SCIENCE CHINA
Earth Sciences

• **RESEARCH PAPER** •

August 2013 Vol.56 No.8: 1398–1412
doi: 10.1007/s11430-012-4505-1

Contributions of climate and human activities to changes in runoff of the Yellow and Yangtze rivers from 1950 to 2008

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Received March 1, 2012; accepted September 18, 2012; published online September 30, 2012

Runoffs in the Yellow River and Yangtze River basins, China, have been changing constantly during the last half century. In this paper, data from eight river gauging stations and 529 meteorological stations, inside and adjacent to the study basins, were analyzed and compared to quantify the hydrological processes involved, and to evaluate the role of human activities in changing river discharges. The Inverse Distance Weighted (IDW) interpolation method was used to obtain climatic data coverage from station observations. According to the runoff coefficient equation, the effect of human activities and climate can be expressed by changes in runoff coefficients and changes in precipitation, respectively. Annual runoff coefficients were calculated for the period 1950–2008, according to the correlation between respective hydrological series and regional precipitation. Annual precipitation showed no obvious trend in the upper reaches of the Yellow River but a marked downward trend in the middle and downstream reaches, with declines of 8.8 and 9.8 mm/10 a, respectively. All annual runoff series for the Yellow River basin showed a significant downward trend. Runoff declined by about 7.8 mm/10 a at Sanmenxia and 10.8 mm/10 a at Lijin. The series results indicated that an abrupt change occurred in the late 1980s to early 1990s. The trend of correlations between annual runoff and precipitation decreased significantly at the Yellow River stations, with rates ranging from 0.013/10 a to 0.019/10 a. For the hydrologic series, all precipitation series showed a downward trend in the Yangtze River basin with declines ranging from about 24.7 mm/10 a at Cuntan to 18.2 mm/10 a at Datong. Annual runoff series for the upper reaches of the Yangtze River decreased significantly, at rates ranging from 9.9 to 7.2 mm/10 a. In the middle and lower reaches, the runoff series showed no significant trend, with rates of change ranging from 2.1 to 2.9 mm/10 a. Human activities had the greatest influence on changes in the hydrological series of runoff, regardless of whether the effect was negative or positive. During 1970–2008, human activities contributed to 83% of the reduction in runoff in the Yellow River basin, and to 71% of the increase in runoff in the Yangtze River basin. Moreover, the impacts of human activities across the entire basin increased over time. In the 2000s, the impact of human activities exceeded that of climate change and was responsible for 84% of the decrease and 73% of the increase in runoff in the Yellow River and Yangtze River basins, respectively. The average annual runoff from 1980 to 2008 fell by about 97%, 83%, 83%, and 91%, compared with 1951–1969, at the Yellow River stations Lanzhou, Sanmenxia, Huayuankou and Lijin, respectively. Most of the reduction in runoff was caused by human activities. Changes in precipitation also caused reductions in runoff of about 3%, 17%, 17%, and 9% at these four stations, respectively. Falling precipitation rates were the main explanation for runoff changes at the Yangtze River stations Cuntan, Yichang, Hankou, and Datong, causing reductions in runoff of 89%, 74%, 43%, and 35%, respectively. Underlying surface changes caused decreases in runoff in the Yellow River basin and increases in runoff in the Yangtze River basin. Runoff decreased in arid areas as a result of increased water usage, but increased in humid and sub-humid areas as a result of land reclamation and mass urbanization leading to decreases in evaporation and infiltration.

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precipitation, runoff, climate change, human activity, Yellow River, Yangtze River, runoff coefficients

Citation: Wang Y, Ding Y J, Ye B S, et al. Contributions of climate and human activities to changes in runoff of the Yellow and Yangtze rivers from 1950 to 2008. Science China: Earth Sciences, 2013, 56: 1398–1412, doi: 10.1007/s11430-012-4505-1

It is understood that hydrological cycles are affected by both climate change and human activities [1–4]. Climate change has resulted in the global rise of atmospheric temperature, and changed precipitation patterns. Climate observations indicate that, during the 20th century, global annual precipitation increased significantly at a rate of about 0.2 mm/a [4], and global surface temperature increased 0.2°C/10 a over the past 30 years, and by 0.8°C in the past century [5]. One of the most important potential consequences of climate change is its impact on global and regional hydrological cycles [6].

The temperature in China has increased by 1.2°C since 1960. Northern China is warming faster than southern China, at a rate of 0.4–0.15°C/10 a. The drier regions of northeastern China are receiving less precipitation in summer and autumn, with a 12% decline since 1960. In contrast, the wetter regions of southern China are experiencing higher precipitation during both summer and winter [7]. The spatial patterns of changes in precipitation are complex and variable in different regions around the world [8].

A number of studies have addressed the potential impacts of climate change on hydrologic variables. Following observations in the Shiyang River basin, a typical arid inland basin in northwestern China, Ma et al. [9] estimated that climate variability, in particular decreased precipitation, accounted for more than 64% of the reduction in mean annual stream flow. Bae et al. [10] found that runoff trends were affected by the inter-annual variation of precipitation and the amount of corresponding evapotranspiration, which was sensitive to temperature and vegetative cover. Chiew et al. [11] estimated an additional 7%–17% increase in mean annual runoff across southeast Australia for the 0.9°C global warming scenario.

Xu et al. [12] investigated a time series of runoff and related climate variables in the Aksu River in northwestern China and found that the cyclic patterns of runoff and regional climate factors were correlated on a 24-year cycle. The annual runoff exhibited a significant, positive correlation with temperature and precipitation factors at 4-, 8-, 16-, and 32-year temporal scales. Zhang et al. [13] suggested that stream flow changes in the Aksu River were strongly dependent on the increase in precipitation and glacier melting in recent decades, particularly after the 1980s.

Franczyk and Chang [14] found that, when compared to scenarios of changes in climate or urbanization alone, an urbanization-climate change scenario resulted in amplification of runoff in the Rock Creek basin in the Portland, Oregon, metropolitan area. Ma et al. [15] estimated that the impact of climate change on surface water, base flow, and stream flow was offset by the impact of land cover change in the Kejie watershed in Yunnan, southwestern China. Ficklin et al. [16] suggested that an increase in CO_2 and changes in temperature and precipitation had significant effects on agricultural runoff in the San Joaquin River watershed in California, USA.

Tang et al. [17] analyzed the changes in spatial patterns of climate and the condition of vegetation in the Yellow River basin from 1960 to 2000. The results showed that precipitation decreased and temperature increased in most parts of the Yellow River basin. The evaporative demand of the atmosphere decreased in the upper reaches and increased in the lower reaches of the river. Human activities had improved the condition of vegetation in irrigation areas. Jiang et al. [18] found a significant positive trend in flood discharges in the middle and lower Yangtze River basin related to spatial patterns and temporal trends of both precipitation and individual rainstorms in the last 40 years. Zhang et al. [19] reported that maximum precipitation patterns in the Yangtze River basin were relatively stable in the 1960s, but changed to variable increasing and decreasing trends in the mid-1970s. With respect to annual variability, the number of rainy days decreased, and precipitation intensity increased significantly in the middle and lower Yangtze River basin.

