

Temporal and spatial patterns of low-flow changes in the Yellow River in the last half century

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Abstract Low-flow is widely regarded as the primary flow conditions for the anthropogenic and aquatic communities in most rivers, particularly in such an arid and semi-arid area as the Yellow River. This study presents a method integrating Mann–Kendall trend test, wavelet transform analysis and spatial mapping techniques to identify the temporal and spatial patterns of low-flow changes in the Yellow River (1955–2005). The results indicate that: (1) no trend can be identified in the major low-flow conditions in the upper Yellow River, but downward trends can be found in the middle and lower Yellow River; (2) similar periodic patterns are detected in

the 7-day minima (AM7Q) in the upper and middle Yellow River, while different patterns are found in the lower Yellow River; (3) the increasing coefficients of variance in the primary low-flow conditions suggest that the variability of the low-flow is increasing from the upper to lower stream; (4) climate change and uneven temporal-spatial patterns of precipitation, jointly with highly intensified water resource utilization, are recognized as the major factors that led to the decrease of low-flow in the lower Yellow River in recent decades. The current investigation should be helpful for regional water resources management in the Yellow River basin, which is characterized by serious water shortage.

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1 Introduction

The Yellow River, the second longest river in China, is the important source of water supply for the Northern China and has experienced major changes in its hydrological regime during the last several decades (Liu 1989; Liu and Zheng 2002). The increasing occurrences of the dry-year were identified in the Yellow River basin during the last 51 years. The increasingly serious water resources problems within the Yellow River have attracted considerable attentions (Liu and Zheng 2002; Liu and Zeng 2004; Liu and Zheng 2004; Yang et al. 2008a; Zhang et al. 2008). Therefore, detailed analysis of streamflow data at different time scales is urgently needed for effective water resources management within the Yellow River Basin. Further

understanding and good knowledge of hydrological features of the low-flow regimes in the whole basin is particularly important to understand the hydrological dynamic processes in order to support integrated water resources management (Beran and Gustard 1977; Belore et al. 1990; Arihood and Glatfelter 1991; Marsh 1999; Liu 1989; Liu and Zheng 2002; Smakhtin 2001; Xu 2001, 2002; Hannaford and Marsh 2006; Chen et al. 2008).

With the intensified human activities and climate change in the region, the Yellow River has been confronting serious water resources problems, especially in the last 30 years. Continuous zero flow periods in the lower reaches have resulted in serious ecological hazards as well as economic losses (Liu and Zheng 2002). Attempts have been made to understand the causes of the changes in streamflow in the basin (Liu 1989, Liu and Zheng 2002). Zheng et al. (2007) addressed that over-allocation of water for irrigation in the middle reaches of the basin has been identified as the main cause of flow reduction in lower reaches of the basin. It is also recognized that other factors, such as climate change or variability and land-use change, might contribute to the changes in the flow regime. From a conventional viewpoint, human intervention to alleviate flow conditions appears to be a growing necessity (Agnew et al. 2000; Hannaford and Marsh 2006). However, evidences for the causes of low-flow changes are mixed, particularly in relation to possible meteorological forces. Besides, although possibly taking effect over a long period of time, a large variety of engineering and non-engineering measures of water and soil conservation, flood control, water supply, hydropower and agricultural irrigation in the middle stream of the Yellow River are widely recognized as the additional causes of the decreasing streamflows (Xu 2001, 2002; Huang and Zhang 2004; Yu 2006; Yang et al. 2008a). However, it is difficult to quantify their individual effects (Wang et al. 2001; Zheng et al. 2007; Yang et al. 2008a, b).

The average annual runoff in the Yellow River Basin was 57 bcm (billion cubic meters) (YRCC 2001, 2002; IWMI and YRCC 2003) during 1956–2000, while the figure in the 90s was only 43 bcm which accounts for a drop of 24% in the drought decade. Groundwater has been extensively utilized in the basin since tubewell usage began in the late 50s. In 2000, groundwater extraction reached 10.7 bcm within the basin and 2.7 bcm outside the basin corridor along the low reach. The annual average per capita share of water resources is 553 m³, which is only 7.5% of the world average and 22% of China's average (YRCC 2001, 2002; IWMI and YRCC 2003).

Moreover, the Yellow River supplies the domestic and industrial water demands of 50 cities and 420 counties in the basin, and has periodical water diversion to Tianjin, Qingdao, and Jinan cities, all of which are thousands of kilometers away of the basin. Thus, the low-flow studies on

the Yellow River are definitely significant and urgent to formulate the regional strategy for sustainable development in North China. Although hydrologists have been investigating water deficit of the basin (Xu 2001, 2002; Liu 1989; Liu and Zheng 2002; Liu and Zeng 2004; Liu and Zheng 2004; Zheng et al. 2007), the past researches concerning low-flow regimes in the Yellow River have not sufficiently and systematically been addressed by using a combination of methods that provide results complementing to each other. For instance, the base-flow, magnitude, duration, timing and frequency of extreme low-flow in the Yellow River have never been discussed before. Therefore, this study aims to: (1) propose a procedure to analyze the temporal and spatial patterns of low-flow changes in large river basins by integrating trend analysis, frequency analysis, and spatial interpolation; (2) identify temporal trends and detect the periodicity of the major components of low-flow conditions under the impacts of climatic changes and human activities; and (3) quantify, map and evaluate the spatial trends, variabilities and expected values of major components of the low-flow condition based on seven hydrological gauging stations in the Yellow River Basin during the last half century. The possible causes of the changing low-flow regime in the lower Yellow River are also addressed for formulating the regional strategy of water resources planning and management.

2 Study area and data availability

2.1 Study area

The Yellow River originates from the Bayangela Mountain in western China and flows through nine provinces and autonomous regions. The length of the Yellow River is 5,400 km with the drainage area of 795,000 km² (Fig. 1). The basin contains 9% of China's population and 17% of agricultural land (YRCC 2001, 2002; IWMI and YRCC 2003). It has different types of climate: an arid and semi-arid continental monsoon climate in the northwest, and a semi-humid climate in the south-east. The basin's average annual temperature ranges from 4 to 14°C. As shown in Table 1, the average precipitation during 1956–2000 was 372 mm in the upper reach, 523 mm in the middle reach, 671 mm in the lower reach, and 454 mm over the entire basin (YRCC 2001, 2002; IWMI and YRCC 2003). More than 60% of the annual precipitation occurs during the period from June to September.

