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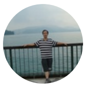
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Assessment of extreme drought and human interference on baseflow of the Yangtze River

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Abstract:

Attention has been given to baseflow in large rivers, but up to now, no study on baseflow for the Yangtze River in combination with extreme drought and extensive human activities has been carried out. Discharge data in 2000–2005 and in the extreme drought years, 1978 and 2006, at stations along the main stream, lakes and distributaries of the Yangtze River were collected to analyse the features of baseflow in 2006 by using baseflow separation technique, HYSEP. It can be seen that the baseflow relative to the streamflow in 2006 was greater than those in other years. The variation of baseflow discharge in the Upper Yangtze River Stream (UYRS) was larger than that in the Mid-Lower Yangtze River Stream (MLYRS). Human activities in MLYRS are more intensive than that in the UYRS and the baseflow discharge was greater. The baseflow is influenced by the extreme climate and human activities along the Yangtze River with the former being the dominant factor in 2006. The contribution of human interference to baseflow discharge was about 10% in 2006.

KEY WORDS baseflow; the Yangtze River; extreme drought; human interference

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INTRODUCTION

Groundwater discharge is the major contributor to stream flow in most rivers not only in rainless periods but also during flood events (Wittenberg, 2003). Knowledge of the magnitude and frequency of groundwater discharge to river flow in different events, e.g. the extreme drought, is important to plan water-supply systems, waste-water discharge, reservoirs and irrigation systems, and to maintain the quality of water for wildlife and recreation (Birtles, 1978; Smakhtin, 2001; Reilly and Kroll, 2003). However, it is nearly impossible to measure groundwater discharge directly. A common way to identify the groundwater infiltrations to stream is linked to the baseflow, which is defined as the net flow from groundwater storage to a stream (Singh, 1968). Baseflow has been used as an approximation of groundwater discharge and play an important role in water resources management (Szilagyi *et al*., 2003; Tung *et al*., 2004). Many investigations on baseflow characteristics, such as baseflow estimation (Singh, 1968; Reilly and Kroll, 2003), baseflow prediction (Tung *et al*., 2004), and impacted factors on the baseflow (Wittenberg, 2003; Kirk *et al*., 2008), have been used in some rivers. The changes of baseflow in response to human activities and climate changes have also been studied (Cooper *et al*., 1995; Wittenberg, 2003; Kirk *et al*., 2008). However, with an increasing tendency for extreme events, i.e. low runoff in drought years, floods during intense rainfall and the warming climate (IPCC, 2001; Romanovicz, 2007), little work has been done on baseflow responses to the extreme drought events, especially to the combination of an extreme drought event and impoundment of the Three Gorges Reservoir (TGR) in the Yangtze River.

The Yangtze River is the largest river in China with a length of 6 300 km, and catchment area of $1{\cdot}8 \times 10^6$ km^2. It can be divided into two parts at Yichang, the Upper Yangtze River Stream (UYRS, upstream of Yichang), and the Mid-Lower Yangtze River Stream (MLYRS, downstream of Yichang). The geomorphology of the Yangtze River basin is characterized by mountains and hills in UYRS area and by extensive fluvial plains with numerous lakes in MLYRS area (Chen *et al*., 2001, 2007). The annual discharge of the Yangtze River into the estuary was rather plentiful with about $0{\cdot}9 \times 10^{12}$ m^3 before 1980s. However, a significant decreasing trend of discharge into the estuary was reported from 1985 to 2004 (Yang *et al*., 2005). In 2006, the annual discharge at Datong, which is the tidal limit of the Yangtze Estuary, was the second lowest in history, with increasing problems related to water resource shortage, water allocation, irrigation and saltwater intrusion in 2006 than in other years (Jia, 2006). It is interesting that in 2006, extreme low discharge coincided with the extreme drought and high human activities, i.e. the second storage phase in the TGR with water level increasing from 135 to 156 m. The discharge in 2006 presented distinct characteristics as 'no flood in the flood season' and 'no drought in dry season' in MLYRS reported by our previous paper

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(Dai *et al.*, 2008). Although these obvious characteristics of the discharge of the Yangtze River in 2006 resulted from the allocation of the TGR in dry season and the supply of the lakes (Dai *et al.*, 2008), groundwater discharge into the stream may be also one of the important factors. However, the function of groundwater discharge to the Yangtze River in an extreme drought year has not been reported yet. Thus, the purposes of this paper are (1) to bring forward the characteristics of the baseflow in 2006-extreme drought year; (2) to discern the factors impacting on the baseflow and (3) to estimate the contribution of the groundwater discharge to the Yangtze River response to extreme drought and human interference.