Apart from climate change effects, anthropic processes are known to affect hydrological processes. Runoff is influenced by both climate change and human activities; therefore, changes in runoff serve as an important indicator of climate/anthropogenic forcing and regional responses. The impact of humans on global water resources is one of the most serious crises faced by the world today [20]. The global water system has already been greatly impacted by humans [21], with more than half of the world’s large river systems significantly affected by human activities including land use change [22, 23], soil and water conservation practices [18], reservoir construction and operation, irrigation, and water abstraction [24].

In recent decades, the global human demand for fresh water has increased rapidly as a result of explosive growth in the world's population and the concurrent economic boom. A large proportion of the world’s population is currently experiencing water stress [25]. Consequently, the response of rivers to changing climate and human activities is an important topic in hydrology and many qualitative studies have been conducted [20, 26–28]. Moussa et al. [29] discussed the importance of the role of tillage and the ditch network on the form of the hydrograph, the lag time, the runoff volume, and the peak discharge.

Recently, research into the impact of climate change and human activities on hydrologic variations in arid regions of China has been conducted. Li et al. [30] estimated that human activities, such as soil conservation measures, were responsible for 87% of the total reduction in annual mean stream flow in the Wuding River, Loess Plateau, China, in the period 1972–1997, while climate variability accounted for 13%. Huo et al. [31] analyzed changes in annual stream flow in the Shiyang River basin and found that human activities such as irrigation accounted for 60% of total flow decreases in the 1970s, but that climate change was predominantly responsible for flow decreases at mountain outlets in the 1980s and 1990s. Miao et al. [24] estimated that during 1970–2008, climate change and human activities contributed 17% and 83%, respectively, to the reduction in river discharge in the Yellow River. Moreover, the impacts of human activities on the whole basin were magnified over time. Du et al. [32] showed that human activities and precipitation changes contributed 53% and 47%, respectively, to increased stream flow in the Zhengshui River basin, China, during 1991–2003. Xu et al. [33] found that runoff in the southern Yangtze River sub-basin had increased more than precipitation would suggest, most likely indicating decreased water storage, decreased evapotranspiration, or both.

Quantitative assessments of the impacts of climate change and human activities on long-term hydrological responses are very important for drainage basin management. However, none of the studies mentioned above specifically investigated the combined effect of climate change and human activities on flows and water levels in the Yangtze River. To the best of our knowledge, no previous studies have compared the temporal trend of precipitation with runoff for major Chinese basins or sub-basins during the past half century. In this study we focused on the two largest rivers in China, the Yellow River and the Yangtze River. We investigated the sensitivity of runoff to climate variation (precipitation changes) and human activities (land use change and economic development), to identify the effects of climate change, rapid economic development, and their combined effect on water resources at the watershed scale.

1 Study area

The Yellow River basin is the second largest river basin in China. The river has a total length of 5464 km and a drainage area of 752443 km^2 (excluding an isolated inflow area of about 42000 km^2). As shown in Figure 1, the river originates on the Tibetan Plateau, winds through the semiarid region around the Loess Plateau, and passes through the North China Plain before finally discharging into the Bohai Sea. Most of the Yellow River basin is characterized by semi-humid, semiarid and arid climates. The average temperature and precipitation level decreases gradually from southeast to northwest [34, 35] . Precipitation in the basin is of low intensity and long duration [36], and therefore natural processes also contribute to the scarcity of water resources in the basin [37].

The Yellow River has undergone major changes in its hydrological regime during the last several decades. Based on its hydrological characteristics, the basin is divided into three parts: the upper reaches; the middle reaches, where most water diversion for irrigation occurs; and the lower reaches, where no stream flow is generated because the channel bed is more than 3 m above the ground [36]. The Yellow River basin is of utmost importance to China in terms of food production, natural resources, and socioeconomic development. It passes through nine provinces and autonomous regions and supports 136 million people. The total cultivated area in the basin is 12.9 million ha, about 13% of the total cultivated area in China, but the basin holds only 3% of the country's water resources. The river also feeds more than 50 cities in the basin, each with a population of more than 500000 people, and significant amounts of water are supplied to the chemical, oil and mining industries in the middle and lower reaches [38]. The Yellow River basin has variable climate and complex land use and management schemes, making it one of the most regulated rivers in China. The hydrologic regimes of the middle and lower reaches of the Yellow River are significantly influenced by anthropic factors, including reservoirs and diversions for irrigation, which are believed to have been largely responsible for occurrences of zero flow in the Yellow River [36].

The Yangtze River originates in the Qinghai-Tibet Plateau and extends 6300 km eastwards to the sea. The catchment basin lies between 91°–122°E and 25°–35°N [39, 40] and covers an area of 1.81×10^6 km^2 (18.8% of China's total area). The climate is subtropical and warm-wet, the mean precipitation is 1000–1400 mm/a, and the evaporative capacity (potentially maximum evaporation) is 700–800 mm/a in the drainage area [41].

Originating from the Tibetan Plateau, the headwater of the Yangtze River's trunk stream is located 5100 m above sea level (a.s.l.) [41], and because of great topographic variability, the terrain of the basin is shaped like a ladder with three stairs. The Qinghai-Tibet Plateau in the west, the highest stair, has an average elevation of more than 3000 m a.s.l. The second stair, where the Sichuan Basin is located, has an average elevation of 1000 m a.s.l. and the third stair, on the East China plain, has an average elevation of about 100 m a.s.l. [18, 42] .

Hydrometric stations at Cuntan and Datong record the water discharges from the upper basin, and from upstream into the estuary, respectively. Downstream from Datong the river is influenced by sea-level fluctuations. According to records from the Datong Hydrometric Station, from 1951–2008 the Yangtze River transported a water discharge of about 8904.55×10^8 m^3/a in to the estuary.

The water discharge from upper Yangtze River, recorded at the Yichang Hydrometric Station, averaged 4284.36×10^8 m^3/a from 1951–1998, about half of the total discharge to the estuary.

Two monsoon events, the Siberian northwestern winter monsoon and the Asian southeastern summer monsoon (known as the Indian southwestern summer monsoon in the upper reaches of the Yangtze) occur each year [43]. Most of the precipitation occurs from May to October as a result of the southeastern monsoon and the annual mean precipitation is about 1100 mm.

There is a large yearly and seasonal fluctuation in water discharge to the sea. The mean monthly discharge has ranged from 84200 m^3/s recorded in August 1954, to 6730 m^3/s recorded in February 1963.