The river is divided into three reaches to facilitate the study as demonstrated in Fig. 1. The upper reach, which drains 51% of the basin area, provides 56% of total basin runoff based on pre-1990s average (IWMI and YRCC 2003). As it moves northward into a desert plain, however,

Fig. 1 Location of the study region and the hydrological stations. The river reach from headwater to Hekou is the upper Yellow River; the river reach between Hekou and Taohuayu is the middle Yellow River, and the river downstream to the Taohuayu is the lower Yellow River

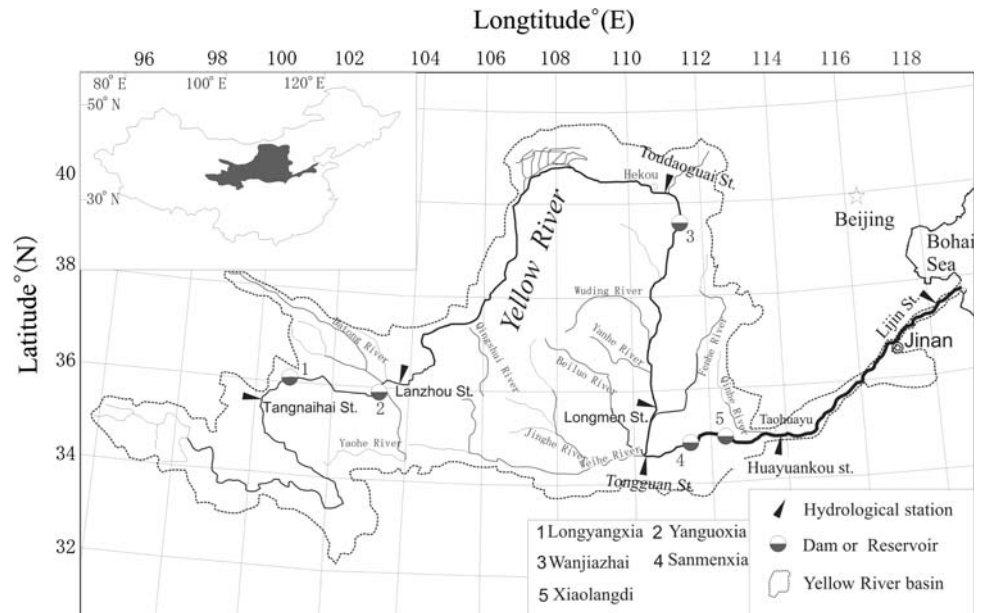


Table 1 Average annual precipitation (mm) in the Yellow River basin

Reaches	Time period				Average
	1956–1970	1971–1980	1981–1990	1991–2000	
Upper	380	374	373	360	372
Middle	570	515	529	456	523
Lower	733	689	616	614	671
Basin total	1,683	1,578	1,518	1,430	1,566

potential evaporation rises to a level of several times higher than precipitation, resulting in a largely reduction of streamflow. The middle reach covers 46% of the basin area and generates 42% of total basin runoff on average. The lower reach is one of the most unique river segments in the world. With almost no inflow, the lower reach contributes only 2% of the basin total runoff. The sediment transported from the middle reach begins to settle in the low reach as the river spills onto the flat North China Plain, producing a consistently aggrading, meandering riverbed, and “suspended” river. The “suspended” river channel poses severe flood threats if the levees break.

Low-flow is regarded as the primary flow conditions in most rivers of the world, especially in such an arid and semi-arid area as the Yellow River. The low-flow levels are sustained by groundwater discharge into the river. The seasonally varying low-flow conditions in a river impose a fundamental constraint on the anthropogenic and aquatic communities relying on the river. It has a strong influence on the diversity and the number of organisms living in the water, and more importantly on human-being’s daily life. Therefore, it is necessary to undertake the investigations of

low-flow conditions in the Yellow River, especially their spatio and temporal changes.

2.2 Data

In this study the daily runoff records from seven hydrological stations along the mainstream of the Yellow River Basin were analyzed. The detailed information of the data can be found in Table 1 and the locations of the hydrological stations can be found in Fig. 1. Prior to the analyses, the daily time series were validated by identifying and rectifying sequences of anomalous flows, and checking their completeness. Incomplete years were estimated from near-neighbor or analogue sites to preserve as much data as possible—annual variables such as minima could still be computed if comparison with nearby sites suggested the minima was unlikely to occur in the missing sequence. The hydrological observations at Longmen and Tongguan gauge during 1955–1964 are missing because these two gauges were set up since 1965. The following low-flow variables were derived by IHA software (Richter et al. 1996; TNC 2001; Chen et al. 2008): Table 2.

- Annual minimum 7-day flow (AM7Q, m³/s);
- Annual minimum 30-day flow (AM30Q, m³/s);
- Annual low-flow in wet and dry season (AFQD, ADQD, above the 75th and below the 50th percentile of monthly flows respectively, m³/s);
- Peak, duration, timing, frequency of extreme low-flow (below the 10th percentile of all low flows);
- Base-flow index (ABFI, 7-day minimum flow/annual mean flow);
- Zero-flow days.

Table 2 Detailed data information of the hydrological gauging stations. The location of the stations can be referred to Fig. 1

No.	Hydrological station	Drainage area (km ²)	Series length	Reaches
1.	Tangnaihai st.	121,972	1956–2005	Upper reach
2.	Lanzhou st.	222,551	1955–2005	Upper reach
3.	Toudaoguai st.	367,898	1958–2005	Middle reach
4.	Longmen st.	497,552	1965–2005	Middle reach
5.	Tongguan st.	680,000	1965–2000	Middle reach
6.	Huayuankou st.	730,036	1957–2005	Lower reach
7.	Lijin st.	751,869	1950–2005	Lower reach

These variables were chosen as the indicators of low-flow magnitude (minima), low-flow duration and frequency for the following reasons. (1) The 7-day over 10 year low-flow (7Q10) is the most widely used index in the USA, UK and many other countries (e.g. Smakhtin 2001). The minimum of 7-day average flow is known as ‘dry weather flow’ or ‘mean annual 7-day minimum flow’ (MAM7) (Smakhtin 2001). The 7- and 30-day period covered by MAM7 eliminates the daily variations of the river flow and analysis based on a time series of 7- and 30-day average flows is less sensitive to measurement errors. (2) The extreme low flow (Richter et al. 1996; TNC 2001) is a remarkable indicator for the health of a river ecosystem. Water chemistry, temperature, and the availability of dissolved oxygen can become highly stressful to many organisms during extreme low-flows period. On the other hand, the extreme low flows may concentrate aquatic prey for some species, or be necessary to dry out low-lying floodplain areas and enable certain plants such as bald cypress to regenerate. (3) The base-flow index and zero-flow days are potential indices to reveal water availability (Smakhtin 2001). Therefore, they were all used in the assessment on the temporal and spatial changes of the low-flow regime in the Yellow River Basin.

