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Impacts of human activities on the flow regime of the Yangtze River

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Abstract The Yangtze River (Changjiang) is one of the most important rivers in the world, and the alterations in its hydrological regime have global-scale impacts. However, with population increase and economic growth, the flow regime of the Yangtze River has been altered to some extent by human activities, including dam construction, soil and water conservation, etc. The alteration in the flow regime of the Yangtze River will unavoidably influence its morphology and geomorphology, delta evolution and ecosystem health and stability. To assess dam-induced alterations in the flow regime of the Yangtze River quantitatively, this paper selected the Danjiangkou reservoir, the Gezhouba reservoir and the Three Gorges reservoir as case study sites, and the whole study period was divided into 4 sub-periods by the years when these three reservoirs started to store water, respectively. On the basis of the time series of daily flow discharge from six key hydrological stations (i.e. Wanxian, Yichang, Hankou, Datong, Baihe and Xiantao stations), the alterations in annual, seasonal, and monthly runoff in different sub-periods and the driving forces were explored. The output of this paper could provide reference for the assessment of impacts of human activities on the health and stability of the Yangtze River ecosystem.

Key words Danjiangkou reservoir; flow regime; Gezhouba reservoir; hydrological alteration; Three Gorges reservoir; Yangtze River

INTRODUCTION

The Yangtze River (Changjiang) is one of the most important rivers in the world. It is the third longest in length, ninth largest in basin size (Wang & Zhu, 1994), third largest in annual runoff (Xia *et al*., 2006) and fourth largest in sediment load (Eisma, 1998). As an artery river on Earth, it plays a critical role in the global water cycle, sediment cycle, energy balance, climate change and ecological development (Chen, 1995; Hong *et al*., 1997; Shen *et al*., 2000; Xia *et al*., 2006). The alterations in its hydrological regime therefore have global-scale impacts. However, with population increase and economic growth, the flow regime of the Yangtze River has to some extent been altered by human activities, particularly dam construction. According to incomplete statistics, 45 694 reservoirs, with a total storage capacity of 1.586×10^{11} m^3 had been built on the upper main stem and tributaries of the Yangtze River by the end of 2000. Out of these reservoirs, 134 large/medium-scale ones have a total storage capacity of 1.064×10^{11} m^3 (Zhang, 2003). Human-induced alterations in the flow regime of the Yangtze River will unavoidably influence its morphology and geomorphology, delta

evolution and ecosystem health and stability. Recently, the study of human impacts on river hydrological regimes, as an important topic associated with the world water cycle, the world sediment cycle, and land–ocean interaction, has been attracting worldwide attention, particularly in large river basins, even more so where human-induced alterations in river hydrological regimes are increasingly becoming crucial with the intensive and extensive development of their water and hydropower resources. The investigation and assessment of human-induced impacts on river flow regimes could provide a vital basis for river management and restoration. This is also the aim of the present study, with the Yangtze River in China as a study case. On the basis of the past several decades of daily flow discharge data collected from the Changjiang River Water Resources Commission, an attempt focusing on the middle and lower reaches of the Yangtze River, was made to quantitatively evaluate the spatio–temporal variations in runoff. This paper also investigates in detail the driving forces of flow regime alterations.

CASE STUDY SITES

With intensified human activities, in particular a large number of dams/reservoirs having been constructed on the Yangtze River, the flow regime has been altered to some extent. The focus of this paper is on the impacts on the flow regime of the Yangtze River of the Danjiangkou reservoir, the Gezhouba reservoir and the Three Gorges reservoir (Fig. 1). The Danjiangkou reservoir, the second largest in terms of storage capacity in the Yangtze River basin, was built in 1967. It has a capacity of $1.745 \times 10^{10} m^3$ and is located on the biggest tributary of the Yangtze River—the Hanjiang River. The Three Gorges reservoir, with a capacity of $3.93 \times 10^{10}\ m^3$, is the largest in storage capacity in the Yangtze River basin, located on the main stem of the Yangtze River, 44 km above the end point of the upper reach of the Yangtze River. The Gezhouba reservoir, with a capacity of $1.58 \times 10^9 m^3$, is a run-of-river reservoir and located on the main stem of the Yangtze River, 38 km below the Three Gorges reservoir. To assess the impacts of these three reservoirs on the flow regime of the Yangtze River, six key hydrological stations, i.e. the Wanxian, the Yichang, the Hankou, the Datong, the Baihe and the Xiantao were selected (Fig. 1). Wanxian station is located in the upper reach of the Yangtze River, 277 km above the Three Gorges reservoir. Yichang station is the controlling point of the upper Yangtze River basin and located at the starting point of the middle reach of the Yangtze River, 44 km below the Three Gorges dam and 6 km below the Gezhouba Dam. Hankou station is on the middle reach of the Yangtze River, located 1.15 km below the confluence of the Yangtze River and the Hanjiang River. Datong station located at the tidal limit of the Yangtze River is the controlling station for the measurements of water and sediment discharges from the Yangtze River to the East Sea. Baihe station, above the Danjiangkou reservoir, is the upper controlling station for water and sediment discharges to the Danjiangkou reservoir. Xiantao, below the Danjiangkou, is the most downstream station on the Hanjiang River, and controls water and sediment discharges to the main stem of the Yangtze River from the Hanjiang River.