The Yangtze River flows through 11 provinces. In order these provinces are Qinghai, Tibet, Sichuan, Yunnan, Chongqing, Hubei, Hunan, Jiangxi, Anhui, Jiangsu, and Shanghai. Its catchment basin had a population of more than 440 million in 2008. Water resources in the Yangtze River Basin are of fundamental importance to the food security of the Chinese nation [44] .

Almost all the water reservoirs in the Yangtze basin are located in the tributaries. In total, 46627 reservoirs were built in the basin from the early 1950s to 1984, with a total volume capacity of 124.80×10^9 m^3, and an efficient volume capacity of about 71.30×10^9 m^3 [40]. Only the Three Gorges Dam (construction started in 1993 and completed in 2009, with a total storage of 39.3×10^9 m^3), and the Gezhouba Dam (construction started in 1970 and completed in the early 1980s, with a total storage of 1.58×10^9 m^3), are located in the main stream [45].

2 Data and methods

2.1 Data Sources

The meteorological data used in this study consist of monthly precipitation measurements and the monthly means of daily mean temperature measurements for 324 stations in the Yangtze River basin, and 205 stations in Yellow River basin (Figure 1). The data were collected from National Climatic Centre of China Meteorological Administration (CMA) (http://cdc.cma.gov.cn/index.jsp), and include records from January 1951 to December 2007 (Table 1). Most of the stations had more than 50 years of data and the new-

Figure 1 Map of the Yellow River and Yangtze River basins showing the location of hydrological and meteorological stations.

est station had 40 years of data. Precipitation data from many stations were found to be incomplete, but most of the missing data were from the 1960s and did not influence the findings of the present study.

The Inverse Distance Weighted (IDW) interpolation method was used to interpolate the calculated trends and to obtain a spatial distribution of temperature and precipitation [46]. It is a commonly used technique for the interpolation of points representing rain gauges to finite difference grids by creating a raster surface. The IDW technique implies that the interpolated raster surface is based on a weighted average of the station value, each station has a local influence that decreases with distance, and the value of each cell is more influenced by nearby stations, and less influenced by more distant stations[43].

Regional monthly precipitation series from 1951 to 2007 were interpolated using the IDW method and data from 529 meteorological stations in and around in Yellow and Yangtze River basins. Annual temperature (in °C) was calculated as the mean of monthly temperature, whereas annual precipitation (in mm/a) was the sum of monthly values.

In this paper, water discharge (Q, in km^3/a) is defined as the volume of water passing a given hydrological gauging station over a certain amount of time. Basin-wide runoff (R, in mm/a) is upstream from the gauging station. Periods of discharge are from the 1950s to 2008, and the earliest year depends on the first available measurement (between 1951 and 1957, Table 1). Figure 1 shows the locations of stations in and around the Yellow River and Yangtze River basins. The present study utilizes hydrologic data from the seven gauging stations listed in Table 1. The observed series cover the period from the 1951s to 2007. Figure 1 and Table 1 provide information on the station locations, associated drainage area, and annual mean runoff.

Four major hydrological gauges in the mainstream of the Yellow River and Yangtze River are used to evaluate the hydrologic trends of these changing rivers. The hydrologic regimes at these stations represent an overview of the hydrologic regime of the entire river.

Additional data were collected from the published literature. Data on China's population from 1950 to 2008 were gathered from the China Compendium of Statistics 1949–2008, which is compiled by the Department of Comprehensive Statistics of the National Bureau of Statistics. Data on the total withdrawal of water from the Yellow and Yangtze Rivers for agriculture, industry, and domestic use were obtained from the Bulletin of Water Resources in China (1997–2008). Water withdrawal rates and data on water consumption in China were also obtained from the sources mentioned above.

2.2 Methodology

The Mann-Kendall nonparametric test is a useful tool for the detection of trends [33, 47], and abrupt changes [32]. The present study applies this test for detecting the significance of trends in annual precipitation, and in runoff time series. Where a trend exists, a positive value indicates an increasing trend, and a negative value indicates a decreasing trend.

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

However, a problem associated with the Mann-Kendall test is that the result is affected by serial correlations of the time series. If a time series is positively correlated, the trend identification test will suggest a significant trend more often than it will for an independent time series[49, 50]. To remedy this situation, a prewhitening approach can be adopted to remove the serial correlation from the data set before applying the Mann-Kendall test [49]. The prewhitening approach consists of the following procedure: (1) Calculate the lag 1 serial correlation r; (2) apply the Mann-Kendall test directly to the original data series if $r < 0.1$; otherwise, employ prewhitening as

$$x_{w_\tau} = x_{\tau+1} - r x_\tau , \tag{2}$$

where x_{w_τ} is the prewhitened value at time τ and x_τ is the original value at time, and (3) apply the Mann-Kendall test to the prewhitened time series [51]. For more details see Hamed [52], Yue and Wang [53], Yue et al. [54], and Fleming and Garry [55].

Table 1 Detailed information on the hydrological stations in the Yellow River and Yangtze River basins

Station name		Data period	Missing	Drainage area (km^2)	Annual average precipitation (10^8 m^3/a)	Annual average water discharge (10^8 m^3/a)
Yellow River	Lanzhou (LZ)	1951–2005	2001	222551	1262.9	308.9
	Sanmenxia (SMX)	1953–2004	1998–2001	688421	3582.4	359.7
	Huayuankou (HYK)	1951–2008		730036	3841.4	379.8
	Lijin (LJ)	1951–2008		751869	3995.2	311.23
Yangtze River	Cuntan (CT)	1951–1998		866559	7747.8	3464.1
	Yichang (YC)	1951–2008		1010000	9840.0	4285.6
	Hankou (HK)	1951–2008		1488036	16352.1	7054.5
	Datong (DT)	1951–2008		1705383	20361.9	8904.5

2.3 Hydrogeological parameters

To separate and quantify the influences of climate change and local human activities on stream flow and sediment load variations under natural conditions, coefficients of river runoff, *a*, can be expressed as river runoff, *R*, divided by precipitation, *P*. Therefore, the change in river runoff can alternatively be defined as

$$\alpha = R/P,$$

$$R = \alpha \times P,$$

$$\Delta R = \Delta(\alpha \times P) = \alpha_n P_n - \alpha_0 P_0 = (\alpha_0 + \Delta\alpha)(P_0 + \Delta P) - \alpha_0 P_0 = \alpha_0 \Delta P + \Delta\alpha P_0 + \Delta\alpha\Delta P, \quad (3)$$

where ΔR is runoff variety; α_0 average annual runoff coefficient change; ΔP Precipitation change; $\Delta\alpha$ variations of runoff coefficients; P_0 average annual precipitation; hence $\Delta\alpha\Delta P$ value was small, assumed to be negligible, the change of runoff can be expressed as

$$\Delta P = \alpha_0 \Delta P + \Delta\alpha P_0. \quad (4)$$

To quantitatively describe the impact of precipitation and human activities on hydrologic variables at different stages, reference periods must be distinguished from affected periods. Reference periods are when there were no, or relatively few, human impacts on the river system during the study period, whereas affected periods are when human activities have had an obvious influence on the river systems. Changes in stream flow as a result of human activities are attributed to land use change, irrigation, abstraction, and treated effluent input.