3 Methods

3.1 Mann–Kendall trend analysis

The Mann–Kendall trend test is regarded as a powerful tool in detecting the trend of a hydrological series (Yu et al. 1993; Van Belle and Hughes 1984; Zhang et al. 2006, 2007, 2008; Stefan et al. 2006; Yang et al. 2008b, 2009). In the current study, the rank-based Mann–Kendall method (MK) (Mann 1945; Kendall 1975) is used to assess the significance of monotonic trends in the streamflow series. This test has the advantage of not assuming any distribution form in the data and has the similar power as other parametric methods. Therefore, it is highly recommended for general use by the World Meteorological Organization (Mitchell et al. 1966). The MK method used in this study is

briefly described here. The null hypothesis H_0 is that the data (x_1, \dots, x_n) are a sample of n independent and identically distributed random variables (Yu et al. 1993). The alternative hypothesis H_1 of a two-sided test is that the distribution of x_k and x_j are not identical for all $k, j \leq n$ with $k \neq j$ (Kahya and Kalayci 2004). The test statistic S is computed by:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (1)$$

with

$$\text{sgn}(x_j - x_k) = \begin{cases} +1, & \text{if } (x_j - x_k) > 0, \\ 0, & \text{if } (x_j - x_k) = 0, \\ -1, & \text{if } (x_j - x_k) < 0. \end{cases} \quad (2)$$

Under the null hypothesis, the statistics S is approximated by a normal distribution when $n \geq 8$, with the mean and the variance as follows:

$$E(S) = 0 \quad \text{and} \\ \text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^n t_i(i-1)(2i+5)}{18},$$

where t_i is the number of ties of extent i .

The standardized statistics (Z) for one-tailed test is formulated as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}}, & \text{if } S > 0, \\ 0, & \text{if } S = 0, \\ \frac{S+1}{\sqrt{\text{Var}(S)}}, & \text{if } S < 0. \end{cases} \quad (3)$$

In a two-sided test for trend, the H_0 should be rejected if $|z| > Z_{1-\alpha/2}$ at the α level of significance. A positive Z indicates upward trend and a negative Z indicates downward trend (Kahya and Kalayci 2004). The effect of the serial correlation on the Mann–Kendall (MK) test was eliminated using the pre-whitening technique (e.g. Yue and Wang 2004).

3.2 Wavelet transform analysis

Wavelet transform is a powerful method to characterize the frequency, intensity, time position and duration of the variations in a climate data series (Jiang et al. 1997; Carl

and Kuhn 2008) by revealing the localized time and frequency information. It does not require the time series to be stationary as required by the Fourier transform and other spectral methods. We use the ‘Mexican hat’ in this study to analyze the low-flow datasets.

The wavelet transform and reconstruction are discussed as follows. The continuous wavelet transform coefficients $W(a, b)$ of a real square integrable signal $f(x)$ with respect to a real integrable wavelet $g(x)$ are defined in Katul et al. (1994) and in Gao and Li (1993) as

$$W(a, b) = (C_g a)^{-\frac{1}{2}} \int_{-\infty}^{\infty} f(t)g[(t - b)/a]dt \tag{4}$$

where $W(a, b)$ represents the wavelet transform function, or the so-called wavelet coefficients, of the raw data function $f(t)$; b is the location parameter and $a(a > 0)$ is the scale parameter. A larger a value corresponds to a longer time-scale or a lower fluctuation frequency; $C_g a$ is an energy normalization term, which ensures that the energy of the scaled ‘daughter wavelet’ equal the energy of the ‘mother wavelet’. The C_g is given as

$$C_g = \int_{-\infty}^{\infty} h^2(k)dk/|k| < \infty \tag{5}$$

where k is the wave number and $h(k)$ is the Fourier transform of $g(x)$ given by

$$h(k) = \int_{-\infty}^{\infty} g(x) \exp(-ikx)dx \tag{6}$$

The condition in Eq. 5 ensures the locality of C_g in the Fourier domain. The function $g(x)$ satisfies

$$\int_{-\infty}^{\infty} g(x)dx = 0 \tag{7}$$

This condition means that the area covered by the wavelet envelope is zero and ensures that the shape of the wavelet function is always in proportion to the parameters a and b while they vary. The ‘mexican hat’ function used in this study is

$$g(x) = (1 - x^2) \exp(-x^2/2) \tag{8}$$

where $x = (t - b)/a$, and defined within $-4 < x < 4$. In this basic wavelet function, a responds to 1/4 cycle. The variance of a wavelet component on the time-scale a is calculated as

$$V(a) = \sum_{b=1}^N W^2(a, b). \tag{9}$$

The raw data function $f(t)$ can be reconstructed from the wavelet coefficients by

$$y(a, t) = C_g^{-\frac{1}{2}} \int_0^{\infty} \int_{-\infty}^{\infty} a^{-\frac{1}{2}} g[(t - b)/a]W(a, b)dbda/a. \tag{10}$$

The wavelet expansion on the time-scale a is calculated as

$$f(t) = C_g^{-\frac{1}{2}} \int_0^{\infty} \int_{-\infty}^{\infty} a^{-\frac{1}{2}} g[(t - b)/a]W(a, b)dbda/a^2. \tag{11}$$

The use of the wavelet transform in the study of climatic changes and hydrological changes and other fields is receiving an increasing attention. Nakken (1999) applied the continuous wavelet transforms (CWTs) to detect the temporal changing characteristics of the precipitation and the runoff processes and their correlations, and separate the roles of climatic changes and human activities on streamflow and flood level changes(e.g. Bradshaw and McIntosh 1994; Fraedrich et al. 1997; Zhang et al. 2006, 2007).

4 Results

4.1 Trend of low-flow conditions

Table 3 provides the MK trends of low flow regimes of the Yellow River. In order to better understand the trends across the Yellow River basin, we discuss the changing properties of low-flow conditions for the upper, middle and lower reaches of the Yellow River Basin, separately.

(1) Upper Yellow River: No statistically significant trends can be detected in the low-flow series of Tangnaihai station. However, downward trends in the annual low-flow in flood season and the duration of extreme low-flow, upward trends in the peak of extreme low-flow and the annual base-flow index can be observed at Lanzhou station (Table 3). The trends may be due to the impact of Longyangxia and Yanguoxia dams (Fig. 1) on hydrological processes in the downstream river. Because there are almost no human perturbations in the upstream of Tangnaihai, the dominant force of streamflow processes is the climatic variations. Figure 2 indicates significantly decreasing trend in the total precipitation series across the entire basin (significant at the 5% level). The annual precipitation in the upper Yellow River demonstrates a similar trend but with a moderate slope in comparison with that of the total precipitation in the entire basin. The annual precipitation in the upper reach decreases at the rate of 5 mm/decade from 380 mm in 1960s to 360 mm in 1990s, in the drainage area upstream to Tangnaihai and Lanzhou station.