MATERIALS AND METHODS

Data collection

Daily measured discharges at stations along the Yangtze River were collected from the Yangtze River Water Conservancy Committee, Ministry of Water Conservancy of China. Temperature and precipitation data were received from the Weather Information Centre, Weather Bureau of China. It can be found from Figure 1 that the stations, Pingshan, Cuntan, Yichang, Luoshan, Hankou and Datong, are on the Yangtze River. Beibei, Wulong, Gebaozhou and Huangzhuang are on the branches, Jialingjiang, Wujiang, Qingjiang and Hanjiang, respectively, of the Yangtze River. And the Chenglingji and Hukou stations gauge the discharge from the Dongting Lake and the Poyang Lake into the Yangtze River. The daily discharge at all stations was available from 2000 to 2006 except at Gebaozhou with data from 2001 to 2006. In addition, the daily discharge in the extreme drought year, 1978, was collected at Yichang, Hankou and Datong. The daily discharge at Cuntan, which is the upstream limit of the TGR, 620 km upstream, represents the upstream discharge into the TGR. Discharge at Yichang, about 40 km downstream from the TGR, represents the discharge from the TGR. Hankou, 660 km downstream from Yichang, controls the discharge in the middle reach of the Yangtze River. The daily discharge at Datong represents the discharge into the estuary.

Methods

Groundwater discharge processes are complex and difficult to quantify, especially under the combined impacts of extreme drought and human activities. To distinguish groundwater discharge from the surface flow, hydrograph analysis has been carried out (Appleby, 1970; Birtles, 1978; Uhlenbrook *et al.*, 2002; Reilly and Kroll, 2003). Hydrograph analysis is an established technique to evaluate groundwater resources and separate streamflow into baseflow and surface runoff, so as to estimate the contribution of the groundwater discharge to streamflow (Birtles, 1978; White and Sloto, 1990; Sloto, 1991; Uhlenbrook *et al.*, 2002; Fenicia *et al.*, 2006; Aksoy *et al.*, 2008). There are two common hydrograph separation methods which include base-flow-recession methods (Olmsted and Hely, 1962; Rorabaugh, 1963) and curve-fitting methods (Pettyjohn and Henning, 1979; Linsley *et al.*, 1983). These traditional hydrograph separation methods should be done manually. However, with the computer hydrograph separation methods comparable to the manual separation (Sloto, 1991), the estimation of baseflow with computer methods has been widely used (Mazvimavi *et al.*, 2004; Corzo and Solomatine, 2007). Computer codes of the hydrograph separation methods are available online such as the iSep (Lim, 2007), WHAT (Lim *et al.*, 2005) and HYSEP (Sloto and Crouse, 1996). The program of HYSEP developed by the United States Geological Survey consists of three methods, which are streamflow hydrograph-fixed

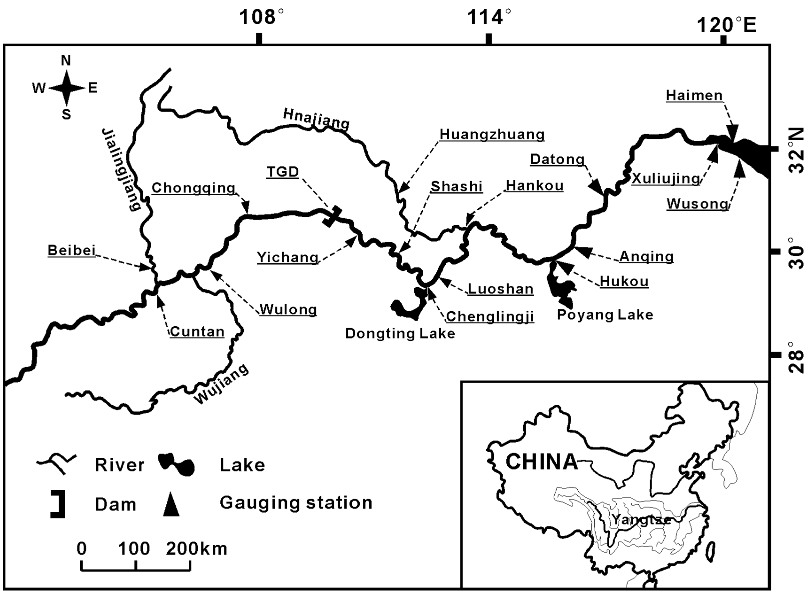

Figure 1. Study area and hydrological gauging stations

interval, sliding interval and local minimum, to separate the baseflow and surface runoff components (Sloto and Crouse, 1996). The local minimum method is used in this study. In this method the lowest points on the hydrograph are connected which provides an estimate of the daily baseflow discharge between local minima by linear interpolation (Sloto and Crouse, 1996). In addition, statistical analysis on the baseflow obtained by HYSEP and streamflow in 2006, in normal years and in the extreme drought year, 1978, was applied to study the characteristics of baseflow in the Yangtze River. The streamflow and baseflow discharge parameters of average (M), standard deviation (SD) and coefficient of variation (Cv) were calculated by moment method (Greenwood *et al.*, 1979).

