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Evaluating the non-stationary relationship between precipitation and streamflow in nine major basins of China during the past 50 years

Zengxin Zhang [a,b], Xi Chen [a,*], Chong-Yu Xu [c,e], Lifeng Yuan [d], Bin Yong [a], Shaofeng Yan [b]

[a] State Key Laboratory of Hydrology – Water Resources and Hydraulics Engineering, Hohai University, Nanjing 210098, China
[b] Jiangsu Key Laboratory of Forestry Ecological Engineering, Nanjing Forestry University, Nanjing 210037, China
[c] Department of Geosciences, University of Oslo, Norway
[d] Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
[e] Department of Earth Sciences, Uppsala University, Sweden

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SUMMARY

In this paper, the trends of the annual streamflow and precipitation and cross correlations between them were analyzed in nine large river basins of China during 1956–2005. The results indicate that: (1) the annual mean streamflow decreases in arid and semi-arid regions of north China; however, increasing trends occur in south and Southwest China; (2) the annual streamflow and precipitation exhibit reasonable correlation in nine large river basins except those located in inland areas. The annual streamflow over most areas of China is fed by precipitation; however, the decline in streamflow is faster than the decreases of precipitation since 1970s in the arid and semi-arid regions of north China. The relationship between the annual precipitation and streamflow presents a non-stationary state in north China. This non-stationary relationship is strongly influenced by both human activities and precipitation changes; (3) a significant increase of water use might be the major factor responsible for the steeper decline in streamflow than in precipitation in Haihe River, Yellow River and Songliao River basins in north China. In inland river areas, increase of water use and actual evapotranspiration might result in decline in streamflow although precipitation has an increase tendency. This paper sheds light on the non-stationary relationship between annual precipitation and streamflow and possible underlying causes, which will be helpful for a better understanding of the changes of precipitation and streamflow in China at large scale and in other regions of the world.

1. Introduction

Access to water is already a serious issue for people in many parts of the world and, given recent United Nations estimates, the situation is not likely to improve (Meek and Meek, 2009). From a resource perspective, streamflow is a measure of sustainable water availability which is most vital for sustainable development, utilization of water resources and better governance (Dong et al., 2009).

It is now common knowledge that human activities including water diversions and land development, in addition to climate, have a significant impact on streamflow and other hydrological processes (Milly et al., 2005). Many previous studies showed that continental runoff had increased during the 20th century despite more intensive human water consumption (Labat et al., 2004; Probst and Tardy, 1987; Shiklomanov, 2000; Gedney et al., 2006). However, it has also been widely discussed that decrease in streamflow in many areas during the past decades is highly influenced by human activity (Zhang et al., 2001, 2007, 2008; Ren et al., 2002). Regional patterns of streamflow changes are complex and less certain than those in temperature. Milly et al. (2005) analyzed the trends of observed global streamflow and found that less runoff occurred in sub-Saharan Africa, southern Europe, southernmost South America, Southern Australia and western mid-latitude North America, while the observed streamflow increases in the La Plate basin of southern South America, Southern through central North America, the Southeastern quadrant of Africa, and northern Australia.

Shortage of water is becoming one of the key restricting factors of the development of Chinese society and economy. Although China's water resources rank sixth in the world by total volume, per capita water availability is roughly one quarter of the world average. Moreover, water resources are not distributed evenly across regions and time. Based on the observed streamflow of 19 key hydrological control stations in the six large basins in east China for the past 50 years, Zhang et al. (2007) found that the observed annual streamflow in the six large basins has generally

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* Corresponding author.
E-mail address: xichen@hhu.edu.cn (X. Chen).

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decreased during the study periods, with significant decreases detected in the northern China. Yangtze River shows only a small and statistically insignificant increase in annual runoff (Piao et al., 2010), but a significant positive trend is found in flood discharges in the middle and lower basins during 1960–2000 (Jiang et al., 2007). Ma et al. (2008) showed the existence of non-stationary relationships between precipitation and streamflow in the arid region of northwest China with larger changes in streamflow than in precipitation. Some river catchments showed a statistically significant change point in streamflow but not in precipitation. For Haihe River catchment with strong human activities, agricultural water use is likely the main driving factor of runoff decline (Yang and Tian, 2009). With farmers' empowerment via the 1978 land reform policy, irrigation has become a routine agronomic practice (Yang and Tian, 2009). For instance, since 1980 irrigated land area increased by 29.35%, 48.70% and 26.42% for Beijing, Hebei and Shanxi in Haihe River catchment, respectively. According to the Department of Water Resources of Hebei Province's (1984) documents, the agricultural water use in most of the mountain counties was higher than 90% in the early 1980s, and the evapotranspiration from farmlands is far higher than annual precipitation (Zhang et al., 2006). The percentage of farmland area is significantly related with runoff decline in Haihe River catchment. Ren et al. (2002) found that sharp decline of runoff in Haihe River catchment was less driven by climate than by human activity, which accounted for 79.22% of the total runoff change. A decline in runoff was also found in the Yellow River over the last five decades (Fu et al., 2004; Piao et al., 2010). Investigation by Piao et al. (2010) shows that climate is dominant in controlling runoff and increased withdrawals can explain about 35% of the declining runoff observed at the Huayuankou station in the lower reaches of Yellow River over the last half-century.

Although many researchers have addressed changing properties of streamflow and possible underlying causes in some regions of China (e.g. Jiang et al., 2007; Piao et al., 2010; Ren et al., 2002; Zhang et al., 2006, 2007, 2009), the streamflow changes and their relationship with precipitation and human influences at basin scales in whole China, have not been analyzed thoroughly so far, and which is of great scientific merits in understanding spatial and temporal patterns of streamflow in China.

Therefore, the purposes of this study were: (1) to detect the temporal and spatial variabilities of annual mean streamflow and precipitation in nine large river basins of China; (2) to evaluate the relationship between the annual streamflow and precipitation in the basins in order to clarify the reasons for the streamflow changes at a large scale; and (3) to analyze human influences on streamflow–precipitation relationship by using effective irrigation area (EIA) and irrigation amount associated with streamflow decreasing. This information will be helpful for further understanding of the changes and possible causes of annual streamflow in China. Particular attention is paid to analyze the non-stationary relationship between the streamflow and precipitation in nine large rivers in China as Milly et al. (2008) pointed out that stationarity is dead and should no longer serve as a central, default assumption in water-resource risk assessment and planning. The methodology and procedure of evaluation on multiyear streamflow variations may also provide useful hint for those who are working on water resources management and planning in other regions of the world.

2. Data and methods

2.1. Study area and data

China is situated in eastern Asia on the western shore of the Pacific Ocean and has a climate dominated by monsoonal winds. It features clear precipitation differences in winter and summer. In addition, precipitation differs from region to region because of the country's extensive territory and complex topography. Generally, the precipitation decreases from southeast to northwest.