(2) Middle Yellow River: The annual minima and frequencies of the extreme low-flow show significantly

Table 3 Results (P -value) of trend test for the annual hydrological components of low-flow using Mann–Kendall statistical test

Hydrological components of low-flow	Tangnaihai	Lanzhou	Toudaoguai	Longmen	Tongguan	Huayuankou	Lijin
Annual minimum 7-day flow (m ³ /s)	0.06 (–)	0.08 (+)	0.01 (–)*	0.01 (–)*	0.01 (–)*	0.26 (+)	0.01 (–)*
Annual minimum 30-day flow (m ³ /s)	0.08 (–)	0.19 (+)	0.01 (–)*	0.01 (–)*	0.01 (–)*	0.55 (+)	0.01 (–)*
Annual low-flow in flood season (m ³ /s)	0.08 (–)	0.01 (–)*	0.03 (–)*	0.22 (–)	0.56 (–)	0.02 (–)*	0.01 (–)*
Annual low-flow in dry season (m ³ /s)	0.18 (–)	0.63 (+)	0.08 (+)	0.09 (–)	0.90 (–)	0.34 (–)	0.01 (–)*
Peak of extreme low-flow (m ³ /s)	0.08 (+)	0.01 (+)*	0.62 (–)	0.73 (+)	0.92 (–)	0.24 (+)	0.12 (–)
Duration of extreme low-flow (days)	0.72 ()	0.03 (–)*	0.95 ()	0.24 (–)	0.40 (–)	0.71 ()	0.77 (–)
Timing of extreme low-flow (Julian date)	0.09 (–)	0.23 (+)	0.51 (–)	0.41 (–)	0.25 (–)	0.01 (+)*	0.20 (–)
Frequency of extreme low-flow	0.19 (+)	0.26 (+)	0.01 (+)*	0.01 (+)*	0.01 (+)*	0.33 (+)	0.01 (+)*
Annual base-flow index	0.85 ()	0.01 (+)*	0.04 (–)*	0.80 ()	0.82 (+)	0.01 (+)*	0.01 (–)*

Annual low-flow in flood season is mean low-flow during July, August and September; annual low-flow in dry season is mean low-flow during December, January and February; Extreme low-flow is defined as the low-flow which is below 10th percentile of all low flows, and annual base-flow index is 7-day minimum flow/annual mean flow. (Richter et al. 1996; TNC 2001)

The ‘(+)’ means an upward trend, the ‘(–)’ means a downward trend, and ‘()’ means no trend

* denotes statistically confidence at >95% level

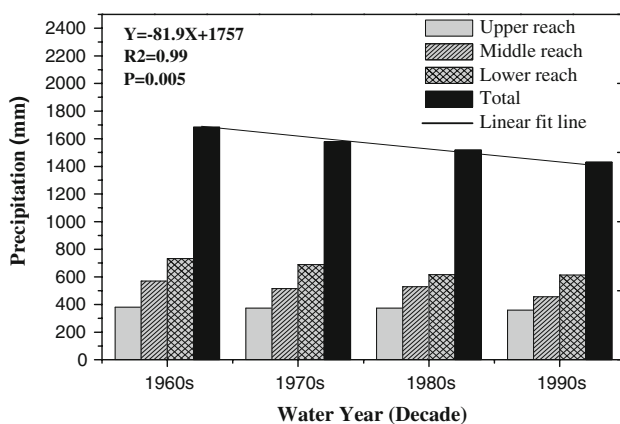


Fig. 2 Precipitation in Yellow River basin and associated linear trend for total precipitation of entire basin (1960–2000) (IWMI and YRCC 2003)

downward and upward trends, respectively (significant at the 5% level) for three stations (Toudaoguai, Longmen and Tongguan) in the middle Yellow River (Table 3). For the annual minima of the 7- and 30-day flow, the MK trends are decreasing. However the MK trend is increasing for the frequency of extreme low-flow. The results indicate that the low-flow regimes of the middle Yellow River is decreasing overwhelmingly. Due to the positive influences of Wanjiashai dam, the annual base-flow indices at Longmen and Tongguan do not decrease as in Toudaoguai, implying the impacts of human activities (i.e. operation of large-dams) on the increase of low-flow in the middle reach of Yellow River. In addition, it is obvious that no significant trends are detected in the other five low-flow components including the annual low-flow in flood, dry season, peak, duration and timing of extreme low-flow in the middle reach of the Yellow River.

(3) Lower Yellow River: It is well identified that the MK trends of the low-flow series at Lijin differ from those at Huayuankou in the lower Yellow River. Most of the low-flow indices at Lijin are decreasing (significant at the 5% level) except the peak, duration and timing of the extreme low-flow (Table 3). We also can conclude that most of the low-flow components at Lijin demonstrate the leading downward trends amongst seven stations throughout the entire basin. However, the major hydrological components of the low-flow series at Huayuankou have no significant trends ($P > 0.05$) except the timing of the extreme low-flow and annual base-flow index show upward trends. Xiaolangdi reservoir, acting as the most important hydro-project in flood control, agricultural irrigation and sediment deposition in the middle and lower Yellow River basin, changed the natural flow-regimes downstream significantly since its completion in 1997 (Yang et al. 2008a). Hence, the increasing trends in the Julian day of the extreme low flow and annual base-flow index can herewith regarded as the result of the impact of reservoir regulation through agricultural irrigation.

4.2 Potential periodicity of the major low-flow variable

AM7Q is generally regarded as the primary component (known as ‘dry weather flow’, Smakhtin 2001) of low-flow regimes. Thus, this sub-section concentrates on the identification of the underlying periodicity of AM7Q at seven hydrological stations along the entire Yellow River.