RESULTS

The baseflow in 2006

The local minimum method was applied to separate baseflow from streamflow. Figure 2 shows the baseflow at stations along the Yangtze River in 2006. The mean monthly baseflow was also computed as shown in Figure 3. The statistical parameters of streamflow and baseflow in different years were calculated by the moment method. The results are shown in Table I. From Table I and Figure 3, it can be seen that the variation of streamflow in MLYRS in 2006 was smaller than in a normal year and in the extreme drought year, 1978. According to Table II, R2, the ratio of baseflows between in 2006 and in other years, is larger than R1, the ratio

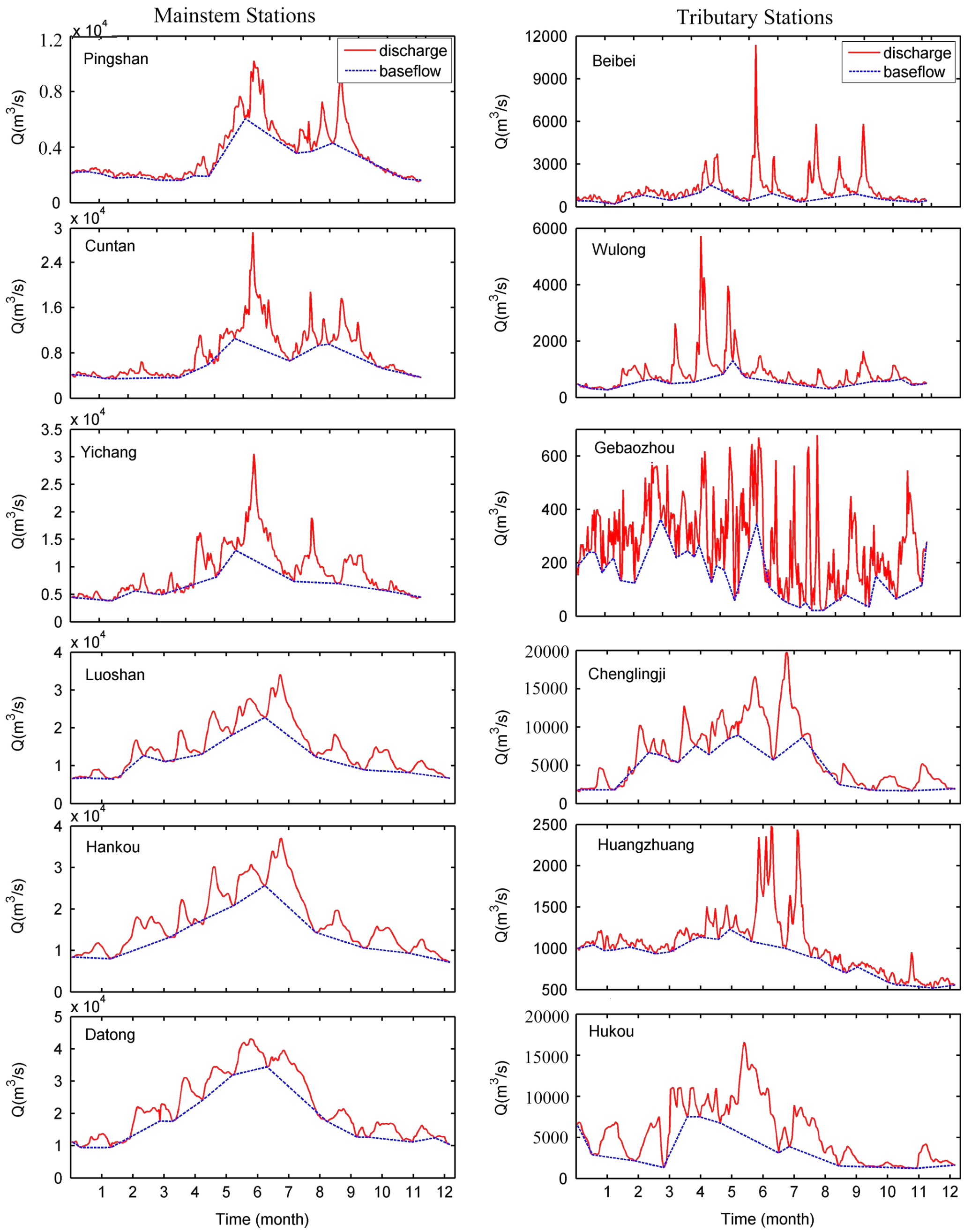

Figure 2. Separation of baseflow from streamflow at stations in 2006

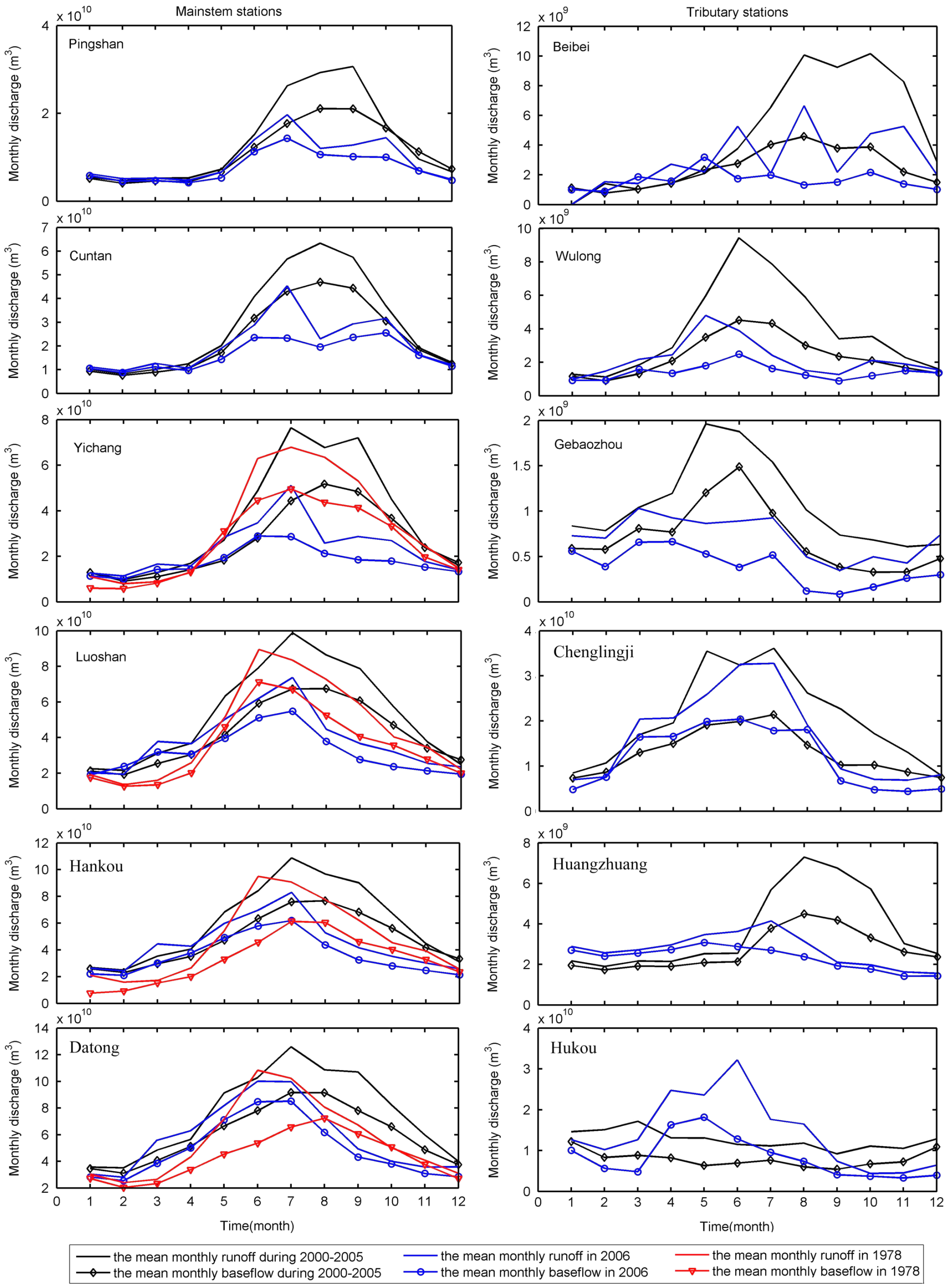

Figure 3. The mean monthly baseflow and streamflow at gauging stations

of streamflows between in 2006 and in other years. In other word, the baseflow in 2006 was relatively more plentiful than that in normal years. The baseflows at stations in MLYRS in 2006 were much larger than those in extreme drought year, 1978. It can be further found from Table I that the SD and Cv of the baseflow in MLYRS are comparable to those in other years. On the other hand, the characteristics of baseflow in UYRS (Pingshan, Cuntan and Yichang) in 2006 follow the same trend of the streamflow changes in normal years.

Baseflow in flood season

The amount of the streamflow in the Yangtze River in 2006 was found to be the lowest in the last 50 years, except in the extreme drought year, 1978. However, the amount of the baseflow in the Yangtze River in the flood season in 2006 was over 75% of the streamflow, and the percentage of baseflow compared with streamflow increased from upstream to downstream, as shown in Table III. According to Table III, there is small variation of the percentage of the baseflow compared with streamflow along the Yangtze River both in normal years and in the extreme drought year, 1978. However, the baseflow in 2006 discharge into the streamflow was larger in the MLYRS than in the UYRS.