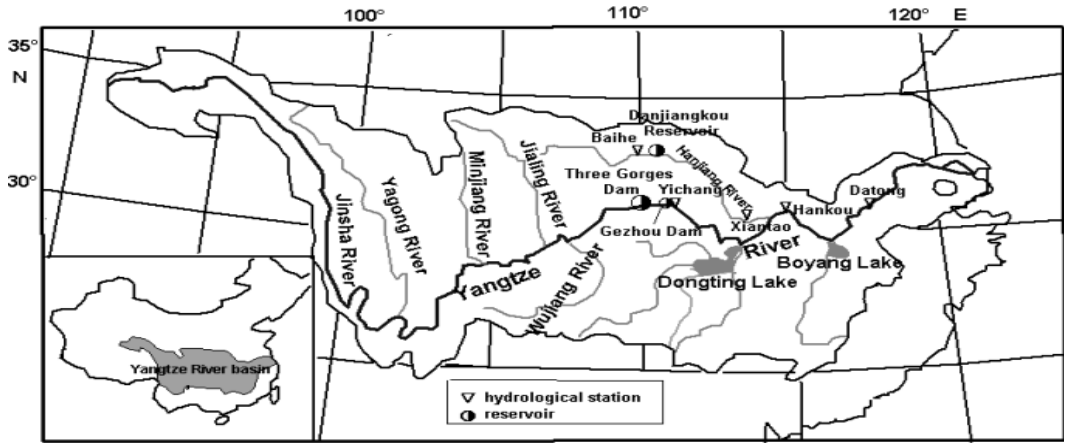

Fig. 1 Location map of hydrological stations and reservoirs.

Table 1 Length of data records and division of study periods.

Hydrological station	Sub–periods				
	I	II	III		IV
Yichang	1955–1966	1967–1980	1981–1986	1981–2002	2003–2004
Hankou	1955–1966	1967–1980	1981–1986	1981–2002	2003–2004
Datong	1955–1966	1967–1980	1981–1986	1981–2002	2003–2004
Wanxian		1967–1980	1981–1986		2003–2004
Baihe	1955–1966	1967–1980	1981–1986		
Xiantao	1955–1966	1967–1980	1981–1986		

Note: Due to difficulties in data collection for the period 1987–2002 at Wanxian, Baihe and Xiantao, the third sub-period was divided into two periods; daily sediment concentration data at Wanxian in 2001 and at Yichang in 2005 were also collected.

DATA AND METHODS

The time series of daily flow discharge for six key hydrological stations were collected from the Yangtze River Water Resources Commission. Due to difficulties in data collection, the length of data records for six stations is different (see Table 1). On the consideration that the Danjiangkou reservoir, the Gezhouba Reservoir and the Three Gorges reservoir may impose impacts on the flow regime of the middle and lower reaches of the Yangtze River to different extents, respectively, the whole study period was divided into four sub-periods by the years when these three reservoirs started to store water, respectively (Table 1). On the basis of time series of daily flow discharge from six stations, annual, wet season (May–October), dry season (November–April) runoff at the six stations and monthly runoff at Yichang and Xiantao in different sub-periods were computed and analysed.

