the drainage area.



**Fig 2** Annual mean discharge and precipitation in different regions of the Yellow River basin. (I: upper basin of the Lanzhou gauge; II: inter-basin between the Lanzhou and Toudaoguai gauges; III: inter-basin between the Toudaoguai and Longmen gauges; IV: inter-basin between the Longmen and Sanmenxia gauges; V: inter-basin between the Sanmenxia and Huayuankou gauges; and VI: inter-basin between the Huayuankou and Lijin gauges. The positive value of runoff is the runoff generated from this inter-basin; the negative value of runoff is the water consumed in this inter-basin.)

from July to October. It is known that the northern part (i.e. the section between Lanzhou and Toudaoguai) has the least precipitation, that is less than 300 mm year<sup>-1</sup>; and the rainy season (July–October) concentration of precipitation is near 70%. The upper basin up to Lanzhou has less artificial water uses. The runoff ratio that was calculated based on the observed discharge is about 37%. Nearly 8% of runoff during the rainy season (July–October) is regulated by reservoirs (mainly Longyangxia and Lujiaxia) and is used for supplying the middle and lower streams in the dry season. The middle reaches from Lanzhou to Huayuankou have two-thirds of the total



**Fig. 3** Annual changes of precipitation in different regions and discharge at different gauges in last 50 years.

drainage areas, but less contributions to the river flow in the lower streams due to the dry climate and heavy agricultural irrigations (Fig. 2).

Figure 3 shows the changes of annual precipitation in different sections and discharge at different locations from 1950 to 2000. For the precipitation no significant trends have been found, but it is clearly seen that the discharges decrease, except those from the Lanzhou gauge. The trend magnitudes for annual discharge and precipitation in past 50 years were estimated by (Burn *et al.*, 2002):

$$\beta = \text{median} \left[ \frac{(x_j - x_i)}{(j - i)} \right] \quad \text{for all } i < j \tag{1}$$

where  $\beta$  is the trend magnitude. A positive value of  $\beta$  indicates an “upward trend”, i.e. increasing values with time, and a negative value of  $\beta$  indicates a “downward trend”, i.e. decreasing with time. In order to detect the significance of the trends for annual and seasonal discharge and precipitation time series, the Mann-Kendall non-parametric test was applied (Zhang *et al.*, 2001; Burn *et al.*, 2002). The estimates of the trends for discharge and precipitation at 5% significance level are given in Table 2. There are decreasing trends of precipitation in most regions. But the trends in the annual totals and the seasonal amounts of precipitation are not significant. Either the annual or seasonal discharges at most locations commonly do have significant decreasing trends. An exception at Lanzhou in the dry season is caused by the reservoir regulations. By

**Table 2** Trend detected for the discharge and precipitation at 5% significance level in the last 50 years ( $\text{mm year}^{-1}$ ).

	Lanzhou		Toudaoguai		Longmen		Sanmenxia		Huayuankou		Lijin ( $Q$ )
	$Q^*$	$P^\dagger$	$Q$	$P$	$Q$	$P$	$Q$	$P$	$Q$	$P$	
Annual	-0.70	(-0.47) <sup>‡</sup>	-0.76	(-0.29)	-0.56	(-0.43)	-0.71	(-0.90)	-0.79	(-1.12)	-1.23
Jul.–Oct.	-0.96	(-0.99)	-0.77	(-0.17)	-0.51	(-0.37)	-0.55	(-0.56)	-0.58	(-0.68)	-0.73
Nov.–Jun.	0.27	(0.52)	(0.01)	(-0.12)	-0.05	(-0.06)	-0.17	(-0.34)	-0.21	(-0.44)	-0.50

\*  $Q$ : discharge;  $P$ : precipitation.

† Values in brackets ( ) are not significant trends.