Baseflow in dry season

The ratios of the baseflow between 2006 and the other years are much larger during the dry season than during the flood season (Table II). The baseflow during the dry

Table I. Statistics of hydrological parameters of baseflow and streamflow in different years

		Streamflow			Baseflow		
		M	SD	Cv	M	SD	Cv
Pinshan	Mean	5 143	3 778	0·7	4 177	2 484	0·6
	2006	3 568	1 858	0·5	2 933	1 264	0·4
Cuntan	Mean	11 001	7 865	0·7	8 880	5 673	0·6
	2006	7 881	4 134	0·5	6 256	2 369	0·4
Yichang	1978	12 331	8 789	0·7	9 793	6 214	0·6
	Mean	13 565	9 452	0·7	9 962	5 754	0·6
	2006	8 959	4 277	0·5	6 748	2 277	0·3
Hankou	1978	18 035	10 749	0·6	12 460	6 896	0·6
	Mean	22 716	11 149	0·5	18 206	7 278	0·4
	2006	16 935	6 942	0·4	13 613	5 360	0·4
Datong	1978	21 385	11 064	0·5	16 355	6 536	0·4
	Mean	28 254	12 079	0·4	22 615	8 159	0·4
	2006	21 909	9 718	0·4	18 514	8 157	0·4

Mean is the mean value of different values during 2000–2005. M is the mean value of streamflow or baseflow in different periods. SD indicates the standard deviation of streamflow or baseflow in different periods. Cv is the variation coefficient for streamflow or baseflow in different periods.

Table II. Comparison of the baseflow and streamflow in 2006 and in other years

Station	Year	Flood		Dry		Total	
		R1(%)	R2(%)	R1(%)	R2(%)	R1(%)	R2(%)
Pingshan	Mean	63	65	90	91	69	71
Cuntan	Mean	64	61	98	101	70	70
Yichang	1978	63	59	109	116	73	72
	Mean	58	56	95	95	66	66
Hankou	1978	80	95	133	145	94	109
	Mean	66	71	95	83	75	75
Datong	1978	92	110	127	120	102	113
	Mean	72	81	90	83	78	82

Mean is the mean value in the different periods during 2000–2005. Flood, dry and total indicate the periods of flood season (May–October), dry season (October–December, January–March) and the whole year, respectively. R1 (R2) represents the ratio of streamflows (baseflows) between in 2006 and in other years.

season of 2006 accounted for over 90% of the baseflow in normal years, and for over 100% of the baseflow during the extreme drought year, 1978. It means that there was more groundwater in 2006 discharging into streamflow than in the extreme drought year, 1978. In Table II the R2 in the dry season in UYRS is larger than that in the MLYRS, as well as different from the situation during the flood season. This could be the result of supply from the Dongting Lake and Poyang Lake to the streamflow in the MLYRS (Dai *et al*., 2008).

DISCUSSION

The impacts of climate change on baseflow

The baseflow is often influenced by natural and anthropogenic factors such as climate, groundwater pumping

Table III. Comparison of baseflow and streamflow in different years

Station	Year	Flood (%)	Dry (%)	Total (%)
Pingshan	Mean	76	85	78
	2006	78	86	81
Cuntan	Mean	78	81	89
	2006	75	80	89
Yichang	1978	79	87	81
	Mean	75	90	80
	2006	76	92	80
Hankou	1978	67	74	69
	Mean	75	93	80
	2006	78	94	82
Datong	1978	73	86	77
	Mean	76	88	80
	2006	86	81	85

Mean is the mean value in the different periods during 2000–2005. Flood, dry and total indicate the periods of flood season (May–October), dry season (October–December, January–March) and the whole year, respectively.

and water consumption (Wittenberg, 2003). Because of lack of data, the climate impact on baseflow along the Yangtze River has not been reported yet, not even after the extreme drought year, 2006. In this paper, the measured temperatures at Chongqing, Hankou and Anqing were collected as representative for the Yangtze River. The annual anomaly in temperature from 1950 to 2008 was plotted in Figure 4. In 2006 an abnormal high temperature occurred at those stations, which would induce increased evaporation from open water bodies (IPCC, 2001). Although there is a query on increased evaporation resulting from the global warming (Thomas, 2000), some observations have indicated a positive relation between the temperature and evaporation in the Yangtze River basin (Zuo *et al*., 2005; Ren and Guo, 2006). With the extreme high temperature in 2006 along the Yangtze River, evaporation in the Yangtze River basin greatly increased. As shown in Figure 5, the precipitation in the Yangtze River basin in 2006 was much lower than that in a normal year: the precipitation in 2006 was 15–25% lower than that in 2000–2005, which agrees with the decreased amounts of streamflow and baseflow in 2006 (Table II). The measured precipitations in 2006 at some stations were even 30% lower than those in normal years (Yangtze Water Resource Commission, 2007). As a consequence, both high evaporation and low precipitation caused an extreme low streamflow in 2006. Accordingly, low streamflow can lead to low water level in streams with a large discharge from groundwater into the Yangtze River compared with normal years.