RESULTS

The variations with time of annual, wet season and dry season runoff at six stations were presented in Figs 2–4. The mean annual values of annual, wet season and dry

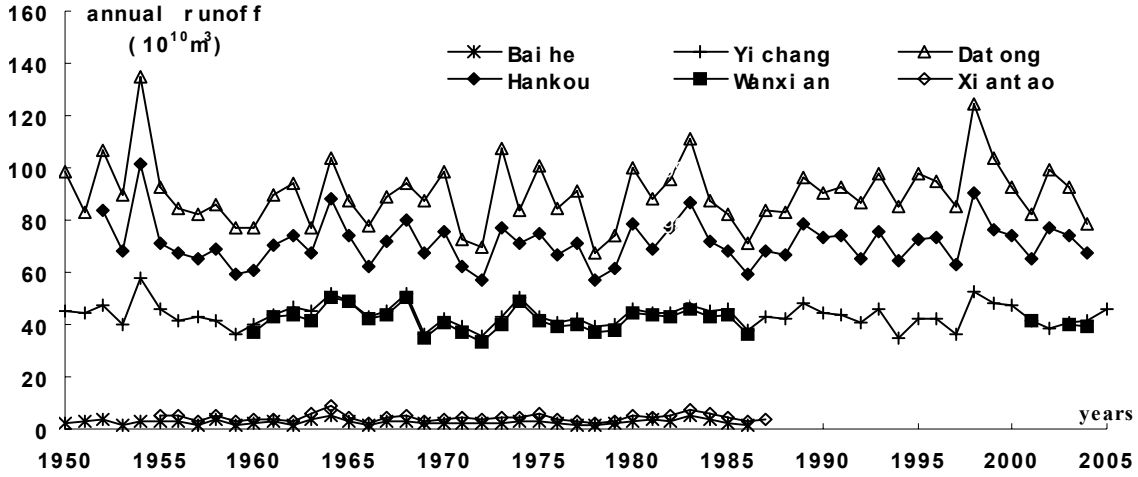

Fig. 2 Variations of annual runoff at six hydrological stations.

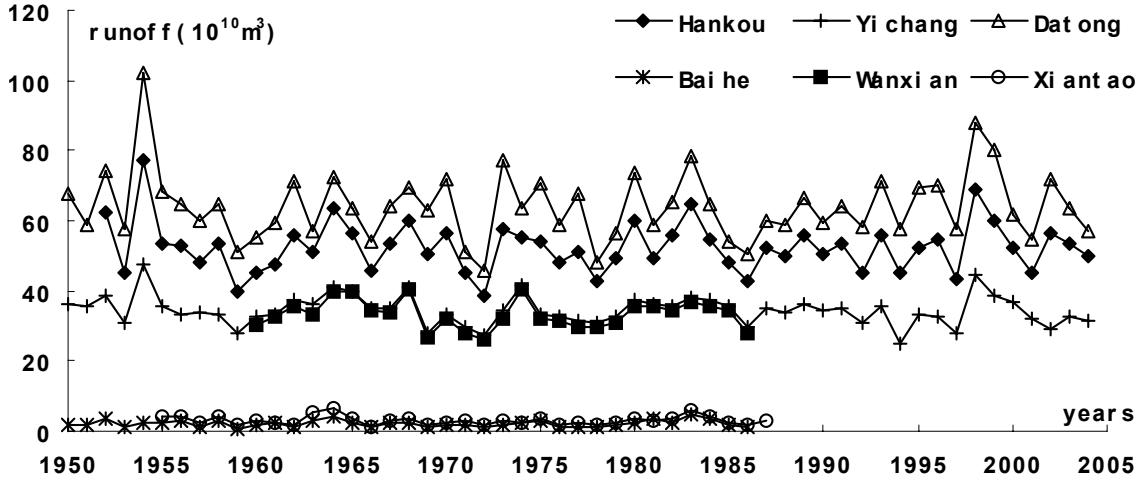

Fig. 3 Variations of wet season runoff at six hydrological stations.