**Table 3** Decade changes of hydrological parameters in the upper basin up to Lanzhou.

Period	Observed annual discharge (mm)	Annual precipitation (mm)	Annual mean temperature ( $^{\circ}\text{C}$ )	Total irrigated area ( $10^4$ ha)	Annual water intake for irrigation (mm)
1951–1970	150.9	431.5	0.3	12.2	5.2
1971–1990	146.3	427.8	0.4	18.4	7.4
1991–2000	116.3	406.7	0.8	22.3	9.0

checking the decade changes of hydrological parameters in the upper basin up to Lanzhou (see Table 3), it was found that the observed runoff decreased 23% from the 1950s to the 1990s, to which the climate change contributed about 20% of this decrease if the irrigation water intake is considered. In general, the decreasing trends are enhanced from the upper to lower reaches due to an increase of artificial water uses in the lower reaches.

## DISTRIBUTED HYDROLOGICAL MODELLING

### Large-scale hydrological model

This methodology presents a grid-based distributed hydrological model for the large basin using both sub-grid hydrological parameterization and the kinematic wave for flow routing. The topography was simulated using the US Geological Survey HYDRO1k data set. Land use was obtained from the USGS 1-km data set of global land cover characterization. The soil properties were obtained from the FAO global soil data set of 5-min resolution. Based on these available data, this model uses a grid system of 10-km size to develop a distributed hydrological model (Fig. 4).

In the geomorphology-based hydrological model (GBHM) developed by Yang *et al.* (2002), the geomorphological properties of river–hillslope formation were used to represent catchment topography. In a similar way, it is assumed that a grid composes a set of hillslopes located along the rivers. In the macroscale sense, the hillslopes located in a grid are viewed as geometrically similar. The same hillslope model (Fig. 4) in the GBHM (Yang *et al.*, 2002) was used, in which the hillslope parameters were calculated using the HYDRO1k data set. The land uses are reclassified into nine categories from the USGS 1-km land cover data. Because the soil data is about 10-km resolution, there is one dominant soil type in a grid. Finally the hillslopes in a grid were grouped according to the vegetation types. The hillslope is the fundamental unit in the hydrological simulation.

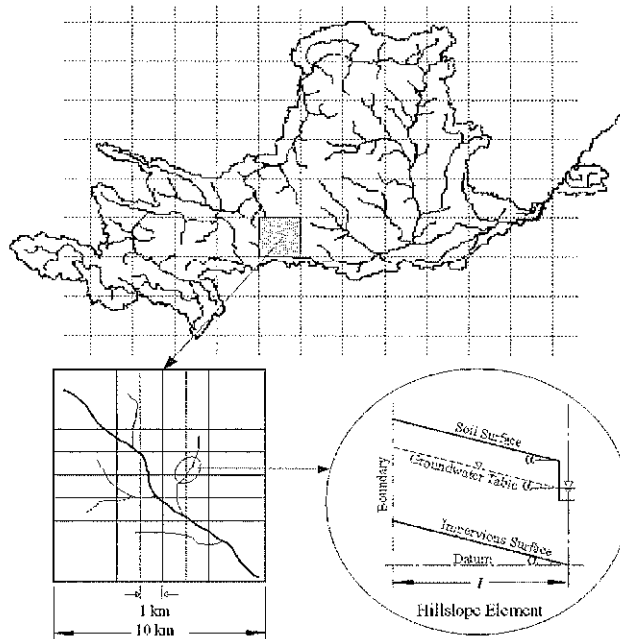


Fig. 4 Concept of the large-scale hydrological model.

A physically-based model is used to simulate hillslope hydrological response, in which the vertical plane was divided into several layers, including canopy, soil surface, unsaturated zone and groundwater aquifer (Yang *et al.*, 2002). A degree-day model is incorporated to simulate snowmelt. The runoff output from one grid is the sum of hillslope responses (both surface and subsurface runoff) within the same grid.

In hydrological modelling practice, it is usually complicated to define the river network in a discrete grid system. Here the Pfafstetter scheme (Yang *et al.*, 2000) was employed to number the river network, which defines the river network as the main rivers and tributaries. The flow sequences among these sub-basins are well defined by the numbering system. Within a derived minimum sub-basin, the river networks are simplified into the main stream on which the simulation of river routing is carried out by the kinematic wave approach. The lateral inflow is the runoff generated from the grids whose locations are given by the flow distances from the outlet.