The regression relationships between streamflow and precipitation and between baseflow and precipitation were analysed with the results shown in Figure 6. Positive relationships of streamflow and baseflow against precipitation can be obtained from this figure. The correlation coefficient at Datong is lower than those at other stations. It is obvious that the change of baseflow in the

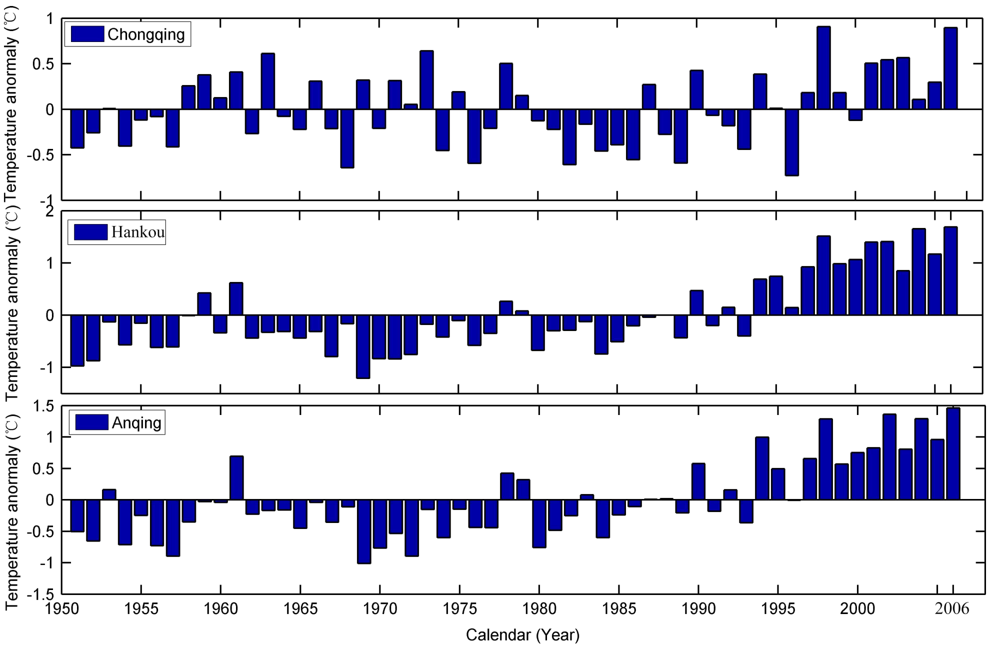

Figure 4. The mean yearly temperature anomaly at the stations

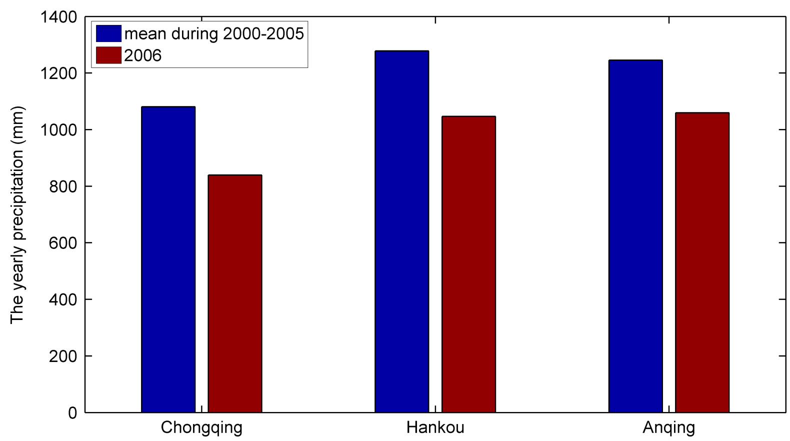

Figure 5. The yearly precipitation at the stations along the Yangtze River

Yangtze River follows the changes of streamflow, which is controlled by the precipitation in the Yangtze River basin. It is noted that the coefficients between baseflow and precipitation at the stations are smaller than that between streamflow and precipitation, which might be explained by the baseflow having a sluggish response of the groundwater discharge to the precipitation. As far as the temperature is concerned, high evaporation due to a high temperature superimposed on low precipitation, not only directly caused a high loss in the surface flow, but also caused parts of the groundwater to be evaporated. This is the main possible reason for low relative baseflow in both the extreme drought years, 2006 and 1978.