(1) Tangnaihai station: Fig. 3a demonstrates nested periods with wetness and droughts in three different scales of the AM7Q. Periods of both 9 and 6 years can be identified as a governing feature on the periodicity of the

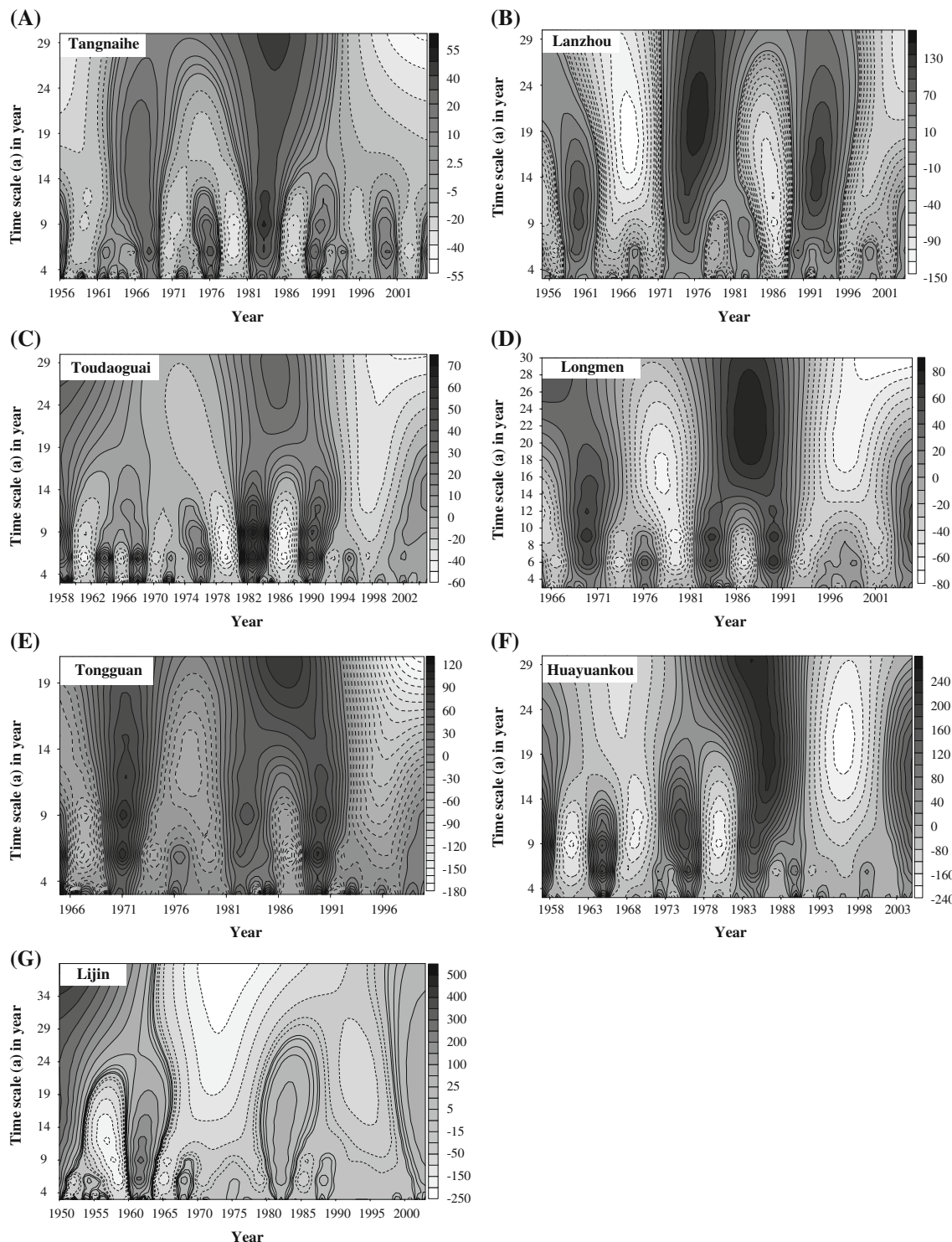


Fig. 3 Wavelet transform analysis of annual minimum of 7-day flow (AM7Q) in the Yellow River during 1955–2005, in which the *dashed isolines* with *light grey* colors denote negative wavelet coefficients,

whereas, the *solid isolines* with *dark grey* colors denote positive wavelet coefficients

low-flow series from wavelet coefficients. The long periods of low-flow regimes are controlled by climate changes, while a variety of human activities (i.e. irrigational influences, land cover changes and hydro-projects construction)

behave as major contributions to hydrological oscillations in short periods.

In addition, the areas in the lightest grey color indicate that Tangnaihai suffered the most serious droughts in 1971,

1978, 1987 and 2003, while those in darkest grey color imply that the AM7Q of Tangnaihai occurs with the highest degrees in 1984 and 1990 during past 50 years (Fig. 3a). Following the implication of dark-grey color, it is obvious that Tangnaihai has been confronting with a rather dry period since 1994, which aggravates the severity of water shortage in the Yellow River.

(2) Lanzhou station: Fig. 3b identified that the periods of AM7Q at Lanzhou are 14, 11, 7 and 4 years. The periods of 1961–1971, 1981–1988 and 1996–2005 are identified as dry periods that Lanzhou ever experienced, amongst which 1961–1971 is undoubtedly the most serious dry period.

(3) Toudaoguai station: it is shown that the AM7Q series at Toudaoguai changed with a medium period of 12–15 years, commencing from wet period (1958–1970) and subsequently followed by dry (1970–1982), wet (1982–1990) and dry period (1990–2005), and containing small alternations with occurrence of 7–8 years (Fig. 3c). In spite of the dry season (1990–2005), an area containing solid isolines in dark-grey color (near year 2004, 2005 in horizontal coordinate) within the wavelet coefficient figure suggest a small upward trend in AM7Q since 2004.

(4) Longmen station: the major periodical characteristics of the AM7Q series between Longmen and Toudaoguai (Fig. 3c, d) are much similar; both of them are dominated by the similar pattern discussed above for Toudaoguai. The confluences of the two tributaries, the Wuding and Yanhe River which could be neglected during dry periods compared with that of mainstream, could not change the principal hydrological behaviors of AM7Q in the mainstream at Longmen. Hence, the major features of Fig. 3c and d are similar.

(5) Tongguan station: apart from the underlying periods of AM7Q at Tongguan (22, 10 and 4 years) demonstrated in Fig. 3e, the same phenomenon on the pattern of hydrologic alternations for AM7Q with medium values can be observed at Toudaoguai and Longmen (Fig. 3c, d). The contribution to the low-flow in mainstream, Beiluohe, Fenhe, and Weihe River, are likewise proved to be small during dry seasons.

(6) Huayuankou station: it is recognized from Fig. 3f that the AM7Q series at Huayuankou changed with periods of 29, 18, 9 and 7 years. AM7Q of Huayuankou station shows downward trends during 1958–1963, 1966–1970, 1978–1980 and 1991–2000, but upward trends in other periods. After 1991, the wavelet coefficient values are negative for long time period, having somewhat similar changing features as those in Longmen station (Fig. 3d).

(7) Lijin station: the light-grey color areas with dashed isolines of the AM7Q series at Lijin (Fig. 3g) imply that the downstream of the Yellow River has confronted serious droughts since 1964 and the drought is most severe amongst seven stations along the entire Yellow River.