China has a large number of rivers with a total length of 420,000 km. There are more than 50,000 rivers with a drainage area of more than 100 km^2 and more than 1500 rivers with a drainage area of more than 1000 km^2. As affected by the topography and climate, the rivers are distributed very unevenly over regions. Most

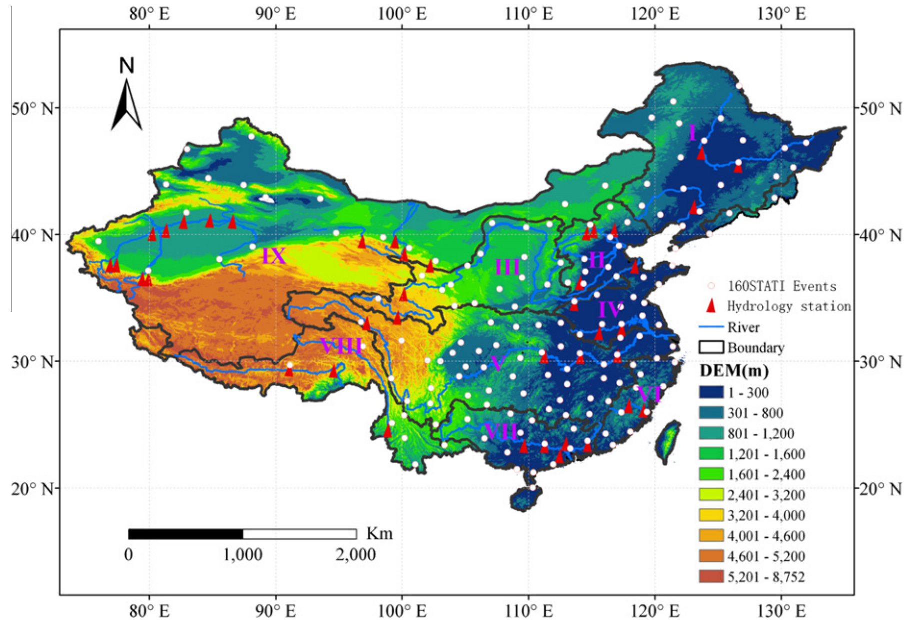

Fig. 1. Locations of the main rivers and concerned hydro-meteorological stations in nine large river basins. (I) Songhuajiang and Liaohe River basin; (II) Haihe River basin; (III) Yellow River basin; (IV) Huaihe River basin; (V) Yangtze River basin; (VI) Rivers in Southeast China basin; (VII) Pearl River basin; (VIII) Rivers in Southwest China basin; (IX) Rivers in northwest China basin (40 hydrologic stations and 160 precipitation gauging stations).

of the rivers are situated in the wet eastern monsoon climatic zone, directly flowing into the sea, with the major ones including the Liaohe River, Huaihe River, Haihe River, Yangtze River, Yellow River, Pearl River, etc. The northwestern China is dry with little precipitation, and has only a small number of rivers, most of which are inland ones without connection to the sea, and there are also large no runoff areas (MWR, 2004).

The depth of natural river runoff, which depends on precipitation, evapotranspiration and physical characteristics of watersheds, gradually descends in magnitude from the southeast towards the northwest. The runoff depth is more than 1000 mm in some southeastern regions and less than 10 mm in some western regions. The total volume of river runoff in the five northern river basins (Songhua-Liaohe, Haihe, Huaihe, Yellow and Inland Rivers with a total catchment area of 2.27 million km^2) accounts for less than 20% of the national total while the total volume of the four southern river basins (Yangtze, Pearl, Southeast and Southwest rivers with a total catchment area of 2.86 million km^2) accounts for more than 80% of the national total. The rivers in the northern areas show a bigger intra-year runoff variation. The highest accumulated runoff of consecutive 4 months (June–September) accounts for more than 80% of the annual total in the northern areas, and this ratio has a value of about 60% for the rivers in the southern areas.

Annual mean streamflow covering 1956–2005 from 40 hydrological stations and annual mean precipitation data from 160 National Meteorological Observatory (NMO) stations within the nine large river basins were used in this study. The discharge stations were chosen considering the location, length of the observation period and quality of the data observed. The meteorological data were provided by the National Climatic Centre (NCC) of the China Meteorological Administration (CMA). The location of the nine large river basins of China and the gauging stations can be referred to Fig. 1 and Table 1. The catchment average precipitation for each river basin was computed using the arithmetic average method. Homogeneity of the meteorological data was calculated using a von Neumann ratio, cumulative deviations, and Bayesian procedures (Buishand, 1982; Peterson et al., 1998). The dataset of 160 meteorological stations tested by these three methods are homogeneous at >95% confidence level (Becker et al., 2007; Zhang et al., 2010a).

2.2. Methods

The Mann–Kendall trend test (MK; Mann, 1945; Kendall, 1975; Sneyers, 1990) is widely used in the literature to analyze trends in the climate data. The MK test has different variants. This study follows the procedure that starts by simply comparing the most recent data with earlier values. A score of +1 is awarded if the most recent value is larger, or a score of −1 is awarded if it is smaller. The total score for the time-series data is the Mann–Kendall

Table 1
Annual streamflow at control hydrological stations in nine large river basins of China.

River basin		River name	Hydrologic stations	Latitude	Longitude	Drainage (km^2)	Annual mean streamflow (10^8 m^3)
Song-Liao R. (I)		Songhuajiang R.	Jiangqiao^0	46°47′N	123°41′E	162,569	644
		Songhuajiang R.	Harbin^1	45°46′N	126°36′E	389,769	1283
		Liaohe R.	Tieling^1	42°2′N	123°5′E	120,764	89
Haihe R. (II)		Zhangweinan R.	Guantai^1	36°2′N	114°5′E	17,800	31
		Yingding R.	Shizhali^1	40°13′N	114°37′E	23,944	14
		Yingding R.	Xiangshuipu^1	40°31′N	115°11′E	14,507	11
		Chaobai R.	Zhangjiafen^1	40°37′N	116°47′E	8506	16
Yellow R. (III)		Yellow R.	Jimai^0	33°46′N	99°39′E	45,019	127
		Yellow R.	Tangnaihai^1	35°3′N	100°09′E	121,972	633
		Yellow R.	Huayuankou^2	34°55′N	113°39′E	730,036	1223
		Yellow R.	Lijin^3	37°49′N	118°25′E	750,000	964
Huaihe R. (IV)		Huaihe R.	Wangjiaba^1	32°26′N	115°36′E	30,630	294
		Huaihe R.	Wujiadu^3	32°56′N	117°23′E	121,330	846
Yangtze R. (V)		Yangtze R.	Zhimenda^0	33°02′N	97°13′E	137,704	385
		Yangtze R.	Yichang^1	30°42′N	111°17′E	1006,000	13,659
		Yangtze R.	Hankou^2	30°37′N	114°8′E	1488,000	22,314
		Yangtze R.	Datong^3	30°46′N	117°4′E	1705,383	28,113
Southeast R. (VI)		Minjiang R.	Yangkou^1	26°48′N	117°55′E	12,669	417
		Minjiang R.	Shijiao^3	23°51′N	112°57′E	38,363	1300
Pearl R. (VII)		Xijiang R.	Wuzhou^1	23°34′N	111°18′E	327,006	6383
		Xijiang R.	Gaoyao^1	22°55′N	112°28′E	351,535	6932
		Dongjiang	Boluo^1	23°44′N	114°42′E	25,325	745
		Qianjiang	Wuxuan^1	23°34′N	109°39′E	196,655	4005
Southwest R. (VIII)		Nujiang R.	Daojieba^3	24°59′N	98°53′E	110,224	1716
		Brahmaputra R.	Lasa^1	29°39′N	91°04′E	26,225	298
		Brahmaputra R.	Nuxia^2	29°28′N	94°34′E	36,652	1883
Inland R. (IX)	Tarim R. (IX-a)	Aksu R.	Xidaqiao^0	40°07′N	80°15′E	42,123	260
		Yarkant R.	Kaqun^0	37°59′N	76°54′E	50,248	210
		Kalakash R.	Wuluwati^0	36°52′N	79°26′E	19,983	143
		Yulongkash R.	Tongguziluoke^0	36°49′N	79°55′E	14,575	
		Kaidu R.	Dashankou^0	37°59′N	76°54′E	18,827	111
		Tarim R.	Alar^1	40°32′N	81°19′E		143
		Tarim R.	Xinquman^2	41°02′N	82°43′E	17,580	119
		Tarim R.	Yingbazha^3	41°12′N	84°47′E	435,508	94
		Tarim R.	Qiala^3	41°04′N	86°35′E		21
	Northwest R. (IX-b)	Heihe R.	Yingluoxia^1	38°48′N	100°11′E	10,009	50
		Heihe R.	Zhengyixia^3	39°49′N	99°28′E	35,634	32
		Shiyanghe R.	Jiutiaoling^1	37°56′N	102°14′E	1077	27
		Shulehe R.	Changmapu^1	39°49′N	96°51′E	10,961	28

Note: 0, 1, 2 and 3 indicates headwater, upstream, midstream, and downstream rivers.