3 Results

3.1 Trends in temperature and precipitation

Annual temperature and precipitation data from each subbasin measured over the last 50 years were analyzed using the nonparametric Mann-Kendall test and linear regression to identify long-term trends. The results of the nonparametric Mann-Kendall test and the Sen's slope are presented for temperature in Table 2, and the results for precipitation and runoff are presented in Table 3.

From 1951 to 2007, annual temperature series for all stations in the Yellow and Yangtze River basins underwent a gradual, increasing trend. In the Yellow River basin, temperature increased at approximately 0.32°C/10 a, 0.23°C/10 a, 0.19°C/10 a, and 0.19°C/10 a, at the Lanzhou, Sanmenxia, Huanyuankou, and Lijin stations, respectively. The results of the Mann-Kendall test showed that the increases were significant at the 99% confidence level for all stations except Lanzhou where increases were significant at the 95% confidence level.

Temperature in the Yangtze River basin was also mainly characterized by upward trends. Regional increases were 0.11°C/10 a, 0.13°C/10 a, 0.13C/10 a, and 0.14°C/10 a, for the Cuntan, Yichang, Hankou, and Datong stations, respectively. The upward temperature trends were significant at the 99% confidence level. However, the magnitude of the temperature change was relatively small in the Yangtze River basin, possibly because the temperature changes were offset by sufficient water resources. Most areas in the Yellow and Yangtze River basins have become warmer over the past half century.

Against the trend observed for temperature, precipitation tended to decrease in the past 50 years. The trends in annual precipitation differed among the hydrological stations on the Yellow River (Table 3). Annual precipitation showed no obvious trend in the upper reaches of the Yellow River, and little change was recorded at Lanzhou. However, there was a marked decline in precipitation in the middle and lower

Table 2 Results of the Mann-Kendall test for trend analysis of annual temperature in the Yellow River and Yangtze River basins

	Station name	Data period	Temperature	
			Slope	Significant (%)
Yellow River	Lanzhou	1953–2007	0.032	95
	Sanmenxia	1951–2007	0.023	99
	Huayuankou	1953–2007	0.019	99
	Lijin	1953–2007	0.019	99
Yangtze River	Cuntan	1957–2007	0.011	99
	Yichang	1957–2007	0.013	99
	Hankou	1957–2007	0.013	99
	Datong	1957–2007	0.014	99

Table 3 Results of the Mann-Kendall test for trend analysis of annual precipitation and runoff in the Yellow River and Yangtze River basins

	Station name	Data period (a)	Precipitation		Runoff	
			Slope	Significant (%)	Slope	Significant (%)
Yellow River	Lanzhou	54	0.00	NS	–0.78	95
	Sanmenxia	48	–0.88	95	–0.75	99
	Huayuankou	57	–0.92	90	–0.76	99
	Lijin	57	–0.98	90	–1.08	99
Yangtze River	Cuntan	48	–2.47	99	–0.99	95
	Yichang	57	–2.02	99	–0.72	90
	Hankou	57	–1.88	99	–0.29	NS
	Datong	57	–1.81	99	–0.21	NS

reaches of the Yellow River. At Sanmenxia, Huayuankou, and Lijin, annual precipitation declined at 8.8 mm/10 a (significant at the 95% confidence level), 9.2 mm/10 a, and 9.8 mm/10 a (significant at the 90% confidence level), respectively.

For the hydrologic series, all precipitation series exhibited a downward trend in the Yangtze River basin. The downward trends were significant at the 95% confidence level in Cuntan, Yichang, Hankou, and Datong. Spatially, the declining precipitation intensified in a downstream direction in the Yangtze River basin. Rates of decline ranged from about 24.7 mm/10 a at Cuntan station to about 18.1 mm/10 a at Datong station.

3.2 Trends and abrupt change points in runoff

The trends in annual runoff for the Yellow and Yangtze River basins during the past five decades are shown in Table 3. The Mann-Kendall test results show that annual flows for all sub-basins of the Yellow River have undergone a significant downward trend since 1950. Of the four hydrology stations, the trend seen for the Lanzhou series was significant at the 95% confidence level, for the other three stations the trends were significant at the 99% confidence level.

The absolute value of the slope reflects the rate of change. Spatially, the declining trend for runoff in the Yellow River basin increased in the downstream direction. The rates of decline ranged from about 7.5 mm/10 a at Sanmenxia station to about 10.8 mm/10 a at Lijin station.

For the Yangtze River, the runoff series recorded at Cuntan and Yichang stations showed downward trends significant at the 95% and 90% confidence levels, respectively. The trend was not significant at Hankou and Datong stations, with a rate of change of 2.9 and 2.3 mm/10 a.

The results of the Mann-Kendall test for abrupt change are shown in Table 4. For the Yellow River runoff series, the Mann-Kendall test indicates that abrupt changes occurred in the late 1980s to early 1990s. These abrupt changes in annual water runoff occurred earlier at the upstream stations and later at the downstream stations. At the Lijin station, the abrupt changes in runoff occurred in 1982.

At Lijin, the annual mean runoff before the abrupt change was 54.8 mm/a, and the corresponding annual mean value after the abrupt change was reduced to 24.0 mm/a. The differences between the pre-change (pre-T) and post-change (post-T) levels at all stations are presented in Table 4.

No significant abrupt changes were detected in the runoff series from the hydrological stations on the Yangtze River.

3.3 Runoff coefficient (α)

The runoff coefficient, α, reflects the effect of the underlying surface on the relationship between precipitation and runoff. Runoff coefficients are widely used as diagnostic variables for runoff generation in process studies, and as important input parameters in hydrologic design. Table 5 lists the runoff coefficients obtained from regression analysis for the different stations.

The results show that the trend in correlations of annual runoff decreased significantly, at the 99% confidence level, in the Yellow River basin. In the Yangtze River basin, the runoff coefficient was not significant at Cuntan and Yichang. The runoff coefficients at Hankou and Datong were significant at the 95% confidence level (Figure 2).

3.4 Double mass curve

Generally, the double mass curve between precipitation and runoff is approximately linear if there has been no impact of human activities on hydrological processes (Figure 3).