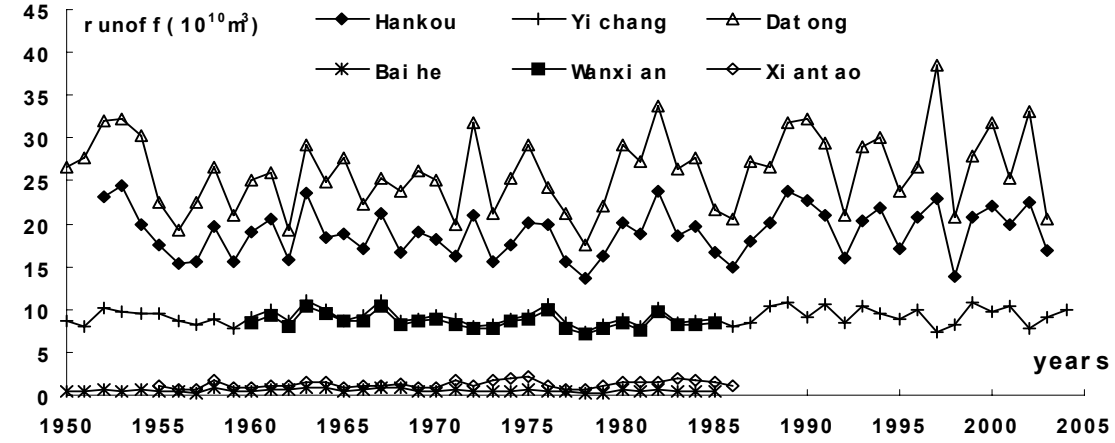

Fig. 4 Variations of dry season runoff at six hydrological stations.

season runoff, and percentage of wet season runoff in annual runoff at six stations in different sub-periods were computed and presented in Table 2. Figures 5–7 showed the monthly runoff distributions at Baihe, Huangzhuang, Xiantao, Wanxian and Yichang during pre-dam and post-dam periods.

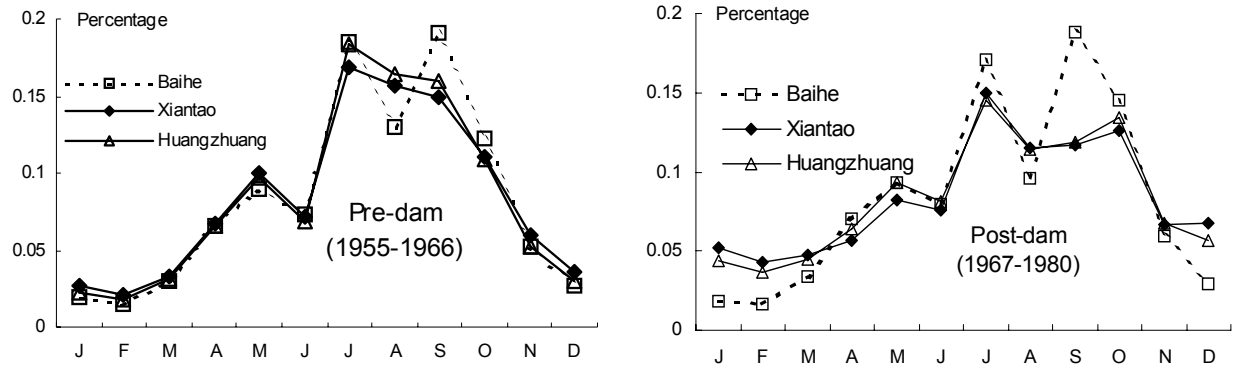

Fig. 5 Impacts of the Danjiangkou on monthly runoff distribution.

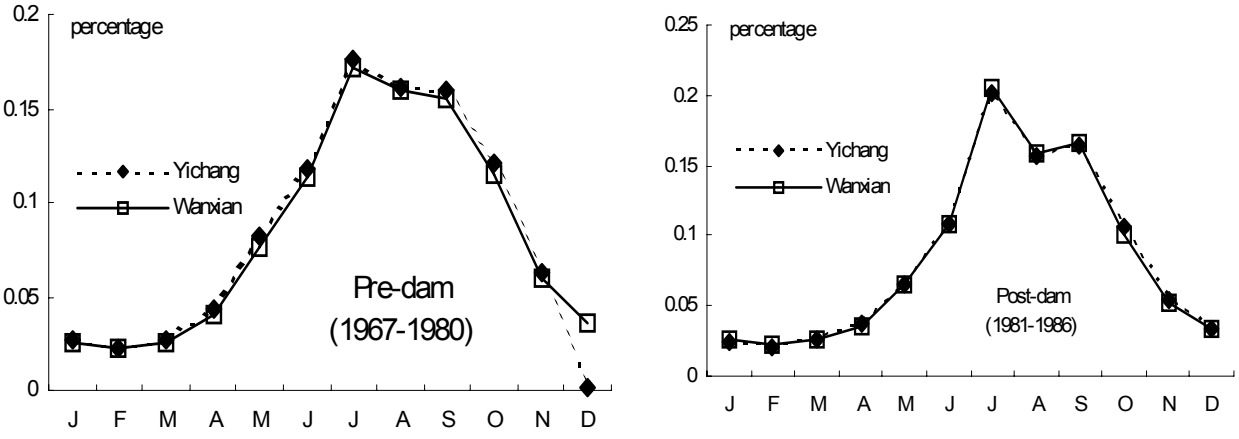

Fig. 6 Impacts of the Gezhouba on monthly runoff distribution.