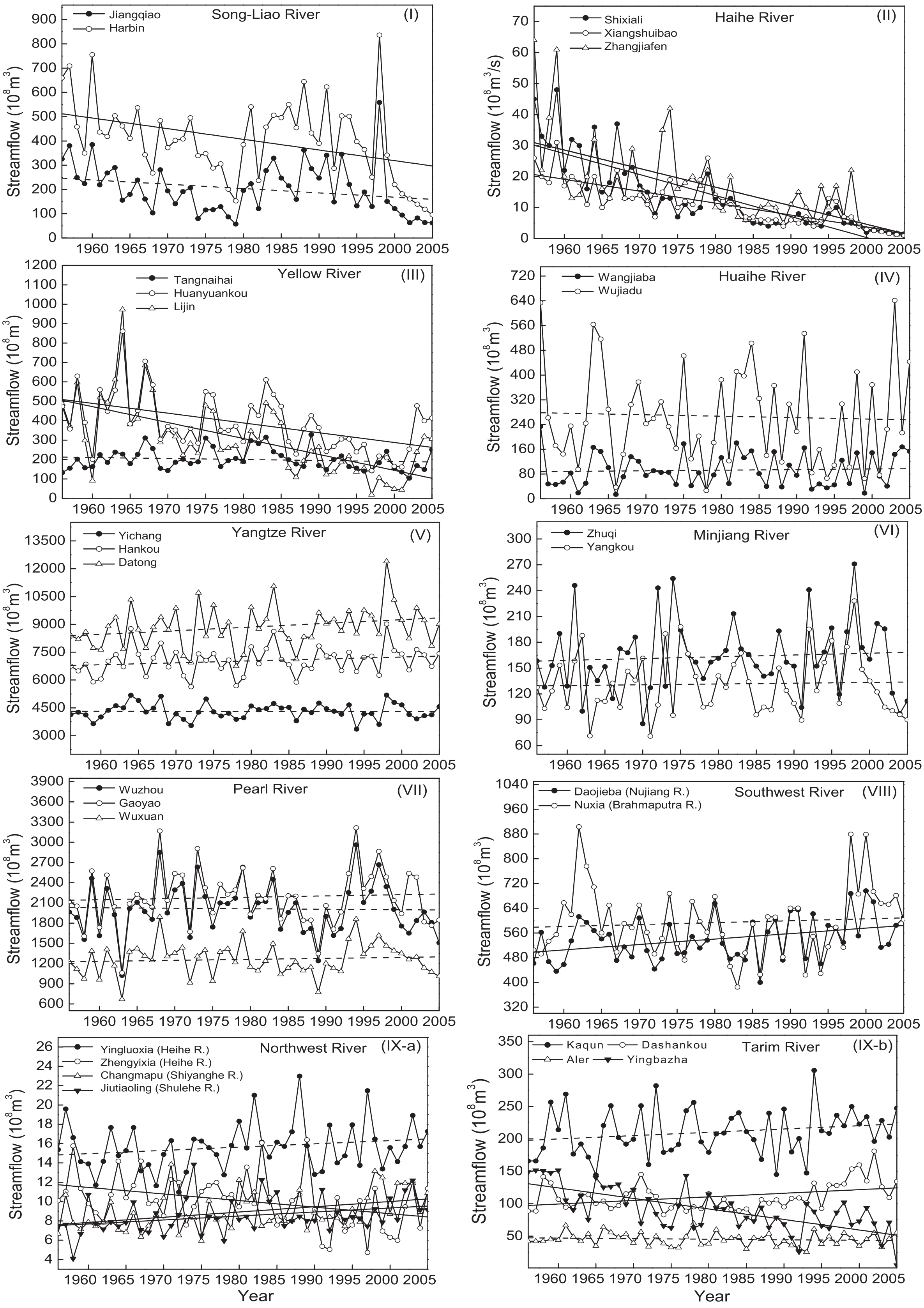

Fig. 2. Annual streamflow and its linear trend in nine large river basins of China during 1956–2005. Note: the order of listed rivers in each figure is from upstream to downstream; I, II, ... , IX are in order of basin number shown in Fig. 1. Solid linear line means the significant linear trend at >95% level and dashed linear means a non-significant linear trend.

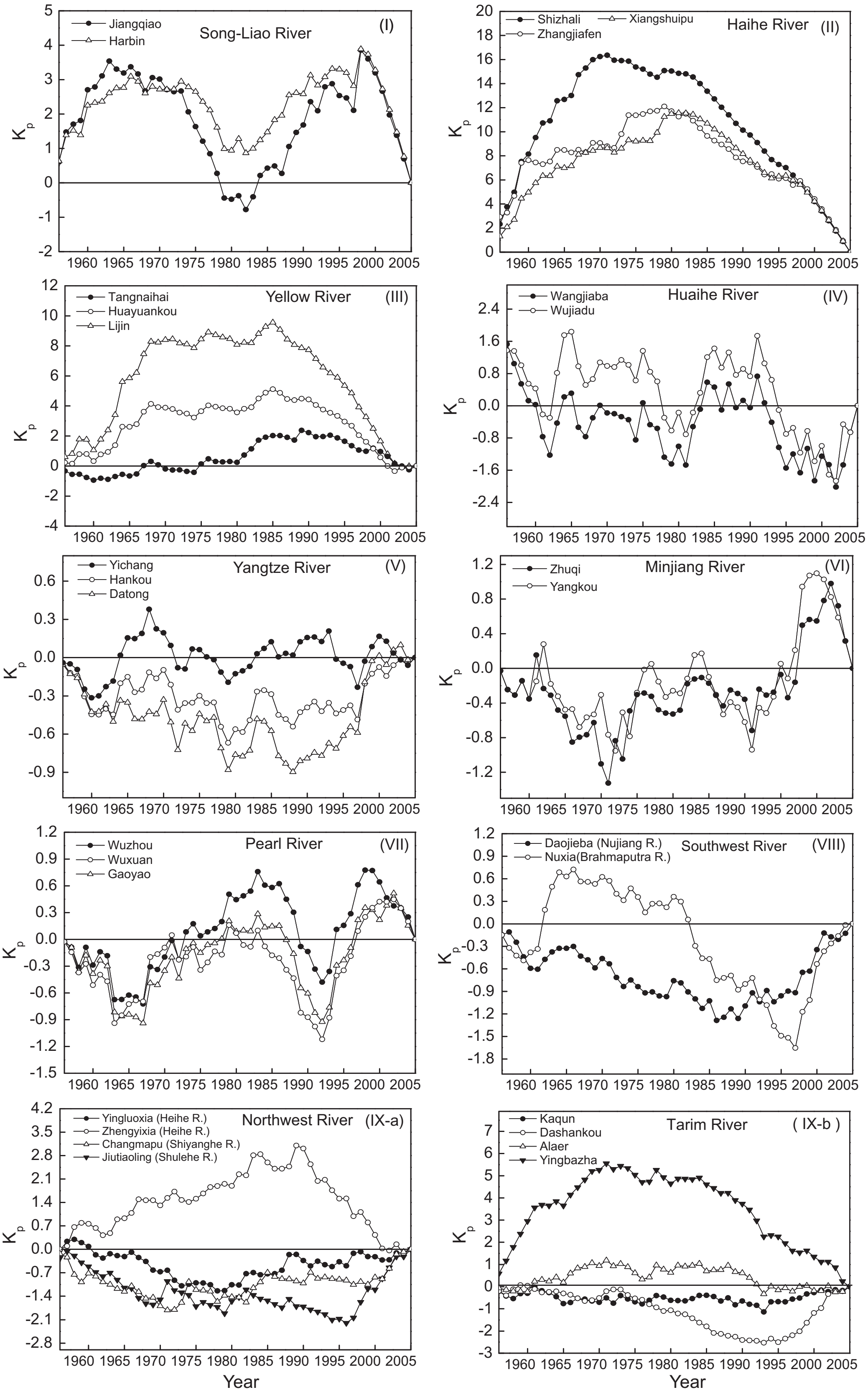

Fig. 3. The distribution of Cumulative Sum of Departures of Modulus Coefficient (K_p) in nine large river basins of China (K_p refers to Eq. (2) and the Y-axis differs in size).