The distribution of cumulative points on the annual precipitation-runoff curve showed no significant change in Lanzhou. In Sanmenxia and Huayuankou the distribution began to fall below the regression line after 1990, and after 1980 in Lijin. The turning point in 1990 was the same as the change point for annual mean runoff detected by the Mann-Kendall test. There were no obvious inflection points for the double mass curve for Cuntan, Yichang, and Hankou. The double cumulative points of annual precipitation-runoff for Datong began to show an upward deviation from the regression line from 1995.

Table 4 Results of the Mann-Kendall test for abrupt changes in runoff in the Yellow River basin

Hydrological station	Runoff (mm/a)			
	Time	Pre-T	Post-T	Change (%)
Lanzhou	1992	146.3	111.8	–23.58
Sanmenxia	1987	58.2	36.3	–37.71
Huayuankou	1990	60.3	32.5	–46.03
Lijin	1982	54.8	24.0	–56.18

Table 5 Temporal variations of precipitation-runoff coefficients in the Yellow River and the Yangtze River basins from 1951 to 2007

Hydrological station	Coefficients of runoff		Hydrological station	Coefficients of runoff	
	Slope	Significant (%)		Slope	Significant (%)
Lanzhou	–0.0014	99	Cuntan	0.0000	NS
Sanmenxia	–0.0013	99	Yichang	0.0001	NS
Huayuankou	–0.0013	99	Hankou	0.0005	95
Lijin	–0.0019	99	Datong	0.0005	95

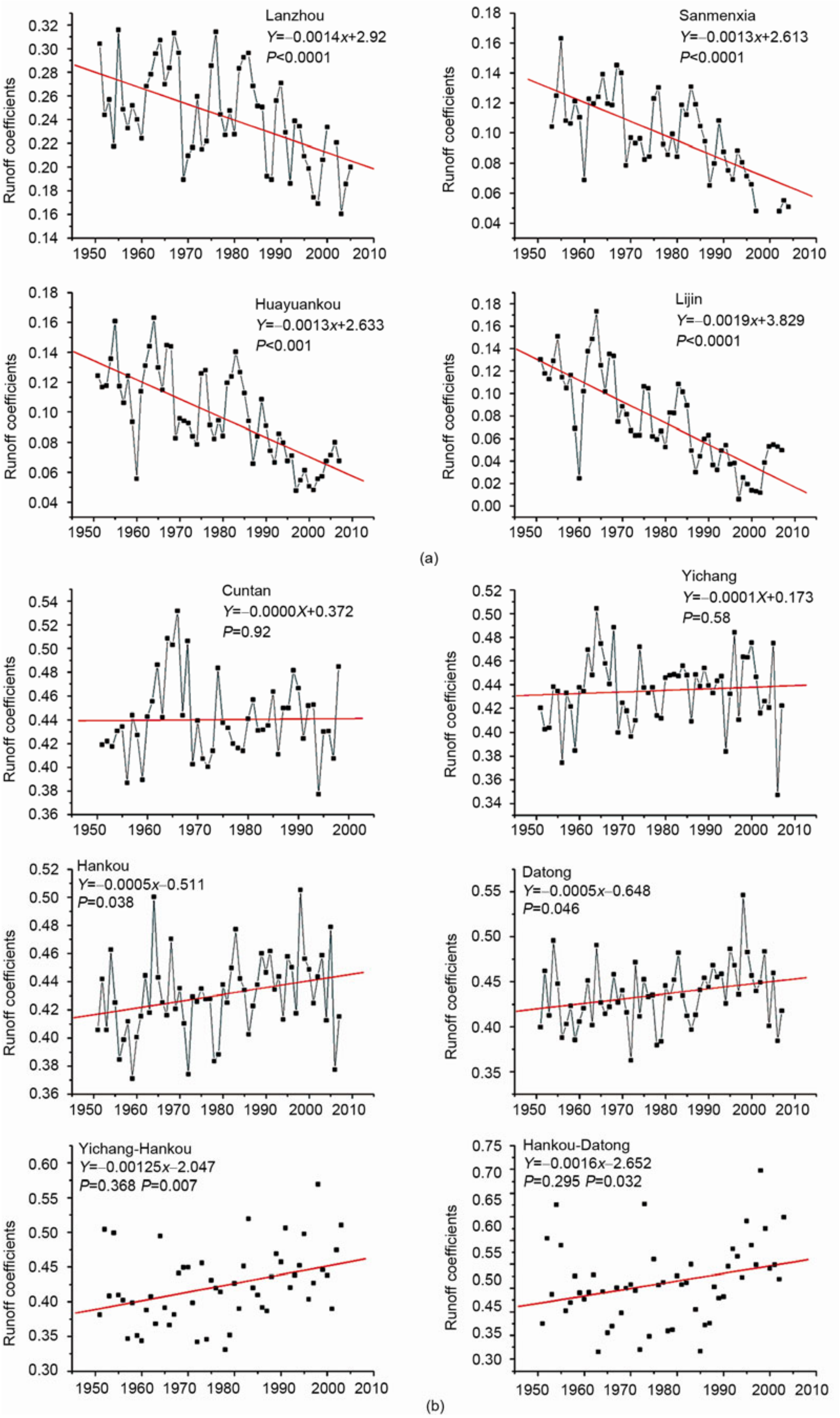

Figure 2 Changes in annual runoff coefficients for the Yellow River (a) and the Yangtze River (b).