The impacts of human activities on baseflow

Although the effect of human behaviour on global warming is not really clear, it is sure that water allocation, irrigation and storage in reservoirs directly are caused by human actions. The Yangtze River is the longest river in China with a basin that is very important for the economic development in China. Great developments have taken place along the river, especial in MLYRS, in the last two decades. The population in the Yangtze River basin has increased by over 440 million since 2000 with a GDP accounting for 42·5% of total GDP of China (Liu, 2002). The population boom and rapid economic development in the Yangtze River basin cause a large demand for water. From Figure 7, it can be seen that the water consumptions increased in recent years due to the increasing consumption of water by industry, while the demand of water for agriculture and living remained the same. In 2006, because of the extreme drought, the water consumption including that by irrigation, industry and pumping was intense compared with that of a normal year (Jia, 2006).

Moreover, there are nearly 50 000 reservoirs constructed in the river basin, which have greatly increased water storage (Yang *et al.*, 2005). The total storage capacity of these reservoirs amounts to 200×10^9 m^3 which is

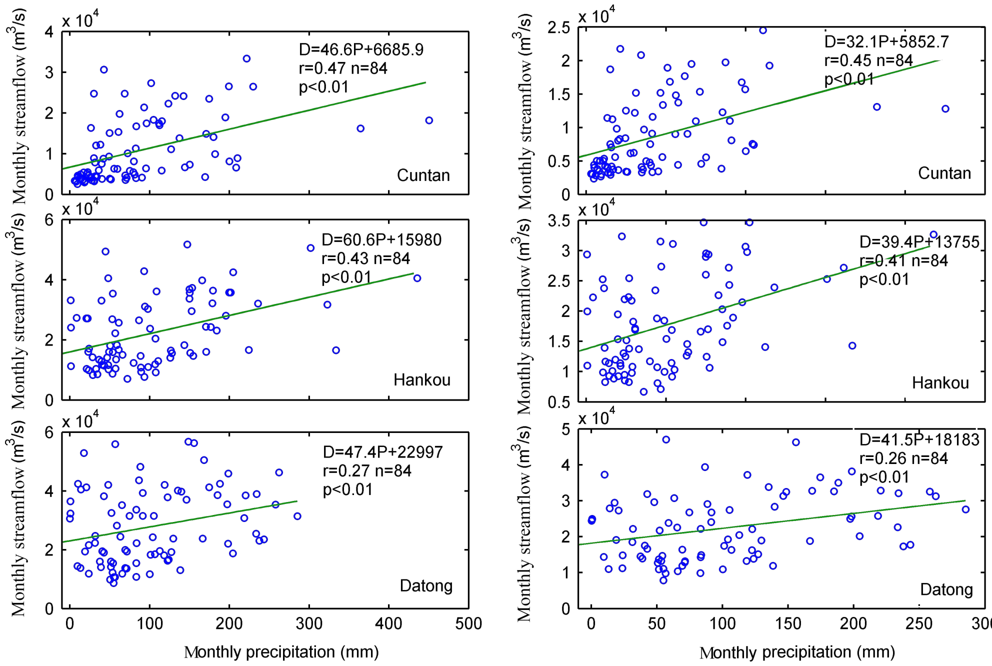

Figure 6. Relation between monthly streamflow and precipitation (2000–2006)

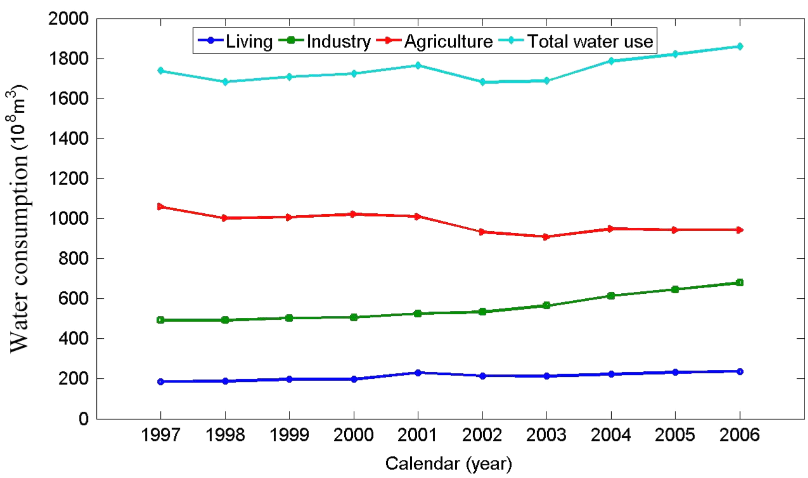

Figure 7. Water consumption in recent years along the Yangtze River

about 22% of the annual discharge of the river (Yang *et al*., 2004). The reservoirs do not only decrease the discharge downstream but also change the allocation pattern along the river. During the second phase of the TGR storage period, from September 20 to October 27 in 2006, 111×10^8 m^3 of water was stored, which resulted in a decrease of discharge and water levels in MLYRS (Dai *et al*., 2008).