statistic, Z, which is then compared to a critical value, $Z_{1-\alpha/2}$ (where α is significance level and $Z_{1-\alpha/2}$ is the Z value found in the standard normal distribution table). In a two sided test for trend, the null hypothesis of no trend, H_o will be rejected if $Z > Z_{1-\alpha/2}$ or $Z < -Z_{1-\alpha/2}$.

As a complementary method of trend analysis, simple linear regression was also used in this paper for long-term linear trend test. The simple linear regression method is a parametric t-test method, which consists of two steps: fitting a linear simple regression equation with the time t as independent variable and the hydrological variable (i.e. precipitation and discharge in this study) Y as dependent variable; testing the statistical significance of the slope of the regression equation by the t-test (Xu, 2001; Zhang et al., 2009). The parametric t-test requires that the data to be tested is normally distributed. The normality of the data series is first tested in the study by applying the Kolmogorov–Smirnov test. The reasons for using the t-test method as a complement to the MK method are (1) the t-test is a parametric method and when the assumptions are fulfilled, it is a powerful test, (2) when results of the t-test method are plotted, changes of the original time series and the linear trend are visible, and (3) using two methods provides a valuable cross-check.

Both the MK and t-test methods are influenced by the serial correlation in the time series, and when the serial correlation exists it has to be eliminated by prewhitening (Yue et al., 2002; Yue and Wang, 2002). 'Prewhitening' is one of the methods used to prevent false indication of trend, where the serial correlation is removed from the data by assuming a certain correlation model, usually a Markovian one (e.g., Storch, 1995).

To evaluate more details on temporal variability of hydrological time series, cumulative curve analysis was also performed. The cumulative curve method was first used by Hurst (1951) to determine the storage capacity of reservoirs on the Nile River. The Cumulative Sum of Departures of Modulus Coefficient (CSDMC) was used in this paper to detect the streamflow variability in different regions. The CSDMC is expressed by the following formula:

$$R_i = Q_i/\overline{Q}(i = 1, 2, 3, \ldots, N) \tag{1}$$

$$K_p = \sum_{i=1}^{p}(R_i - 1)\ (p = 1, 2, 3, \ldots, N) \tag{2}$$

where i is the sequential value of a time series of N years, K_p is the cumulative sum of departures of CSDMC during $1 \sim p$ years, Q_i is annual streamflow, $\overline{Q}$ is long-term annual mean streamflow. The periods with downward trends of K_p (negative slope) represent intervals of lower streamflow than average, while upward trends (positive slope) represent intervals of higher streamflow than average (McGilchrist et al., 1975). Cumulative sum charts (CUSUM) is used for abrupt change point detection in climate series. A sudden change in the direction of the CUSUM indicates a sudden shift in the average. A period where the CUSUM chart follows a relatively straight path indicates a period where the average does not change.

3. Results

3.1. Trends of annual mean streamflow in nine large river basins in China

The variabilities and linear trends of annual mean streamflow in the nine large river basins in China are shown in Fig. 2 for the representative hydrological stations selected from each river basin in Table 1. The order of the 10 graphs in Fig. 2I, II, . . . , IX-a, IX-b) corresponds to the location of the basins showed in Fig. 1. It is seen that for the Song-Liao River, Haihe River, and Yellow River, the mainstream runoff showed significant decreasing trends by t-test (Fig. 2I–III), while increasing trends occurred in the Yangtze River, Minjiang River, Pearl River and Southwest Rivers (Fig. 2V–VIII). However, for the streamflow in Inland Rivers, such as the northwest rivers of Heihe River, Shiyanghe River and Shulehe River (Fig. 2IX-a) and Tarim River (Fig. 2IX-b), increasing trends can be found in the headwater and upstream areas, while decreasing trends are found in the lower reach of the mainstream.

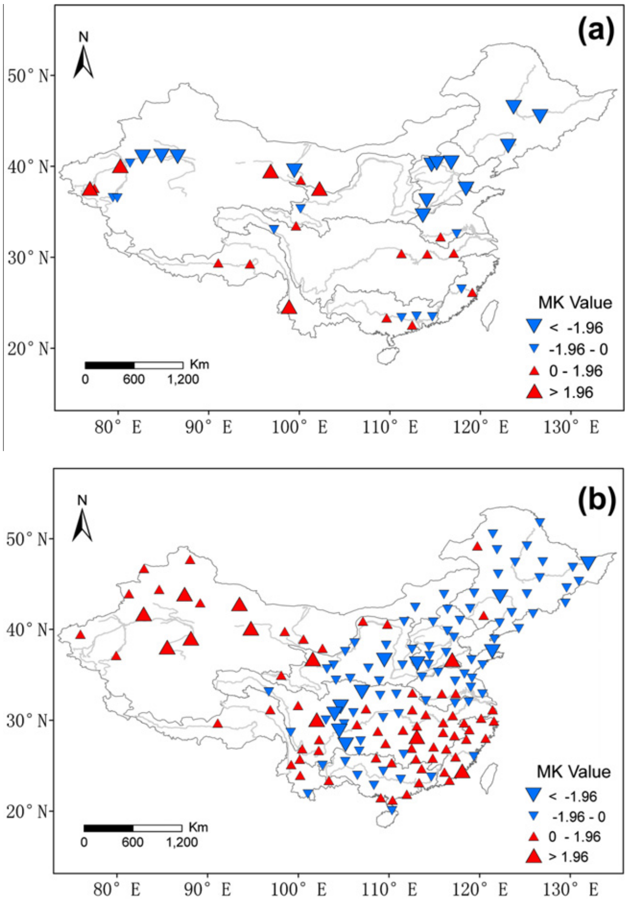

Fig. 4. Trends of annual streamflow (a) and precipitation (b) in China by using MK method.

The distribution curves of CSDMC for the nine large river basins are shown in Fig. 3. It is see that for Song-Liao river basin, three change points can be detected from the CSDMC variations with two peaks in around 1965 and 1999 and a valley in around 1982 (Fig. 3I). One change point for Haihe River basin (Fig. 3II) can be

Table 2
Comparison of the results of MK and t-test methods in detecting trend in precipitation and discharge data in China (1956–2005).