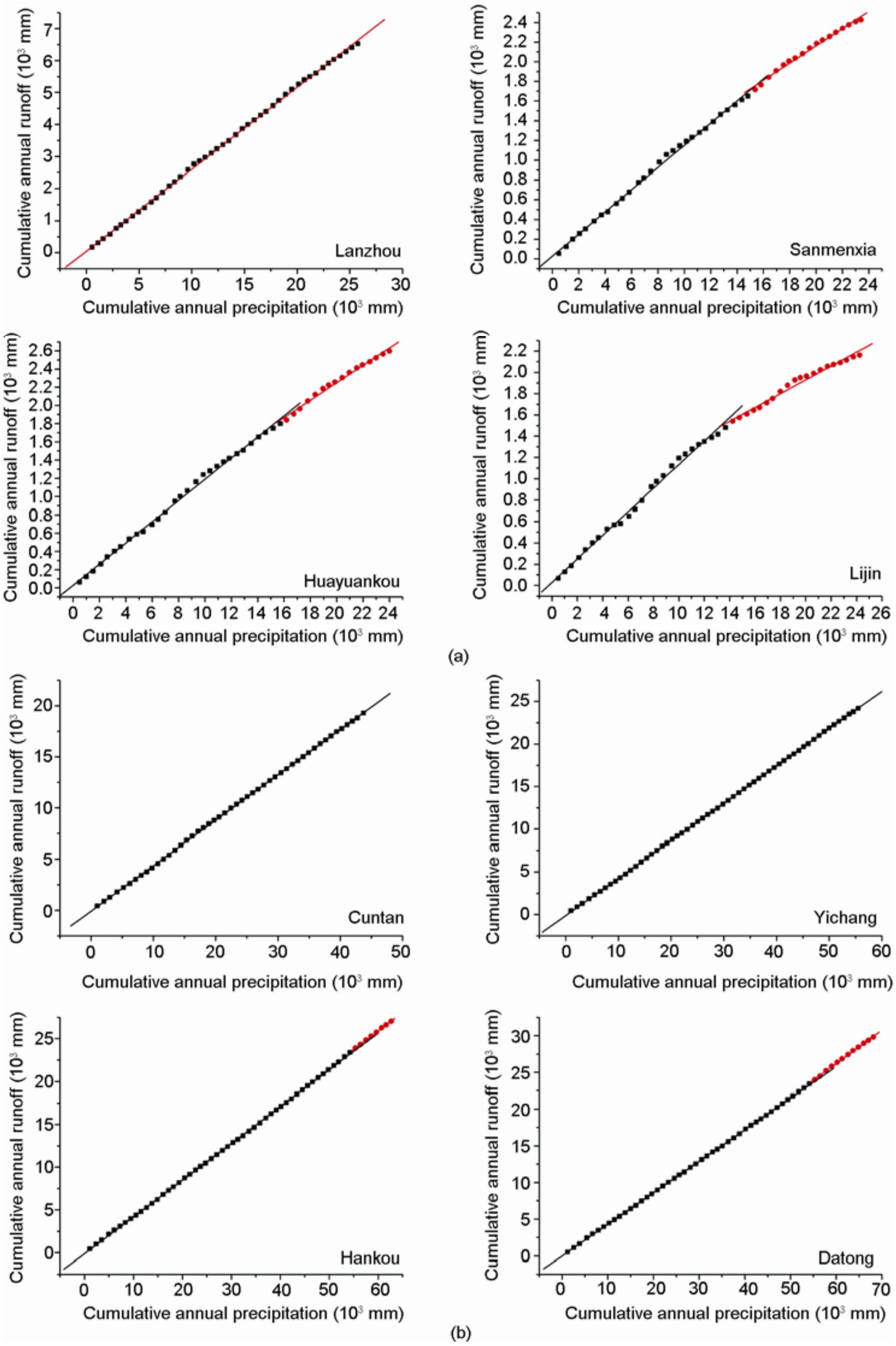

Figure 3 Double mass curves for annual precipitation and runoff for the Yellow River (a) and the Yangtze River (b).

3.5 Correlation between precipitation and runoff

Simple linear relationships between annual precipitation and annual runoff were used to identify the relationship between precipitation and hydrologic variations. In the Yellow River basin, the natural land cover has been significantly changed by large-scale development and construction activities since the 1970s [20, 48, 56]. To separate and quantify the influences of climate change and local human activities on stream flow variations, the 1950s–1960s were taken as the baseline or benchmark period. The linear regression relationships between annual runoff and annual precipitation for the reference and affected periods for the Yellow and Yangtze Rivers are plotted in Figure 4.

All correlations between annual precipitation and annual runoff before 1970 were significant at the 99% confidence

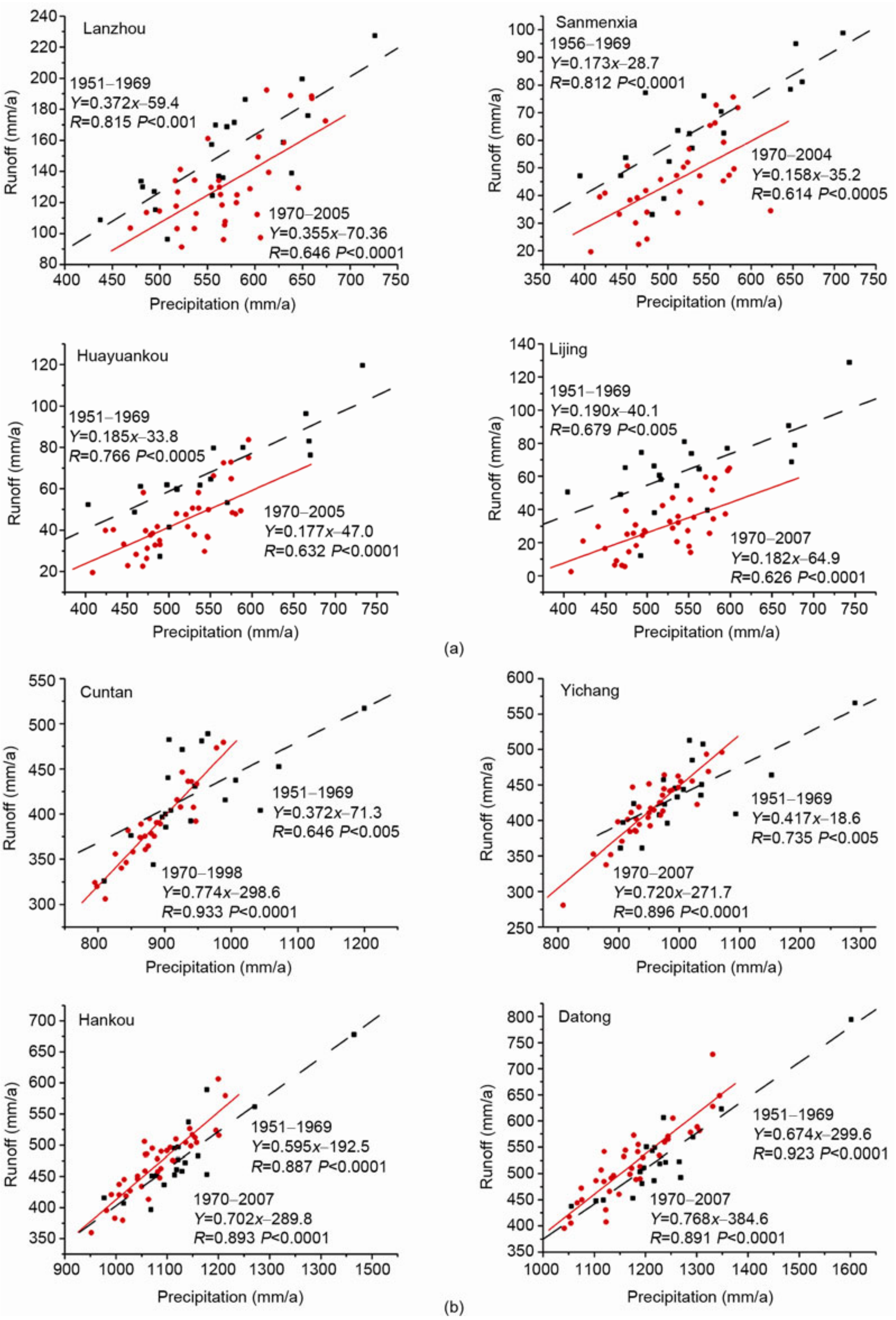

Figure 4 Double mass curves for annual precipitation and runoff in the Yellow River(a) and the Yangtze River basins (b).

level. In the middle and lower reaches of the Yellow River, the correlation was lower in 1960–1970 than in 1970–2008. In 1951–1969, results for precipitation correlated runoff for the Lanzhou, Sanmenxia, Huayuankou, and Lijin stations were 0.372, 0.173, 0.185, and 0.190, respectively. After the 1960s correlations decreased to 0.355, 0.158, 0.177, and 0.182, respectively. These results show that the correlation was greatly impacted by human activities after the 1960s in the middle and lower reaches of the Yellow River. The fitted line for the reference period 1970–2008 is above that for the affected period 1951–1969, suggesting that annual stream flow increased with precipitation.