Over-utilization in the upstream and non-joining inflow from the first order tributaries (which contributes to 3% of the basin total runoff, Fig. 1) is the major causes responsible for the driest condition at Lijin. Figure 3g also suggests that the possible periods of the AM7Q series at Lijin are 22, 28, 9–10 and 4 years.

4.3 Spatial patterns of the trends and variability of low-flow regime

4.3.1 Spatial mapping of trend of low-flow regimes

The MK trends of the six major low-flow hydrological components in the Yellow River (1955–2005) enable us to examine the underlying low-flow patterns under the combined influences of climatic change and human activities (e.g. deforestation, dam construction and operation, intensive irrigation, groundwater over-extraction). The results presented in Fig. 4 and Table 3 indicate the following points: (a) The spatial trends of AM7Q in the Yellow River are identified as same as that of AM30Q (Fig. 4a, b), that is, the reach from Lanzhou to Tongguan and the downstream reach of Huayuankou demonstrate downward trends ($P < 0.05$), whereas the other reaches do not have statistically significant trends ($P > 0.05$). Therefore, they are undoubtedly replaceable of each other in trend analysis of the Yellow River. (b) Unlike ALQF (Fig. 4c, d), ALQD does not show significant trend in most of the reaches except for the reach from Huayuankou to Lijin, suggesting that the downstream reach of Huayuankou is confronted with more and more serious water shortage while the demands for water resources are increasing. (c) Opposite to the AM7Q and AM30Q, the FELQ in most of the reaches show the upward trends, meaning that the frequencies of the extreme low-flow in most reaches are significantly increasing. (d) Fig. 4f illustrates that ABFI in two reaches (Tangnaihai to Lanzhou, Tongguan to Huayuankou) are significantly increasing because of the considerable influences of reservoirs (Longyangxia, Yanguoxia, Sanmenxia and Xiaolangdi) on the subsurface flow.

4.3.2 Evaluation on spatial variability of low-flow components

The expected values together with coefficients of variance (CV) of ten low-flow hydrological components including the magnitude, extremes, duration, timing and frequency of low-flow conditions for seven representative stations associated with three reaches are presented in Table 4 to assess the spatial variability in the Yellow River (1955–2005). The results indicate that: (a) High magnitudes (7-, 30-day min, dry flow and Xflow peak) of the low-flow at are identified at Lanzhou (the upper Yellow River) and

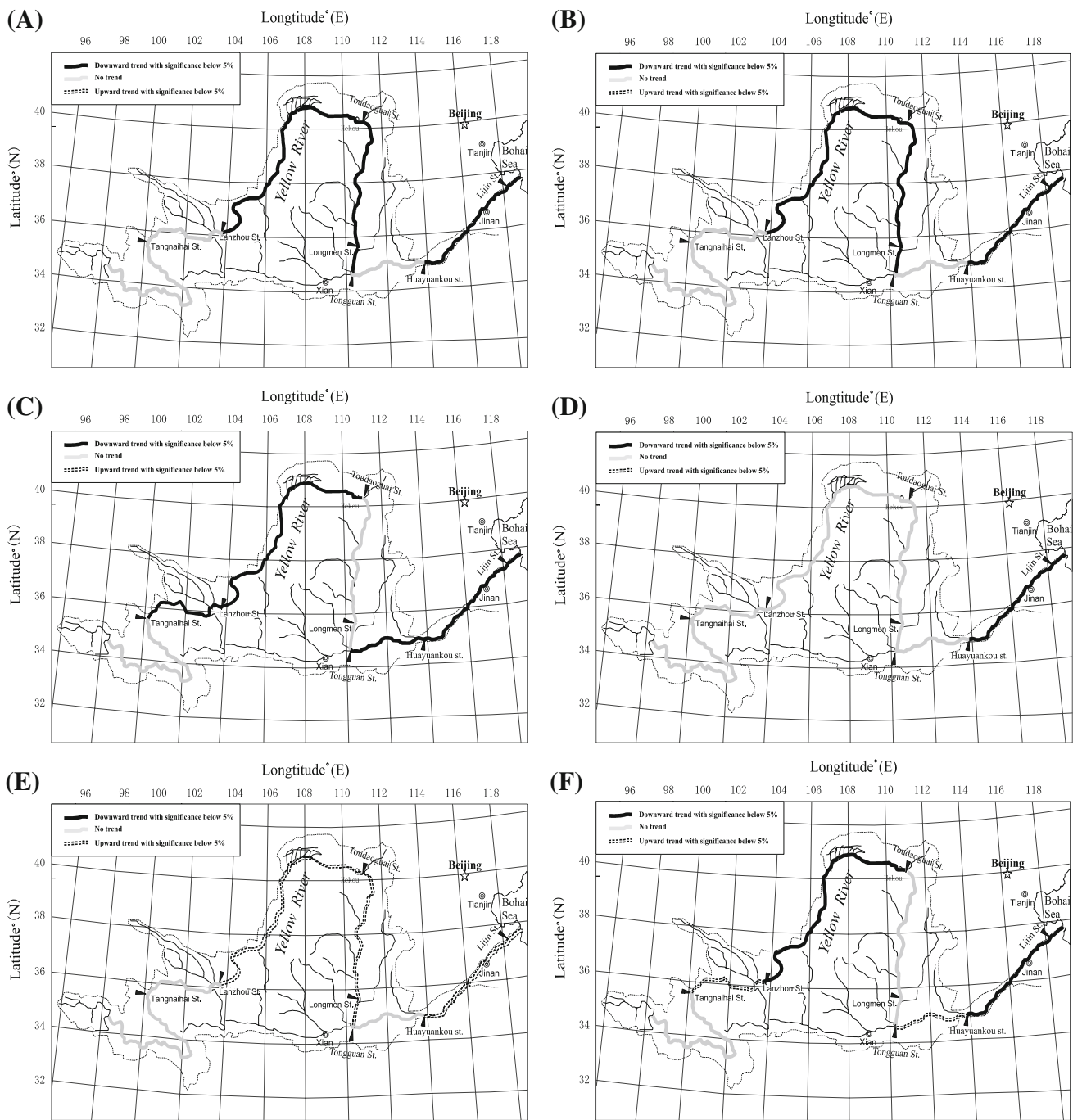


Fig. 4 The MK trend of the six major low-flow hydrological components in the Yellow River during 1955–2005, which represents: **a** Annual minimum 7-day flow (AM7Q); **b** Annual minimum 30-day

flow (AM30Q); **c** Annual low-flow in flood season (ALQF); **d** Annual low-flow in dry season (ALQD); **e** Frequency of extreme low-flow (FELQ); **f** Annual base-flow index (ABFI)