### Hydrological simulation and results

Based on 15 years (1979–1993) of daily meteorological data, the model was initiated using the data of 1979, i.e. the hydrological status at the end of the simulation of 1979 was used as the initial condition for this application. The 10-year (1980–1989) simulations were carried out in hourly time steps. The monthly hydrographs at Lanzhou and Huayuankou from 1980 to 1989 are shown in Fig. 5(a), in which the river discharge was simulated without considering artificial effects. Figure 5(b) shows the 10-year mean monthly hydrographs. The main differences of the flow peaks between

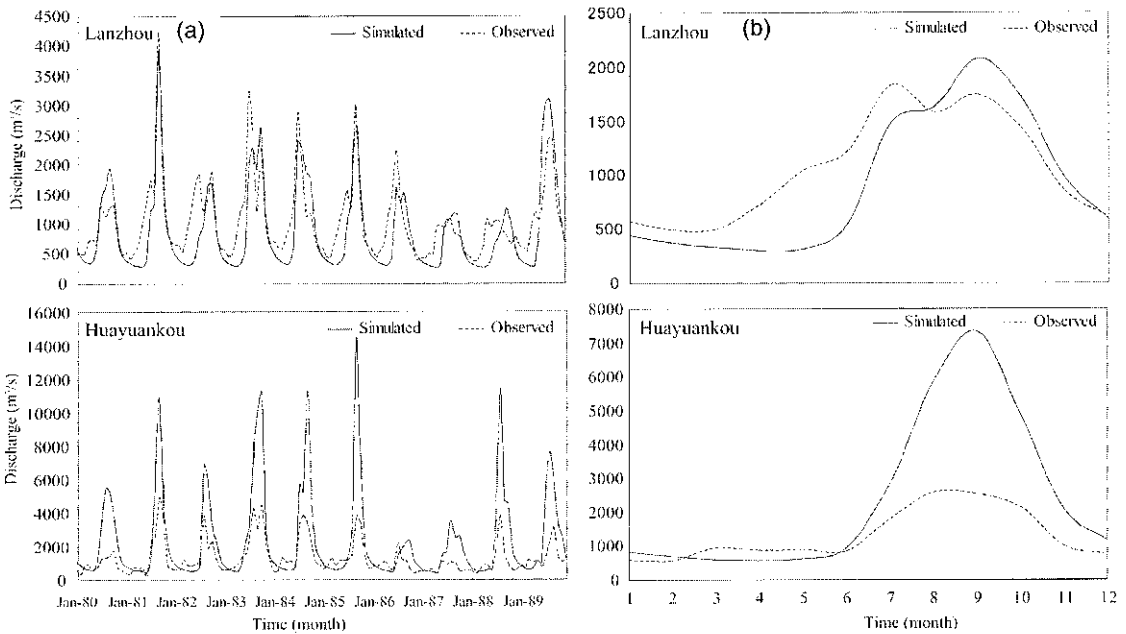


Fig. 5 Simulation results: (a) monthly hydrographs from 1980–1989, (b) the 10-year mean.

Table 4 Historical records of river dry-up during 1979–1989.

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
Days of dry-up	8	36	10	5	0	0	0	17	5	24
Dry-up distance (km)	104	662	278	104	0	0	0	216	150	277

the simulation and observation can be caused by artificial water controls, such as irrigation and reservoirs. The runoff was underestimated in the upper basin up to the Lanzhou station, due to insufficient precipitation data, especially snowfall.

Comparing the simulated and observed annual runoffs in the northern part and middle reaches, more than 70% of annual runoff is consumed artificially for irrigation. Table 4 gives historical records of river dry-up in the lower reaches in the 1980s. Comparing dry-up records with the monthly natural hydrographs in Fig. 5(a), it is known that the days and extents of dry-up in a year is closely related the amount of natural runoff in the previous year. Since there were high natural runoffs during 1983–1985, no dry-up occurred from 1984 to 1986, even though there was very lower natural runoff in 1986. The rivers were never dried-up under natural conditions in the hydrological simulation; river dry-up is caused by artificial water use during the dry season, especially in the spring, and the dry-up situation is adjusted by the reservoir operations.