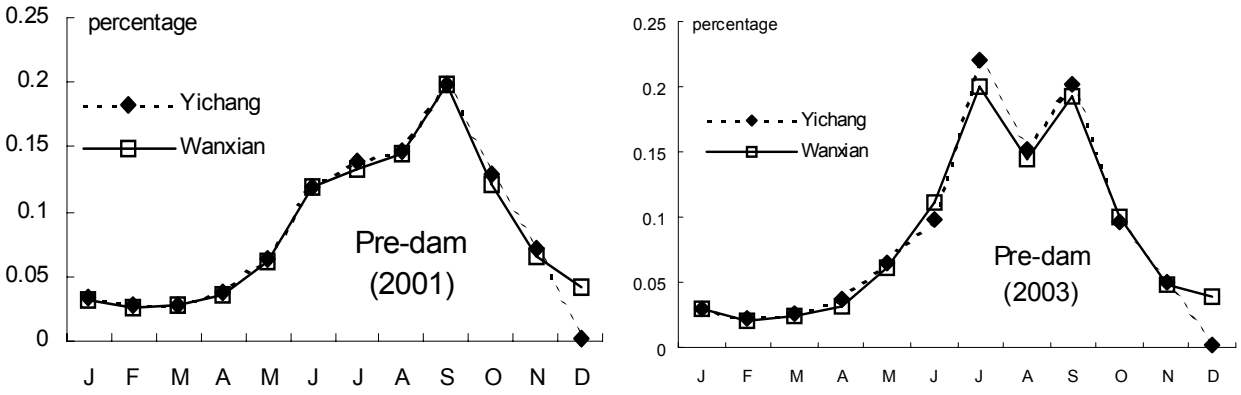

Fig. 7 Impacts of the Three Gorges on monthly runoff distribution.

DISCUSSION

Annual runoff

Variations in annual runoff of the Yangtze River main stem From Fig. 2 it can be seen that annual runoff at Wanxian, Yichang, Hankou and Datong showed similar variation patterns with the runoff in the upper reach being less than that in the middle and lower reaches in the same year. This means that annual runoff downstream is closely associated with that upstream, and that the runoffs from the middle and lower Yangtze River basins are important components in the total runoffs at Hankou and Datong, respectively. It has been recognized that mean annual runoff at Yichang accounts for about three fifths of that at Hankou, and about half at Datong. The fluctuations of annual runoff at the four stations corresponded well, but the degree of fluctuation of annual runoff varied with length. The fluctuation of annual runoff was fiercest at Datong and least at Yichang. This reveals that the interannual variation of runoff generated from the lower Yangtze River basin was more significant than that in the upper Yangtze River. This indicates that the interannual variation in rainfall in the lower Yangtze River basin was more serious in the past decades. In spite of a large number of reservoirs/dams having been constructed with time, the annual runoffs at the four stations did not show signs of having been affected by dam construction in the past decades as annual sediment loads did. This is because these reservoirs are seasonal-storage reservoirs.

Variations in annual runoff of the Hanjiang River From Table 2 it can be found that the ratios of mean annual runoffs at Baihe and Xiantao during the periods of 1955–1966 and 1967–1980 are almost equal. This means that the operation of the Danjiangkou reservoir did not influence annual runoff at Xiantao. No changes in the ratios of mean annual runoffs at Wanxian and Yichang during the periods of 1967–1980, 1981–1986 and 2003–2004 (Table 2) demonstrated that the operation of the Gezhouba and the Three Gorges did not affect annual runoff at Yichang. Since the Three Gorges reservoir and the Danjiangkou reservoir are seasonal-storage reservoirs in terms of mean annual runoff, and the Gezhouba is a run-of-river reservoir, their storage capacities are not big enough to regulate the interannual distribution of runoff downstream.

Seasonal runoff

Influences of the Gezhouba reservoir During 1967–1980 the mean annual percentage of wet season runoff in annual runoff at Yichang was 78.9%, a little bit lower than 79.1% at Wanxian, and these percentages at Yichang and Wanxian rose to 80.2% and 80.4%, respectively, during 1981–1986 (see Table 2), but the percentage at Yichang was still a little bit lower than that at Wanxian. According to the t-test for a confidence level of 95%, the Gezhouba had little influence on seasonal runoff distribution downstream. Figures 3 and 4 also verified this conclusion. The Gezhouba was not actually designated for flood detention.