Tongguan (the middle Yellow River), while low magnitudes are found at Tangnaihai (the upper Yellow River) and Toudaoguai (the middle Yellow River). Meanwhile, the overall CV of the low-flow demonstrates an increasing trend along the river, meaning that the variability is increasing from upstream to downstream. The increasing variability of the annual low-flow along the Yellow River

leads to various influences in many aspects including water resources management, stream ecology and fluvial geomorphology. (b) The durations and frequencies of the extreme low-flow among all the sites do not follow a single governing trend. (c) The increasing timing of the extreme low-flow indicates that the Julian date of Extreme low-flow in middle stream (in early-June) and downstream (in late-

Table 4 Statistical summary for the ten primary low-flow hydrological components in the Yellow River (1955–2005)

Station	Reach	7-day min		30-day min		Zero days		Base-flow index		Dry flow		Flood flow		Xlow peak		Xlow dur		Xlow time		Xlow freq	
		Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
	Upper	150.3	0.23	157.3	0.23	0	–	0.24	0.19	672.6	0.16	189.3	0.17	132.5	0.10	11.0	1.54	23.8	0.59	3.9	0.55
	Upper	359.3	0.21	416.1	0.22	0	–	0.39	0.29	521.7	0.19	943.1	0.18	326.3	0.17	4.3	2.17	64.9	1.13	6.7	0.81
	Middle	92.6	0.54	157.3	0.57	0	–	0.14	0.38	406.6	0.27	469.7	0.28	84.7	0.29	12.2	1.01	183.8	0.39	2.6	0.64
	Middle	143.2	0.41	229.2	0.43	0	–	0.19	0.37	492.7	0.16	529.4	0.29	127.4	0.13	4.5	0.78	189.6	0.46	4.5	0.90
	Middle	245.5	0.46	357.0	0.39	0	–	0.23	0.43	518.0	0.19	562.0	0.50	232.7	0.23	6.5	1.89	172.7	0.57	5.0	0.74
	Lower	196.7	0.73	317.5	0.53	0	–	0.18	0.67	557.5	0.26	808.8	0.30	162.8	0.34	9.6	1.19	139.3	0.76	3.5	0.83
	Lower	104.7	1.73	188.0	1.20	48	–	0.08	1.39	423.3	0.50	608.0	0.52	2.0	1.44	6.0	0.80	149.0	0.38	3.9	0.79
	Upper	254.8	0.23	286.7	0.24	0	–	0.32	0.24	597.2	0.18	566.2	0.18	229.4	0.14	7.7	1.86	44.4	0.86	5.3	0.68
	Middle	160.4	0.46	247.8	0.39	0	–	0.19	0.39	472.4	0.21	520.4	0.36	148.3	0.22	7.7	1.23	182.0	0.47	4.0	0.76
	Lower	150.7	0.87	252.8	1.03	24	–	0.13	1.03	490.4	0.38	708.4	0.41	82.4	0.89	7.8	1.00	144.2	0.57	3.7	0.81

7-day min represents annual minimum 7-day flow (AM7Q, m³/s), 30-day min represents annual minimum 30-day flow (AM30Q, m³/s), Zero days represents zero-flow days, Base flow represents Base-flow index (ABFI), Dry flow represents annual low-flow in dry season (ALQD, m³/s), Flood flow represents annual low-flow in flood season (AFQD, m³/s), Xlow peak, Xlow dur, Xlow time and Xlow freq means Peak (m³/s), duration (days), timing (Julian date) and frequency (times) of extreme low-flow respectively
CV coefficient of variance, – not applicable

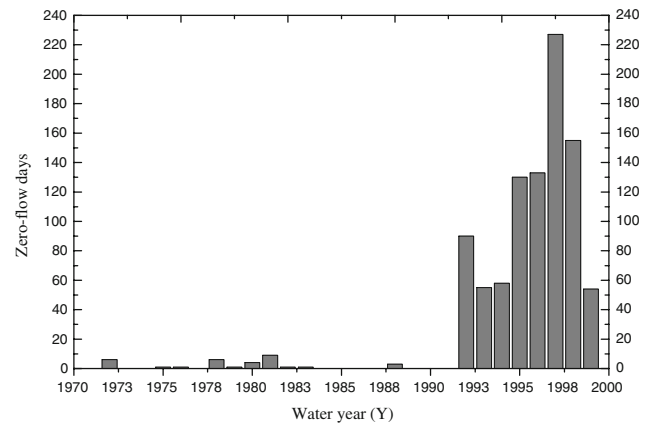


Fig. 5 Zero-flow days in each year that drying out of the Yellow River recorded at the Lijin Station

April) is later than that in upstream (in mid-February) due to the influences of dam operation. (d) The spatially decreasing base-flow index from upstream to downstream demonstrates that the subsurface flow in the Yellow River is decreasing along with the runoff processes to the sea. (e) The zero-flow days at the Lijin station increased dramatically from 1992 to 1997 with the longest zero-flow days of 227 days in 1997, and subsequently decreased since then (Fig. 5).

4.4 Probable causes for the decreasing low-flow in the lower Yellow River

4.4.1 Natural factors

The climate changes and uneven temporal-spatial patterns of precipitation determine the water availability across the Yellow River. The area upstream to Lanzhou accounts for 29.6% of the watershed, its runoff is 33.7 billion m³ accounting for 50% of total runoff in the whole basin but water consumption is only 6.3% of the total. The area from Lanzhou to Hekou is 163,000 km² accounting for 21.7% of the basin’s total area (YRCC 2001, 2002; IWMI and YRCC 2003) but its net runoff is negative because it is very arid with intensive river evaporation and infiltration (Liu 1989). However, the water consumption in this area accounts for 41% of the basin total. In the Huayuankou to Lijin section in the lower reach, locally generated runoff accounts for only 1.8% of the total, while the water consumption accounts for 35.1%. In addition, 60% of the annual flow occurs during the wet season (July–October). In some tributaries of the Loess Plateau (Middle stream), runoff distribution is highly concentrated with 80–90% of the annual total discharge (YRCC 2001, 2002; IWMI and YRCC 2003). In the spring there is very little precipitation and limited runoff in the Yellow River basin. However, irrigation in the spring, especially for wheat, needs a lot of water and therefore the drying up of the river occurs quite

frequently (Liu 1989; Liu and Zeng 2004; Liu and Zheng 2004; IWMI and YRCC 2003). Herein, uneven temporal–spatial patterns of the runoff processes, together with the reduction of precipitation (climate changes) in the 1990s played a very important role in the drying up of the lower reaches of the Yellow River.