Station number	MK method		t-Test method	
	Precipitation	Streamflow	Precipitation	Streamflow
Increasing trends	62	12	61	12
Decreasing trends	77	10	80	10
Significantly increasing trends	11	5	10	6
Significantly decreasing trends	10	13	9	12

Note: the numbers respesent the number of stations with (significant at 5% level) trend. Total number of stations for precipitation is 160, and for discharge is 40.

detected from the CSDMC with a single apex. The CSDMC of Haihe River basin presents most significant variations with largest K_p values among the nine larger river basins. Change points from positive to negative direction occurred in early 1970s at Shizhali station and in the late 1970s for other two stations. As for Yellow River basin (Fig. 3III), departure from the average becomes more significant

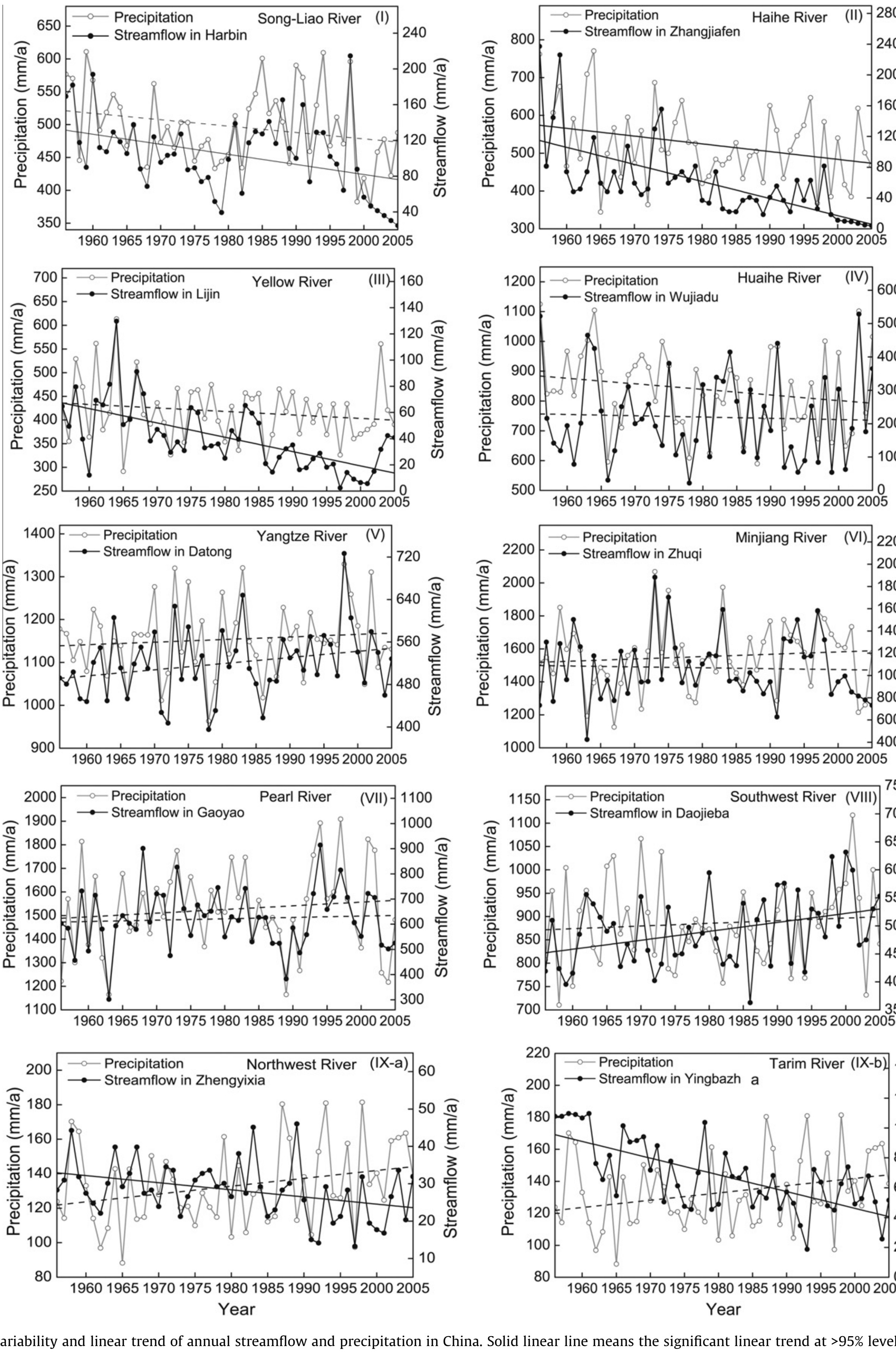

Fig. 5. The variability and linear trend of annual streamflow and precipitation in China. Solid linear line means the significant linear trend at >95% level and dashed linear means a non-significant linear trend.

Table 3
The correlation coefficients between precipitation and streamflow in nine larger river basins of China.

River basin	Control hydrological station	Correlation coefficient	Runoff coefficient (%)
Song-Liaohe R. (I)	Harbin	0.66[a]	21
Haihe R. (II)	Guantai	0.59[a]	11
Yellow R. (III)	Lijin	0.57[a]	9
Huaihe R. (IV)	Wujiadu	0.75[a]	25
Yangtze R. (V)	Datong	0.85[a]	45
Southeast R. (VI)	Shijiao	0.67[a]	68
Pearl R. (VII)	Gaoyao	0.75[a]	41
Southwest R. (VIII)	Nuxia	0.39[a]	56
Inland R. (IX-a)	Yingbazhua	0.09	5
	Zhengyixia	0.21	22

[a] Indicates that the correlation is significant at >95% confidence level.

at the stations located toward downstream. Streamflow changed in positive direction from 1950s until end of 1960s. Between 1970s and middle 1980s, the annual streamflow of Huayuankou and Lijin changed around the average (Figs. 2 and 3). After about 1985, a sharp change in negative direction was found for both stations. From the plot of CSDMC, we can see that mean annual streamflow for Huaihe River, Yangtze River, Minjiang River, Pearl River and rivers in southwest do not change as much as that of north rivers although smaller variabilities are seen (Fig. 3IV–VIII). The patterns of streamflow changes in Minjiang River are consistent with that in Pearl River: streamflow is large during the 1970s and 1990s, and small in the 1960s and 1980s. Larger variabilities of annual streamflow were found for Inland Rivers (rivers in northwest and Tarim River) (Fig. 3IX-a and IX-b), of which the streamflow variabilities in the downstream reach are opposite to those in the upstream. For the northwest rivers in Fig. 3IX-a, a negative change of the streamflow was found during the first half of the period, and a positive change since then in the headstream. In the downstream, however, a positive change of the streamflow was found up to late 1980s, and negative change since then. For the downstream of Tarim River in Fig. 3IX-b, the change point from positive to negative direction occurred in the early 1970s.

3.2. The relationship between the annual streamflow and precipitation

Fig. 4 shows the spatial distribution of the MK trend of annual streamflow for all hydrological stations in Table 1 and precipitation trends for 160 stations in nine representative rivers in China during 1956–2005. In general, decreasing trends of precipitation could be seen in Song-Liao River basin, Yellow River basin, Haihe River basin and upper Yangtze River basin, but increasing trends were found in lower and middle Yangtze River basin, Minjiang River basin, Southwest River basin and Inland areas. The comparison of the results of the MK and *t*-test methods for the same data sets is shown in Table 2. It is seen that the methods result in very similar results, and the minor difference found in the table is because the value of testing statistics lies close to the critical value.

The change tendency of annual streamflow accords with that of annual precipitation except for Inland Rivers in the western China. For Inland Rivers, three upper rivers of Yingluoxia, Changmapu and Jiutiaoling stations in Northwest River (Fig. 2IX-a region), and two headwater rivers of Kaqun and Dashankou stations in Tarim River (Fig. 2IX-b region) present positive trends of both streamflow and precipitation. However, for lower and downstream rivers, opposite trends (negative streamflow and positive precipitation) were found.

Fig. 5 also shows that, except for the Inland areas (Fig. 5IX-a and IX-b), the trend of streamflow at the outlet station of the river is in line with the trend of areal precipitation, but the decrease of annual streamflow is more dramatic than that of annual precipitation in north China. The straight line slopes of streamflow for Song-Liao River, Haihe River and Yellow River are −1.12, −2.22, −1.09 mm/a^2, respectively, steeper than −0.97, −2.05, −0.74 mm/a^2 for precipitation (Fig. 5I–III). Opposite trends between basin outlet streamflow and precipitation are seen in the extremely drought region of inland basins.