A large volume of water stored in the TGR and intense water consumption in the river basin induce a low water level in the river and increase the groundwater discharge into the river. The population density and the economic development are much lower in the UYRS than in the MLYRS, which means lower water consumption in the UYRS. The storage in the TGR causes an obvious flow change in the MLYRS. In addition, there is more water supply from the Dongting Lake and Poyang Lake to the Yangtze River in the MLYRS. This can explain the difference of streamflow and baseflow in the UYRS compared with the MLYRS. Moreover, the storage around the end of the flood season aggravates the water shortage in the MLYRS, which leads to a higher groundwater water level during the dry season than during the flood season and a large contribution of groundwater discharge to the streamflow. However, because of complex human activities and lack of detailed data about water consumption, it is difficult to distinguish the impact of the TGR from the other human activities.

Estimation of baseflow contributions to streamflow

In 2006, both the streamflow and baseflow decreased along the Yangtze River and its distributaries in comparison with those in a normal year. However, the amount of baseflow at Datong in 2006 was higher than that in the extreme drought year, 1978. And the supply from lakes, the Poyang Lake and the Dongting Lake, also was higher than in a normal year (Figure 3). It suggests that there was more groundwater in 2006 discharging into the stream than in normal years and in the extreme drought year, 1978. In reality, the annual discharge into the Dongting Lake includes water supply from the Yangtze River besides from other tributaries. The discharge at Chenglingji represents the discharge into the Yangtze River from the Dongting Lake (Li *et al.*, 2005). In 2006, the discharge into the Dongting Lake was $1{\cdot}93 \times 10^{11}$ m^3, and the measured discharge at the Chenglingji is $1{\cdot}99 \times 10^{11}$ m^3, i.e. a difference of -60×10^8 m^3. In addition, water supply from the Yangtze River into the Dongting Lake has carried only 15% of that from Yichang in recent years (Xu *et al.*, 2007). As during the same period, the amount of water stored in the Dongting Lake remained the same, this figure represents the groundwater discharge into the Yangtze River from the Dongting Lake.

Based on the change of baseflow, the amount of groundwater discharge induced by the extreme drought and by human activities can be estimated for 2006. Here, the combined natural and anthropogenic impacts on the change of ground water discharge are taken into account, because the influence of human interference, e.g. water consumption and impoundment can not be separated from the natural impacts. The natural characteristics in 1978 were similar to those in 2006, with a comparable temperature and precipitation. Therefore it might be assumed that the change of baseflow due to nature in the extreme drought year, 1978, is comparable to that in 2006. The amount of baseflow in 1978 can be considered as the groundwater discharge in 2006 without impacts of human activities. The difference of baseflow between 1978 and 2006 could be caused by difference of human activities in these two years. More groundwater discharge at Datong could be obtained in 2006 than in 1978 with $3{\cdot}54 \times 10^{10}$ m^3 during the flood season, $3{\cdot}27 \times 10^{10}$ m^3 during the dry season, and $6{\cdot}81 \times 10^{10}$ m^3 in total. In 2006 the streamflow at Datong was about $4{\cdot}44 \times 10^{11}$ m^3 during the flood season, $2{\cdot}49 \times 10^{11}$ m^3 during the dry season and a total of $6{\cdot}93 \times 10^{11}$ m^3. Thus, it can be seen that the contribution of groundwater discharge to streamflow due to human activities in 2006 was about 8% during the flood season, 13% during the dry season and 10% in the whole year.

CONCLUSIONS

Using the baseflow separation technique of HYSEP, the baseflow along the Yangtze River in 2006 and in the other years was discussed. Conclusions can be drawn as follows.

1. The baseflow is an important supply to the streamflow in the Yangtze River, especially during the extreme drought year, 2006. The volume of baseflow in 2006 was smaller than in 2000–2005, but larger than in the similar extreme drought year, 1978. However, the baseflow relative to the streamflow was larger in 2006 than in other years.
2. The baseflow is influenced by the extreme climate and human activities along the Yangtze River. The extreme climate is the dominating factor influencing baseflow discharge into streamflow. The human activities in the MLYRS are more intensive than that in UYRS with more baseflow discharge. The variation of baseflow discharge in UYRS is larger than that in MLYRS.
3. There was relatively more baseflow discharge to the river in 2006 than in the extreme drought year, 1978, as a result of more intensive human activities. The contribution of baseflow discharge into the river, due to human activities, was about 8% during the flood season, 13% during the dry season and 10% in the whole year.

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