Before the 1970s, the correlations for the Yangtze River stations were relatively low, with tendencies of 0.372, 0.417, 0.595, and 0.674, for Cuntan, Yichang, Hankou, and Datong, respectively, while after the 1960s the correlations increased to 0.774, 0.417, 0.702, and 0.768, respectively.

3.6 Quantitative hydrological responses to climate change and human activities

In the Yellow River basin, during 1970–2008, climate change and human activities contributed 11% and 83% to reductions in runoff, respectively. The corresponding contribution percentages for the Yangtze River basin were 29% and 71%, respectively. Regarding the Yellow River basin as a whole, it is obvious that the impact of human activities on changes to the hydrological series has been increasing almost monotonically over the past 40 years (Table 5). For water discharge, the impact of changes resulting from human activities has far exceeded those resulting from climate change during the 2000s. Human activities in the basin as a whole, in the 2000s, are directly responsible for 84% and 73% of the reductions in runoff in the Yellow River and Yangtze River basins, respectively.

Table 5 summarizes the contributions of climate change and human activities to the changes in runoff. These contributions can have either negative or positive effects on the hydrological series. The diversion of water had a positive impact on decreasing stream flow. The data listed in Table 5 are arithmetic average values, and the sign reflects the direction of dominant impacts. It should be noted that some of the largest percentage changes are a result of the small total change in the denominator.

In general, it is evident that human activities have contributed much more to changes in the hydrological series than climate change, no matter whether the effect was negative or positive. The impacts of human activities have been greater in the Yellow River basin than in the Yangtze River basin. In addition, human activities have played a dominant role in the Lanzhou and Lanzhou-Sanmenxia drainage area, while climate change has caused a greater decrease in runoff in the Sanmenxia-Huayuankou drainage area.

Human activities in the Huayuankou-Lijin area have caused the greatest reductions in water discharge, compared with other regions, and these reductions have continued over time. In the drainage area above Lanzhou, climate change causes alternating, but somewhat inconsistent, negative and positive impacts on water discharge.

At Cuntan station in the upper reaches of the Yangtze River basin, reduced runoff was caused primarily by human activities, while changes in precipitation played a small role. Both climate change and human activities in the Cuntan-Yichang area contributed to increasing runoff over all the periods studied. Human activities in the Yichang-Hankou drainage area also increased the values of the hydrological series, except in the 1970s. The most notable impact on changes in runoff in the Yangtze River basin is a reduction of about 190 mm/a, which occurred after the 1990s in the lower reaches, and is a result of human activities.

By comparing changes in runoff in the Yellow and Yangtze River basins between 1951–1969 and 1970–2007, decreases have generally occurred in the latter period. In the Yellow River basin, the main cause for decrease has been the over-utilization of water resources. The annual average runoff from 1980–2008 fell by 97%, 83%, 83%, and 91% compared to 1951–1969, at Lanzhou, Sanmenxia, Huayuankou, and Lijin, respectively. Most of the lost runoff was a result of human activities.

Changes in precipitation levels also caused a slight increase in runoff of about 1 mm at Lanzhou, whereas reductions of 3%, 17%, 17% and 9% were recorded at Lanzhou, Sanmenxia, Huayuankou, and Lijin, respectively.

Less precipitation was the main cause of runoff change, with 89%, 74%, 43%, and 35% reductions in runoff at Cuntan, Yichang, Hankou, and Datong, respectively. Changes in the underlying surface resulted in an 11% increase in runoff at Cuntan, while the influence of underlying surface on runoff at Yichang was not so apparent. At Hankou and Datong, runoff increased by 10 and 13 mm, respectively, as a result of human activities (Figure 5).

Decreasing levels of precipitation led to reduced runoff in the arid and semi-arid Yellow River basin and the humid and sub-humid Yangtze River basin. The impact of changes to the underlying surface caused by human activities differed between the two river basins. In the Yellow River basin these changes led to decreased runoff whereas they resulted in increased runoff in the Yangtze River basin.

4 Discussion

Evaporation in the Yellow River and Yangtze River basins

Table 5 Quantification of the impact of changes in the Yellow River and Yangtze River basins from 1970–2008

Data period	Runoff variation (mm)	Underlying surfaces variation (%)	Precipitation change (%)	Data period	Runoff variation (mm)	Underlying surfaces variation (%)	Precipitation change (%)
1970s	–505	75	18	1970s	126	62	36
1980s	–618	86	9	1980s	147	71	30
1990s	–670	85	7	1990s	251	77	24
2000s	–656	84	8	2000s	167	73	26
Average	–612	83	11	Average	173	71	29

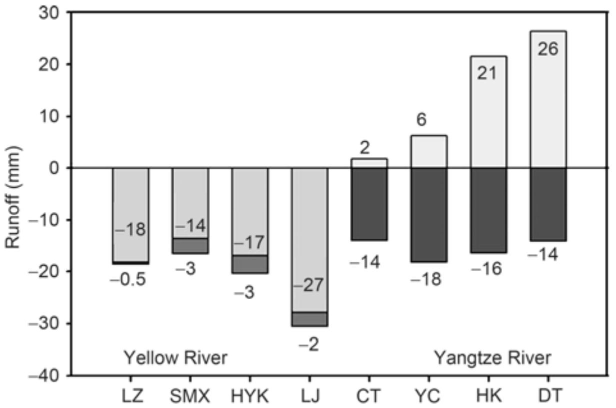

Figure 5 Quantification of the impact of changes in runoff from 1970–2008 in the Yellow and Yangtze River basins. The dark bars indicate the impact of changes in precipitation on runoff; the light bars indicate the impact of changes in underlying surfaces on runoff.

has decreased in the past 10 years. Previous studies have shown that the simulated annual evaporation in the Yangtze River basin has decreased significantly, as a result of decreasing net radiation and wind speed [57, 58]. Although a decrease in natural precipitation is the direct cause of decreasing stream flow, the effects of human activities, especially water-related human activities, on hydrology have intensified in recent years with economic development and the growing population. Potential human influences and the impact on the Yellow River and Yangtze River basins are summarized in the following sections.