Table 3 lists the correlation coefficients between annual streamflow at control stations (outlets of rivers) and areal precipitation in the nine large river basins during 1956–2005. We can find that there are good relationships between the annual streamflow and precipitation in large river basins except those in Inland areas. The extremely low correlations between precipitation and streamflow in the Inland areas indicate that streamflow changes are not controlled by precipitation variations.

To assess the deviations of the annual streamflow from annual precipitation during the past 50 years, the cumulative curve of precipitation and runoff depth was calculated and plotted for the nine large river basins of China (Fig. 6). It is seen that, the cumulative annual precipitation in the nine large river basins is characterized by a straight line, while the cumulative lines of streamflow are quite different from that of precipitation in north China rivers (e.g. Haihe River, Yellow River, Heihe River, Tarim River). The cumulative runoff depth for most areas in north China slowed down from 1970s at different extent (Fig. 6I–III and IX-b). The discrepancy of cumulative annual precipitation and streamflow indicates that significant change of rainfall-runoff relationship has occurred since then.

The changes of rainfall–runoff relationship can be further analyzed by using runoff coefficient, which represents annual runoff amount in unit precipitation. Fig. 7 shows the variability and linear trend of runoff coefficient in north China during 1956–2005. We can find that the trends of runoff coefficient significantly decreased for Song-Liao River, Haihe River and Yellow River in north China (Fig. 7a), and Heihe River and Tarim River in northwest China (Fig. 7e and f) while increased in south China (e.g. Yangtze R. and Nujiang R. in Fig. 7c and d). Runoff coefficient for Huaihe River in Fig. 7b has not presented any trend or tendency. After 1970s, runoff coefficients for the three rivers of Song-Liao River, Haihe River and Yellow River are extremely lower than those during 1950s and 1960s. Mean of runoff coefficient is 19.1%, 8.6% and 7.4% after 1970s for Song-Liao River, Haihe River and Yellow River, respectively, compared with 23.6%, 16.5% and 14.2% during 1950s and 1960s. The runoff coefficients of Haihe River and Yellow River after 1970s were reduced by half of those in 1950s and 1960s.

3.3. Human influences on streamflow – precipitation relationship

Runoff was not only driven by precipitation but also by evapotranspiration and human activities, such as irrigation, dam constructions and land use and land cover changes. The estimated annual actual evapotranspiration presents a decreasing trend in most areas east of 100°E in China and increase in areas west of it between 1960 and 2002 (details referring to Gao et al., 2007). The decreasing trends range from about 30 mm/10 years to 10 mm/10 years for most parts of the Haihe River basin. From the aspect of multi-year water balance in a catchment without any human interference, the decrease trend of annual actual evapotranspiration should slow down runoff decrease. The discrepancy of cumulative annual precipitation and streamflow (Fig. 6) and faster decreases of runoff than precipitation in north China (Fig. 5) indicate that in addition to precipitation changes, strong human activities have interfered on streamflow since 1970s.

The increasing water use taken from river course and reservoirs for irrigation is a main cause for the decreases of observed runoff in the northern part of China (Ren et al., 2002). Fig. 8a shows effective irrigation area (EIA) in China and a typical region of Hebei province in Haihe River basin, where agriculture primarily depends on irrigation. We can see that EIA linearly increases by a factor of 5 during 1950–2005, from 10 million hm^2 in the earlier 1950s to 55 million hm^2 in 2005 for whole China, and from less than 1 million hm^2 to 4.7 million hm^2 in Hebei province which area occupies more than half of Haihe River basin. For the total irrigation amount of north China showed in Fig. 8b, it linearly increases from 10 billion m^3 to 55 billion m^3 during the earlier 1950s–middle of 1970s, maintains steady amount around 55 billion m^3 during middle of 1970s–middle of 1990s, and decreases after then. The 55 billion m^3 irrigation water is about half of total outlet streamflow of three large north China rivers of Song-Liaohe River, Haihe River and Yellow River. Although the irrigation water has little increase since 1970s, industry and domestic water use increased dramatically

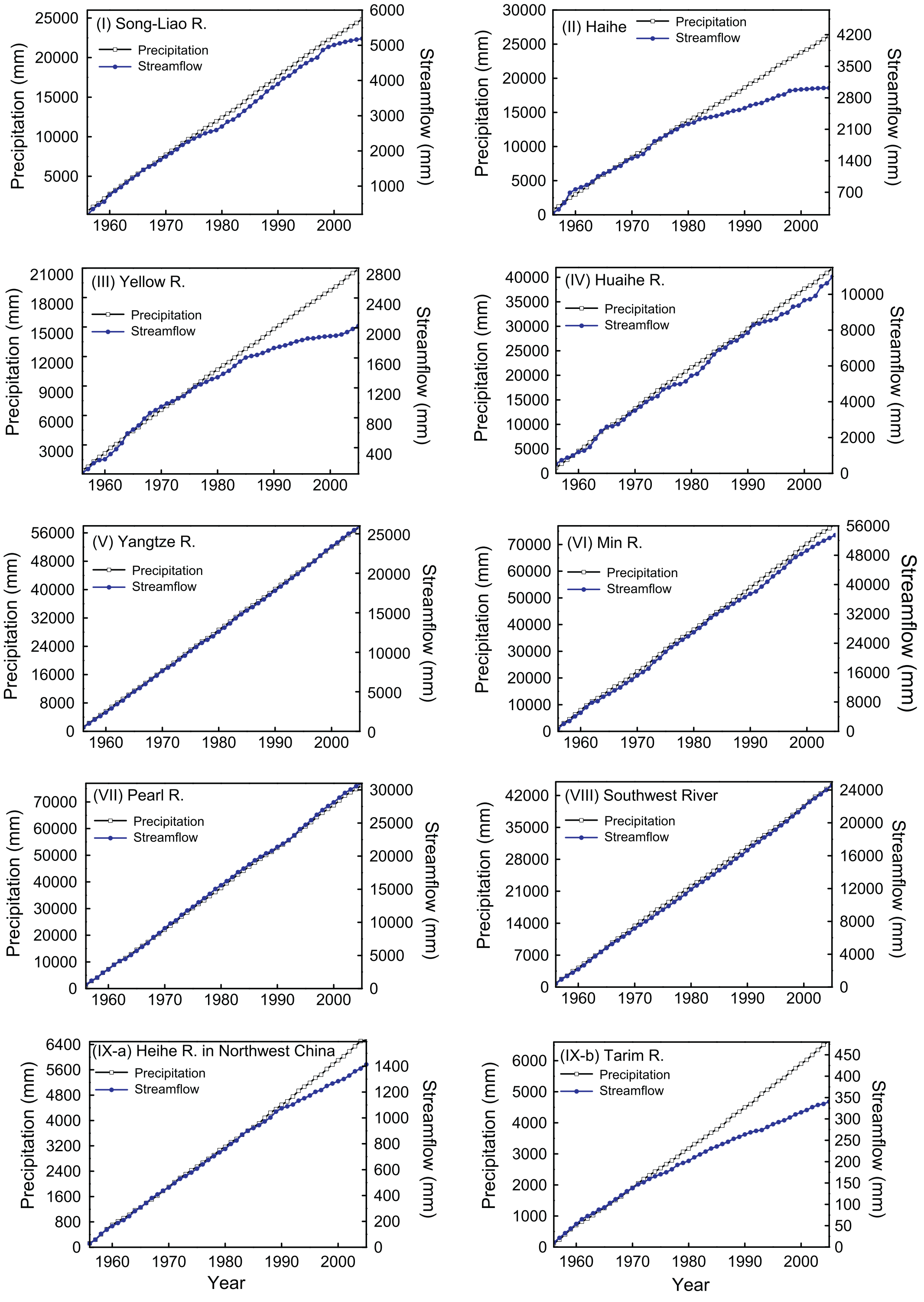

Fig. 6. The cumulative curve of precipitation (CCP) and runoff depth (RH) in nine large river basins of China.

from 7.0 billion m^3 in 1980 to 21 billion m^3 in 2005 (China sustainable development strategy report, 2007). As the actual evapotranspiration decreases, the increasing water use is the main reason that streamflow decline is faster than precipitation decease for these three rivers in the north China.