4.4.2 Human activities

The major water consumption in the Yellow River basin is irrigation, which accounts for 80% of the total water use (YRCC 2001, 2002; IWMI and YRCC 2003). Since the 1950s, the pressure on land and food has been arising with the growing population, causing the increasing water demand for irrigation. The irrigation water is mainly pumped from the Yellow River. Figure 6 shows that the irrigated area in the 1990s (4.87 million hm²) was 3.5 times that of the 1950s (1.4 million hm²). The water consumption, including agriculture, industry and domestic water use, was 12.3 billion m³ in the 1950s but rose to 17.8, 25.0 and 29.6 billion m³ in 1960, 1970, and 1980s, respectively. The total water consumption was 30 billion m³ in the first 6 years of the 1990s (Liu and Zheng 2002; Liu and Zeng 2004; Liu and Zheng 2004). The total area of irrigated land is 2.3 million hm³ in the lower reaches of the Yellow River where there are 122 pumping and channeling engineering facilities with capacity of 4,000 m³/s. The total pumping and channeling capacity along the Yellow river is 6,000 m³/s, which is much larger than the available water resources. Over utilization on water resource speeded up the drying out of the river.

5 Conclusions and discussion

The Mann–Kendall trend test and wavelet transform analysis are powerful tools to detect the temporal-spatial

patterns of time series. In this study these tools are used to identify the spatio-temporal patterns of the low-flow regimes in the Yellow River (1955–2005). The following points can be concluded from the investigation:

- (1) The major hydrological conditions for low-flow are identified to have no trend in the upper Yellow River, and downward trends in middle and lower reach except Huayuankou.
- (2) Resulted from similar climate changes, similar periodicities were detected in the AM7Q of low-flow for the two sites (Tangnaihai and Lanzhou) in the upper Yellow River, and three sites (Toudaiguai, Longmen and Tongguan) in the middle Yellow River. However, the periodic patterns are different for the two sites (Huayuanou and Lijin) in the lower reach.
- (3) From upstream to downstream, the magnitudes (7-day min, 30-day min, dry flow and Xflow peak) of low-flow are identified to be decreasing except Toudaiguai in the middle Yellow River, at which a sudden drop on low-flow is detected. Meanwhile, the coefficients of variance of low-flow demonstrate increasing trends along the river, meaning that the variability is increasing from upstream to downstream.
- (4) The climate change and uneven temporal-spatial patterns of precipitation, together with highly intensive water resource utilization by human being, are the primary factors resulting in the decreasing of low-flow and drying up of the lower Yellow River since 1990s. The human water use (particular the over-allocation of water for irrigation in the middle reaches during 1992–2000), to a certain degree, offsets the impacts of precipitation on streamflow changes. In 1999, the Chinese central government altered the past allocation policy of water utilization in the Yellow River. As a result, zero-flow days never happened since then.

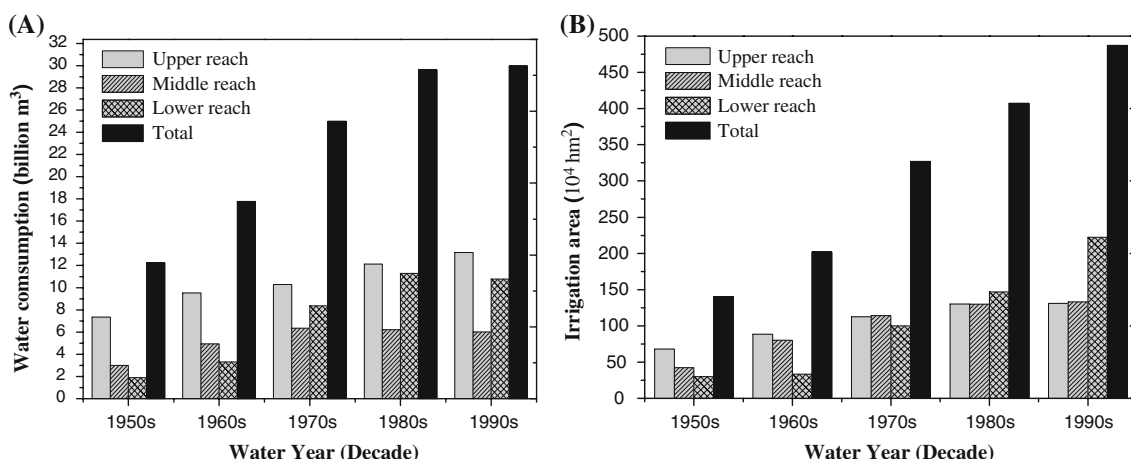


Fig. 6 Water consumption (billion m³) and irrigation area (10⁴ hm²) in Yellow River basin (1950–1995) (Source: Liu 1989; Liu and Zheng 2002). Here water consumption includes water consumed in agriculture, industry and drinking water

The low flow conditions are more sensitive to climatic change and human activities than the high flow events (Zhang et al. 2008). Climate variability and change have led to significant impacts on low-flow regimes in the Yellow River (1955–2005).

As the Yellow River basin is located in the semi-humid, semi-arid and arid regions, precipitation and evaporation play the important role in the local hydrologic cycle. Meanwhile, the thriving economic development and fast growth of population in the Yellow River basin further intensify water shortage. Water wastage worsens during the drying up of the river. Even though water resources may be very limited, wastage is tremendous and keeps increasing over time. Investigations indicate that the irrigation is the major water consumption with quota of 8,246 m³/hm² within the Yellow River Basin (Liu 1989, 1999), compared with about 4,000–6,000 m³/hm² for the developed countries. In the Ning-meng river region which is dominated by a typical arid climate, the irrigation quota can reach to 12,000–17,000 m³/hm², which is two to three times that of the humid region in China. Sometimes, the irrigation quota can reach to 22,000–27,000 m³/hm² in the Yellow River basin (Liu 1989, 1999). The main irrigation method is free flow irrigation, since it is cheap and easy to use. However, drainage facilities are not installed, channels are not lined properly and channel maintenance is ignored after the completion of construction. Channel transportation is running at a very low level of efficiency. Therefore, low water use efficiency is a very important issue in water resources management. Furthermore, industry water wastage is also very serious. The general industrial quota is high and the recycling rate is low. These human activities exerted considerable interference on the runoff processes, resulted in more complexity in low-flow changes in the region, and severely changed the balance of natural eco-flow regime with substantial threat to wild species as well.

By using the MK trend test and wavelet transform analysis, the changes in the temporal and spatial patterns of low-flow conditions over recent five decades were systematically investigated. The results of this study will be greatly helpful for the future management of water resources and eco-environment restoration as well in the Yellow River.

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