4.1 Water consumption

Over the last 50 years, land use in the Yellow River and Yangtze River basins has changed as a result of increased anthropic pressure. In agricultural areas, water-related activities refer mainly to water extraction for irrigation. With population growth and expanding agriculture and industrial needs, major Chinese watersheds have been impacted by extensive anthropic activities, including damming, groundwater withdrawal, and water consumption. Water withdrawal is when water is directly withdrawn from surface or groundwater resources for agricultural, industrial or domestic use. Water consumption is defined as water directly lost to the watershed mainly through evapotranspiration.

Since 1950, both water withdrawal and water consumption in China have increased about 5-fold, as a result of a doubling of the population and increased irrigation and industrial activity. Most withdrawn water has been for agricultural use, with lesser amounts taken for industrial and domestic purposes. However, since 1980 industrial and domestic uses have doubled but agricultural use has not changed to a great extent. Given the rapid economic development in China, in the future industrial use may become more important.

In 2008, water consumption was 384.2×10^8 m^3 and 1951.5×10^8 m^3 for the Yangtze River and Yellow River basins, respectively [Data are from the Bulletin of Water Resources in China (1997–2008)].

Although water consumption in the Yangtze River watershed has been greater than that in the Yellow River watershed, Yangtze River water consumption represents only 10% of its annual discharge (957 km^3/a) whereas consumption for the Yellow River is 60% of its annual discharge (35 km^3/a). This finding explains why the water crisis has been much more severe in northern China than in southern China. Although decreased precipitation can partly explain the decreased runoff in northern China, increased water consumption appears to have been far more important.

4.2 Lake degradation

Lakes have been degraded by human activities at a rapid rate. The total area of natural lakes in China was about 46000 km^2, but between 1950 and 2000 about 30% of these lakes have vanished, mainly as a result of water withdrawal and lake reclamation [33].

In the 1950s, the lake areas in the Yellow and Yangtze River basins were about 1500 and 4350 km^2, respectively. The total lake area in the middle reaches of the Yangtze was 11711 km^2 in the 1930s, but by the year 2000 the total lake area had reduced to 4910 km^2. The most dramatic reduction in lake area occurred between the 1950s and 1970s when the lake area reduced by 5153 km^2.

The lake area in the Jianghan Plain in the Yangtze River basin has fallen markedly at a rate of 207.5 km^2/a. The number of lakes in the Jianghan Plain has also dropped by 116. By the 1970s, the total lake area in the middle reaches of the Yangtze River basin was only 5950 km^2 [59].

The lakes in Hubei province also changed rapidly in the last 50 years of the 20th century, especially in the 1960s–1980s, and cultivation was the main reason for the change. In the middle of the twentieth century, the area of lakes in Hubei province was about 8503.7 km^2， but it had decreased by 3025.6 km^2 in 2005, to 35.57% of the area 100 years before. There were 1309 lakes in Hubei Province in the 1950s, but by 2005 only 979 lakes remained.

By the year 2000 the total lake area in the middle reaches of the Yangtze River was 4910 km^2. Although the lake area and number of lakes continued to decrease between the 1970s and 2000, the rate of reduction had slowed to 41.6 km^2/a. The number of lakes that disappeared during this period was only 32 as compared to the loss of 116 lakes during 1950– the 1970s. Some lakes had vanished completely or were used for cultivation or other purposes. Human activities were the main cause of changes in the lakes in Hubei Province [60].

The area of Dongting Lake in the Yangtze River basin also shrunk rapidly during this period because of the inflow of sands from the Yangtze River and reclamation, resulting in the raising of the basin.

The water surface area of Dongting Lake decreased by 49.2%, from 4955 km^2 in the 1930s to 2518 km^2 in 1998, an average decrease of 38.1 km^2/a over the past seven decades. The degradation of lakes can be attributed largely to a rapidly growing human population in the lake regions, and to extensive reclamation [61].

Evaporation is water-limited in dry areas and energy-limited (radiation and air temperature) in wet areas [62]. The Yangtze River basin has been experiencing an overall rapid warming and wetting while wind speed and solar radiation have been declining in the past two decades, and in addition to changes in lake storage, there have been changes in evaporation. Since the evaporation rate of water is generally greater from lakes than from soil or sediment, the loss of lakes would result in a decrease in evaporation.

4.3 Urbanization

In the past two decades, the Yellow River and Yangtze River basins have undergone a rapid urbanization characterized by decreases in farmland and increases in urban land. Human activities and land-use changes have dramatically affected the regional water environment. In the Yellow River basin the urban population has increased from 8.62×10^6 in 1950, to 409×10^6 in 2008. In the Yangtze River basin, the urban population has increased from 1.1×10^7 to 18×10^7. Because water flow is less hindered over hardscape, the interconnection of developed areas is expected to increase the drainage capacity of the watershed. Studies have indicated that an expansion of urban land use will result in an increase in mean annual runoff [14]. The increase in urbanized areas and rural housing land will lead to less infiltration and higher discharge.

5 Conclusions

In addition to climate change, land use changes also have a profound influence on hydrological processes. Previous studies have identified global and regional climate change (mainly changes in precipitation) and local human activities as the two main factors that impact on the hydrological cycle.

In this preliminary study, we have estimated the relative contributions of human activities and climate change to the hydrological response of the Yellow River and Yangtze River basins. Several significant conclusions can be drawn from the analysis. In the last five decades, runoff has decreased significantly in the Yellow River basin; however, the changes in runoff in the Yangtze River basin have been minimal. Runoff in the Yellow River basin showed the most significant downward trends at most time scales, with an abrupt downward change from the late 1980s to the early 1990s. During 1970–2008, climate change and human activities contributed 11% and 83% to the reduction in runoff in the Yellow River basin, respectively, and 29% and 71% to the increase in the Yangtze River basin, respectively.

This study revealed that the impacts of human activities on the whole basin have increased with time. In the 2000s, the impact of human activities exceeded that of climate change, with human activities directly responsible for 84% of the reduction in water discharge in the Yellow River basin, and 73% of the reduction in the Yangtze River basin. In arid and subarid areas, the use of water for irrigation, industry, and domestic purposes has increased with rapid population growth, resulting in a significant change in runoff. A decrease in radiation in the last two decades has led to a decrease in evaporation and an increase in wet areas. In humid and sub-humid areas, reclamation of land from lakes and mass urbanization, and decreased evaporation and infiltration have all resulted in increases in runoff.

This work was supported by National Basic Research Program of China (Grant No. 2010CB951404), National Natural Science Foundation of China (Grant Nos. 41030527 and 41130368) and Hundred Talents Program of Chinese Academy of Sciences.

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