Besides the river flow, the distributed model also produced the spatial distribution of the hydrological parameters. To show the seasonal changes of soil moisture, the 10-year average values of root zone soil moisture for each season have been calculated. Figure 6 gives the seasonal changes of soil moisture in the root zone. Despite the high

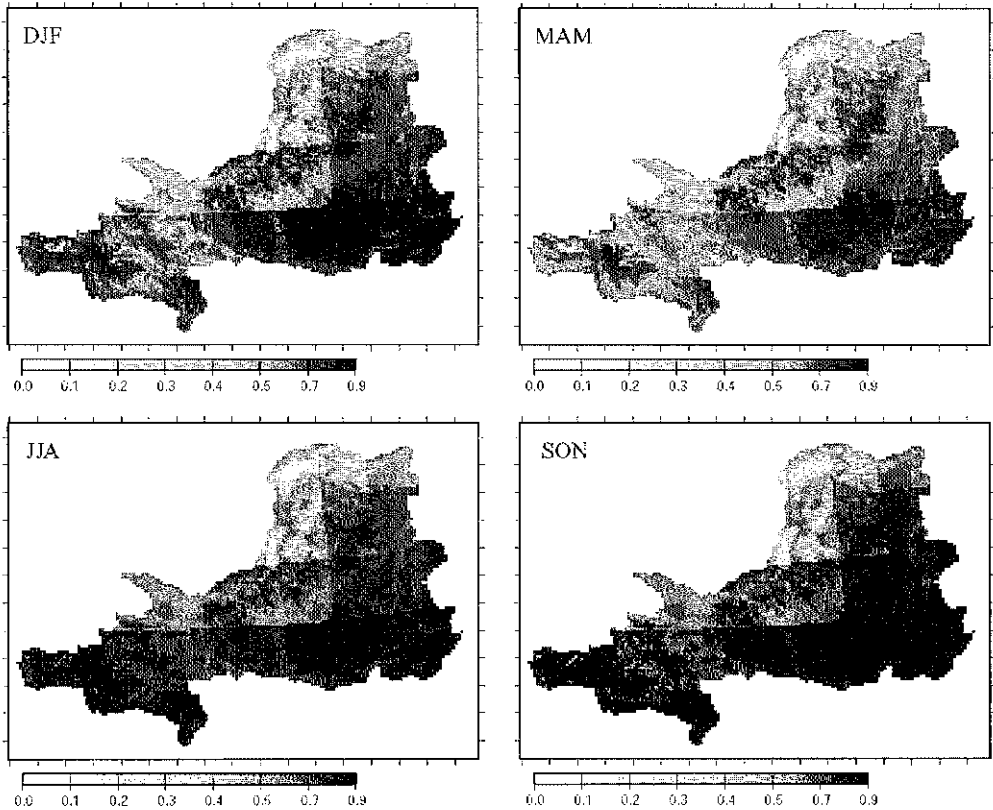


Fig. 6 Seasonal changes of soil moisture of the root zone (10-year mean, in saturation).

heterogeneity of the topography, vegetation and soil, the boundaries of the original climate data of  $2^\circ$  spatial resolution are clearly seen from the results shown in the spatial pattern of root zone soil moisture. This implies that high resolution climate data is necessary for grasping the spatial variability of hydrological characteristics.

## CONCLUSIONS

The statistical analysis has shown a clear decreasing trend for both precipitation and river discharge, but the decreasing trend for precipitation is not significant. In the upper basin up to Lanzhou station, it was found that the observed runoff decreased by 23% from the 1950s to the 1990s, in which the climate change contributed about 20% of this decrease if the irrigation water intake is considered. The middle reaches contribute less than 20% of annual runoff at Huayankou gauge due to large amount of irrigation. The water resources supplying to the lower reaches mainly come from the upper basin above the Lanzhou gauge. A distributed hydrological model has been applied to this basin for investigating the hydrological mechanisms of river dry-up. The hydrological simulation demonstrated that the rivers never dry-up in natural conditions; river dry-up is caused by artificial water uses during the dry season,

especially the spring, and the dry-up situation is adjusted by the reservoir operations. Relatively dry climate conditions in a year may cause river dry-up during the spring in the next year. The river dry-ups along the lower reaches were caused by both climate change and artificial water uses.

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