The streamflow in Haihe River catchment has been found decreased significantly which might affect the water use for irrigation and drinking. The annual irrigation amount during 1990s is about 28.5 billion m^3, larger than 21.6 billion m^3 of the total streamflow. The deficit part of the water needs for irrigation was partly obtained by extracting groundwater and partly obtained by importing water from other basins.

The correlation between the EIA of Hebei province and streamflow of four river basins in Haihe River is shown in Fig. 9. It is seen that the correlation between the EIA and streamflow is even higher than that between streamflow and precipitation (Table 3). Therefore, the human activity combined with precipitation decline are identified as the main driving factors of runoff decline in the arid and semi-arid regions of China (Fig. 9 and Table 3). The significant increasing trend of EIA is also found in the whole China which might be related to the decline in runoff coefficient in other basins of China during the past 50 years.

For extremely dry Inland Rivers, the total water utilization for irrigation, industry and domestic (more than 80% for irrigation) excesses the multiyear average streamflow. In Tarim River basin, irrigation area increased from 0.35 million hm^2 in 1950s to 0.78 million hm^2 in 1990s, and irrigation amount reached 0.148 billion m^3 in 1990s, twice over that in 1950s (Wang et al., 2003). Meanwhile, the annual actual evapotranspiration driven by more precipitation and higher temperature tended to increase since 1960 (Gao et al., 2007). Therefore, although streamflow in the headwater rivers presents increase tendency due to increases of precipitation and snow melting (Jian and Shuo, 2006), this increase could not compensate for the loss of streamflow in the lower and downstream areas due to increase of evapotranspiration and irrigation.

4. Discussions

The annual variability of streamflow is mainly controlled by the annual cycle of precipitation, evapotranspiration and catchment management practice. The study shows that, there have been significant decreasing trends in annual streamflow in north China

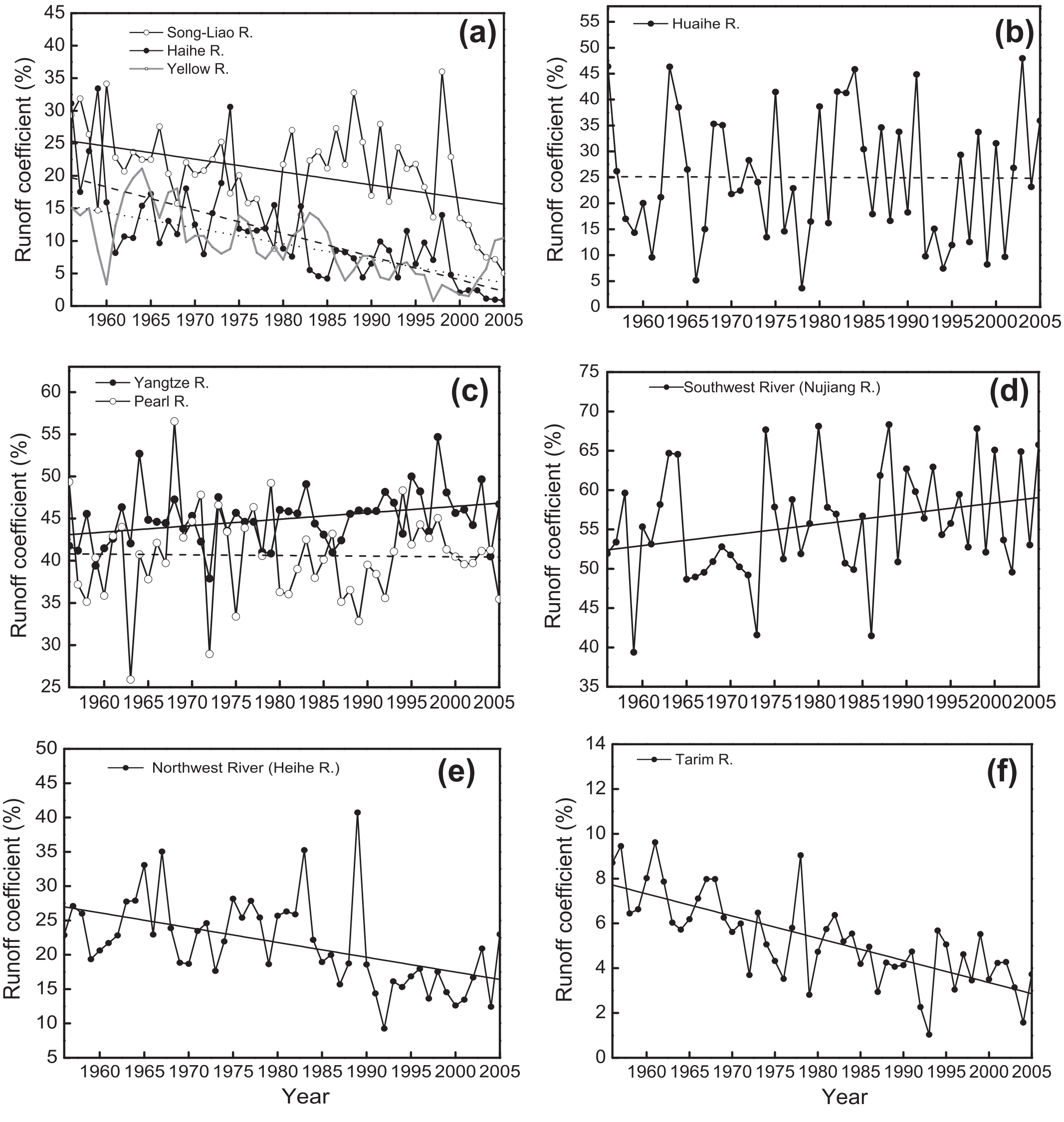

Fig. 7. The variability and linear trend of runoff coefficient of basins in (a) north China, (b) Huaihe R., (c) Yangtze R. and Pearl R., (d) Southwest China (Nujiang R.), (e) Norwest China (Heihe R.), and (f) Tarim R. Solid linear line means the significant linear trend at >95% level and dashed linear means a non-significant linear trend.

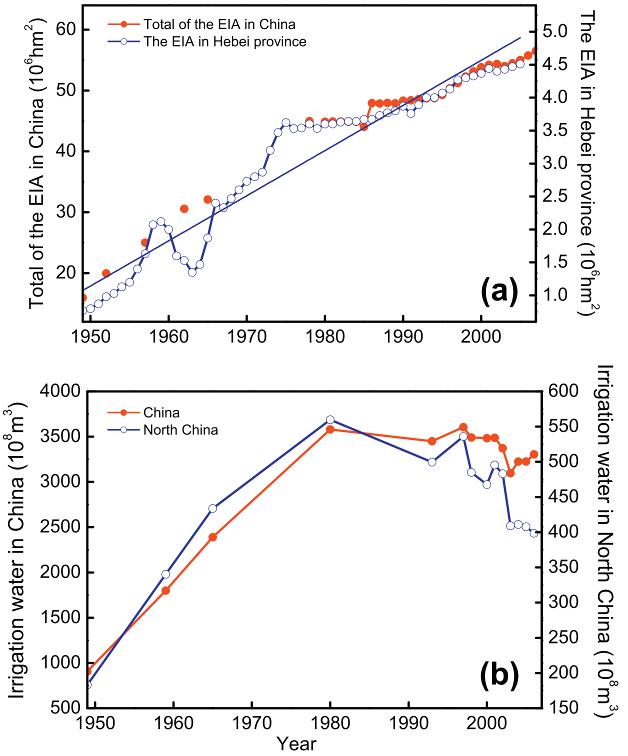

Fig. 8. The variability of effective irrigation area (EIA) and irrigation water in China during 1949–2009. The EIA data comes from: China Statistics Yearbook (http://www.stats.gov.cn/tjsj/ndsj/2008/indexch.htm) and Statistical Yearbook of Hebei Province. The irrigation water data comes from Yu and Wu (2009).