Influences of the Three Gorges reservoir The percentage of wet season runoff at Wanxian and Yichang (Table 2) in 2003–2004 revealed that the Three Gorges

Table 2 Mean annual values at six hydrological stations in different sub-periods.

Station	Periods	Runoff ($10^{11}m^3$)			Percentage of wet seasonal runoff in annual runoff (%)
		Wet season	Dry season	Annual	
Yichang	1955–1966	3.494	0.914	4.405	79.3
	1967–1980	3.348	0.890	4.242	78.9
	1981–1986	3.550	0.865	4.425	80.2
	1981–2002	3.426	0.922	4.348	78.8
	2003–2004	3.226	0.915	4.119	78.3
Wanxian	1969–1980	3.210	0.846	4.060	79.1
	1981–1986	3.426	0.840	4.260	80.4
	2003–2004	3.114	0.840	3.954	78.8
Hankou	1955–1966	5.110	1.807	6.913	73.9
	1967–1980	5.162	1.793	6.941	74.4
	1981–1986	5.253	1.876	7.196	73.0
	1981–2002	5.254	1.981	7.227	72.7
	2003–2004	5.165	1.680	7.077	73.0
Baihe	1955–1966	0.214	0.058	0.270	79.1
	1967–1980	0.181	0.052	0.235	77.3
	1981–1986	0.273	0.050	0.324	84.4
Xiantao	1955–1966	0.326	0.109	0.445	73.3
	1967–1980	0.264	0.127	0.392	67.4
	1981–1987	0.348	0.153	0.508	68.4
Datong	1955–1966	6.185	2.384	8.581	72.1
	1967–1980	6.301	2.442	8.718	72.3
	1981–1986	6.197	2.622	8.856	70.0
	1981–2002	6.466	2.785	9.241	70.0
	2003–2004	6.035	2.060	8.562	70.5

reservoir had a minor effect on seasonal runoff distribution at Yichang. The first 10-day (1–10 June, 2003) filling up of the reservoir and the operation mode of "storing clear water and releasing turbid water" adopted by the Three Gorges had an obvious influence on runoff percentage at Yichang in June to September of 2003 and unobvious impacts on runoff percentage at Yichang in other months of 2003 (see Fig. 7). Therefore, the impacts of the Three Gorges on the seasonal runoff distribution at Yichang were generally very limited.

Influences of the Danjiangkou reservoir Before 1967 wet season runoff at Xiantao was generally higher than that at Baihe in the same year (Fig. 3), even more so in wet years,. But from 1967 the difference between wet season runoff at Xiantao and that at Baihe in wet years significantly reduced (Fig. 3). Dry season runoff at Xiantao presented a different changing pattern (see Fig. 4). Before 1967 dry season runoff at Xiantao and Baihe showed similar variation pattern, and the difference between dry seasonal runoff at Xiantao and that at Baihe was small and stable, but from 1967 the difference between dry season runoff at Xiantao and that at Baihe enlarged, particularly in wet years. This indicates that the operation mode of "retaining high floods in wet seasons" adopted by the Danjiangkou apparently affected the seasonal runoff distribution downstream by making the seasonal distribution even more. The percentage of wet season runoff in the annual runoff at Xiantao and Baihe during the same periods (see Table 2) also proved this variation pattern. Before 1967 the

percentage of wet season runoff at Baihe was 79.1%, 1.8% higher than 77.3% at Baihe during 1967–1980, but the percentage of wet season runoff at Xiantao before 1967 was 73.3%, 5.9% higher than 67.4% at Xiantao during 1967–1980. This reflects that the operation of the Danjiangkou resulted in a reduction in the percentage of wet season runoff and an increase in the percentage of dry season runoff downstream.

Conjunctive influences of reservoirs on seasonal runoff at Hankou The percentage of wet season runoff at Hankou in the period 1967–1980 increased, although the percentage of wet seasonal runoff at both Xiantao and Yichang reduced. This is because the Yichang-Hankou sub-basin experienced some wet years in the 1970s, while the upper Yangtze River basin experienced dry years in the period 1967–1978 (Li *et al*., 2004). Thus it can be concluded that the high runoff that occurred in the Yichang-Hankou sub-basin could change the seasonal runoff distribution at Hankou. Compared with the percentage of wet season runoff in 1967–1980, this value at Hankou during 1981–2002 decreased due to flood attenuation by the Danjiangkou, although there was almost no change in the percentage of wet season runoff at Yichang. This demonstrates that the operation of the Danjiangkou could also influence the seasonal runoff distribution at Hankou, but less than at Xiantao, due to Hankou being far away from the Danjiangkou and more than half of the runoff at Hankou coming from Yichang (see Table 2). As the Gezhouba had no effect on seasonal runoff distribution at Yichang, it had also little influence on seasonal runoff distribution at Hankou. During 2003–2004, the percentage of wet season runoff at Hankou did not show the same changing pattern as Yichang did because of the occurrence of high floods in the Yichang-Hankou sub-basin. The operation of the Three Gorges had a much less significant impact on seasonal runoff distribution at Hankou than at Yichang due to the regulation of the Yichang-Hankou sub-basin for river runoff.

Conjunctive influences of reservoirs on seasonal runoff at Datong Since the Datong is far away from the Danjiangkou and the Three Gorges, and the Hankou-Datong sub-basin acted as a regulator for the river runoff, the operation of these two reservoirs produced much less influence on the seasonal runoff distribution at Datong than at Hankou. Similar to Hankou, the Gezhouba has little influence on seasonal runoff distribution at Datong. From Table 2 it can be concluded that the percentage of wet seasonal runoff at Datong presented the same variation pattern as at Hankou in all sub-periods, but seasonal runoff distribution was more even at Datong than at Hankou.

Monthly runoff

This paper only analysed the impacts of the Danjiangkou, the Gezhouba and the Three Gorges on monthly runoff distribution at Xiantao, Huangzhuang (on the Hanjiang River and located in the middle of the Danjiangkou dam and Xiantao) and Yichang.

Influences of the Danjiangkou reservoir From Fig. 5 it can be seen that the Danjiangkou imposed a significant influence on monthly runoff distribution at Huangzhuang and Xiantao. The percentage of monthly runoff in the months of the wet season at both stations clearly decreased due to the retention of high floods by the reservoir in the wet season and the percentage in the months of dry season evidently increased. This indicates that the operation of the Danjiangkou made monthly runoff

distribution downstream more even. Compared with Xiantao, Huangzhuang was affected more seriously owing to Huangzhuang being closer to the Danjiangkou than Xiantao (see Fig. 5).

Influences of the Gezhouba reservoir From Fig. 6 it can be concluded that the Gezhouba had little influence on monthly runoff distribution downstream due to the Gezhouba reservoir having relatively small storage capacity.

Influences of the Three Gorges reservoir Figure 7 disclosed that the first filling up of the reservoir made the runoff percentage at Yichang in June 2003 reduce and that the operation mode of "storing clear water and releasing turbid water" by the Three Gorges caused an increase in runoff percentage at Yichang during July to September 2003, but the magnitudes in reduction and increase are very limited. This indicates that the effect of the Three Gorges on monthly runoff distribution at Yichang is limited.

It should be noted that the impact of the Three Gorges on seasonal and monthly runoff distribution in the downstream of the reservoir can be expected to increase after 2009 when it is completed.

CONCLUSIONS

This paper evaluated the impacts of human activities, in particular reservoir construction, on the flow regime of the Yangtze River. The results revealed:

- the impacts of reservoirs on river flow regime varied with reservoir regulation capacity, reservoir operation pattern and the distance between target reservoir and study site;
- the operation of the Gezhouba has little influence on annual, seasonal and monthly runoff downstream;
- the Three Gorges had little influence on annual runoff downstream, but limited effect on seasonal and monthly runoff distribution downstream due to the filling up of the reservoir and the operation mode of "storing clear water and releasing turbid water" being implemented;
- the operation mode of "retaining high floods in wet seasons" having been implemented by the Danjiangkou did not affect annual runoff downstream, but led to more even seasonal and monthly runoff distribution downstream;
- seasonal and monthly runoff distribution at Hankou and Datong was not only affected by reservoir operation upstream, but also by the runoff generated from the sub-basin between the Yichang and the Datong. This sub-basin acted as a regulator for the river runoff although the runoff from Yichang is an important component of the runoff at Hankou and Datong.

The output of this paper could be a reference for water resources managers in reservoir operation.

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