(arid and semi/arid regions). The absolute and relative reductions in streamflow were greater than the changes in precipitation since 1970s.

The water resources in China are inconsistent with the distribution of population, farmland and economy. The four northern river basins account for 46% of the national population, 45% of the national GDP, 65% of the national farmland, 59% of the national irrigated farmland, but less than 20% of the national water resources and the per capita volume of water resources is only 1/3 of that in the southern river basins (Chen, 2005). The plain areas in the lower reaches of the Yellow, Huaihe and Haihe rivers account for 1/3 of the national GDP and industrial output, but only 7.7% of the national water resources, while the Southwestern Rivers account for 21.3% of the national water resources, but only 0.7% of the national GDP and industrial output (Chen, 2005).

Stramflow decrease would result in serious ecological and environment problems. Most of the grassland in China has degraded or is degrading due to streamflow decrease. Wetlands and lakes have been drastically shrunk during last few decades due to climate change, water resource exploitation and land use change. About 800 lakes with a total area of 13,000 km^2 have disappeared since the 1950s (Pu et al., 1991). Since the 1990s, river dry-up in north China has attracted more attention, and was considered as one of the critical ecological problems in China. As river dries up, the river habitat is completely destroyed and the wetlands related to the river disappear. The Yellow River dried up in 1972 for the first time. Annual average dry-up days were 13 in the 1970s. Since then it has run dry sporadically. As a fitting indicator of the worsening situation, from 1985 the river has run dry for part of each year. In 1997, a drought year, the Yellow River failed to reach the sea for a record of 226 days. Before 1990, the dry-up episodes occurred mainly in early summer (May, June and July). Since the 1990s, the river dried up for varying numbers of days in almost every month. In response to this and related problems, in 2000 the Chinese government launched the 'South-to-North Water Diversion Project', which, together with a better water resources management policy, to a certain degree alleviated the serious water deficit. After 2000, zero-flow hydrological events seem to disappear. However, as Zhang et al. (2010b) pointed out that this does not mean that the

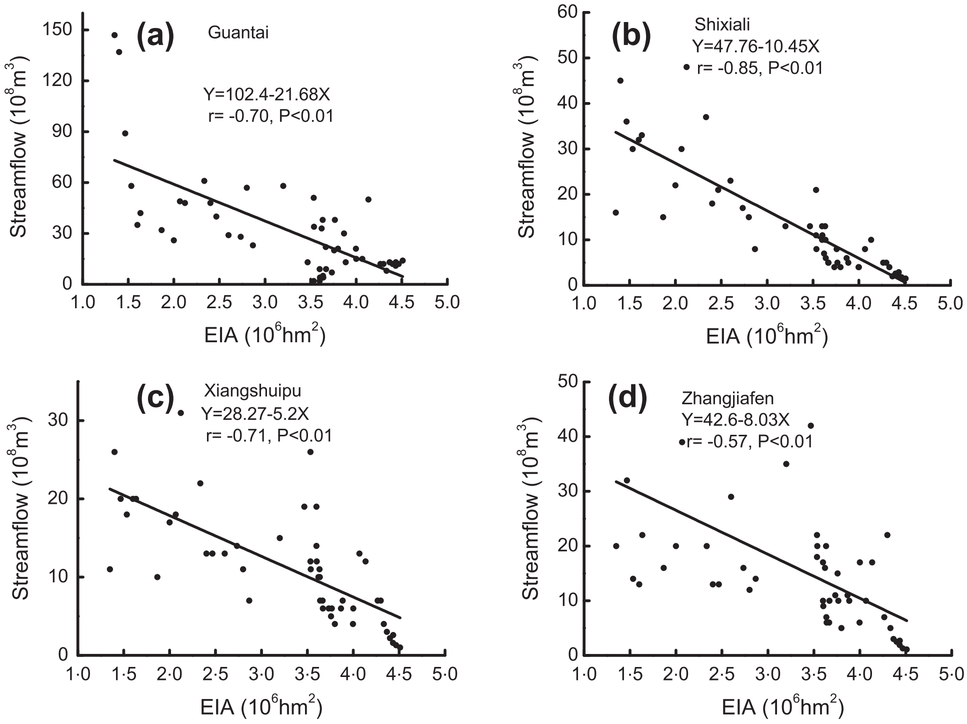

Fig. 9. Correlations between the streamflow and effective irrigation area (EIA) in Haihe River basin. (*R* is the correlation coefficient and *P* is the significance level. *P*-values smaller than 0.01 indicate that the correlation is significant at >99% confidence level).

water shortage problems in the Yellow River basin were solved. Sound water resource management is still urgently needed.

5. Conclusions

In this study, we analyzed the variations of annual streamflow and relationship between the annual streamflow and precipitation during 1956–2005 in China with the aim of exploring the changes in streamflow in nine large river basins and possible causes for decline in streamflow in China. Some interesting conclusions are obtained as follows:

(1) Annual mean streamflow significantly decreased in north and northwest China, such as Song-Liao River basin, Yellow River basin, Haihe River basin and the downstream region in Inland River basin, while increased in upstream region of Inland River basin, and for rivers in south and Southwest China during the past 50 years.
(2) Relatively, a good relationship between the annual streamflow and precipitation exists in most large river basins where the trend of streamflow is led by the changes of precipitation in a large scale, but the change of streamflow is greater than precipitation in the arid and semi-arid regions of north China and Inland area.
(3) A comparison of the cumulative annual precipitation and streamflow curves in nine large river basins in China showed that cumulative curves of streamflow depart from that of precipitation curves for north China and the Inland Rivers since 1970s, meaning that other factors than precipitation have caused the decline of streamflow. The runoff coefficient in north basins with heavy human interferences decreased sharply. There exists a non-stationary relationship between the annual precipitation and streamflow in north China and the Inland River basins during the past 50 years.
(4) Significant increasing trend of effective irrigation area (EIA) and water use is found both in whole China and in Hebei province. As actual evapotranspiration increases during the last 50 years for Haihe River, Yellow River and Songliao River in north China, faster decline in streamflow than precipitation decrease indicates that human activities significantly influence the relationship between precipitation and runoff. For inland areas where actual evapotranspiration increases along with precipitation increase, decline in streamflow of downstream rivers is primarily caused by human activities and temperature increase.

Quantitative evaluation of the relationship between streamflow and irrigation water use as well as other causes for the whole China is yet to be done when more data are made available. It is worth of noting that quantifying the causes of the runoff changes at large scale is both an important and challenging task given the limitations of the availability of data and robustness of methodology. Furthermore, in order to provide reference results for water resources planning, irrigation scheme designing and operation and for industrial and domestic water supply, variability of streamflow and its causes at finer time scale (i.e. seasonal and monthly) need to be studied, which imposes further challenge on future research. Nevertheless, this paper sheds light on the relationship between annual precipitation and streamflow in a large scale, which will be greatly helpful for better understanding of the decline in streamflow and underlying causes in China.

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