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Recent changes of water discharge and sediment load in the Yellow River basin, China

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Abstract: The Yellow River basin contributes about 6% of the total river sediment load in the world. Recent variations in water discharge and sediment load of the Yellow River basin are important, as its annual runoff directly supports 12% of the Chinese population. The present study considers the annual hydrologic series of water discharge and sediment load of the Yellow River basin obtained from 15 gauging stations (10 mainstream, 5 tributaries). The Mann-Kendall test is used to detect both gradual trends and abrupt changes in the hydrological series since the 1950s. The results show, except for the area draining to the Upper Tangnaihai station, that both water discharge and sediment load have decreased significantly ($p<0.05$). These trends intensify in the downstream direction. The drainage area is strongly correlated with the rates of decline. Abrupt changes in river discharge occurred in a period lasting from the late 1980s to the early 1990s because of the increased abstraction of water for human consumption. The sediment load also experienced disruption due to the construction and operation of several large reservoirs.

Keywords: Yellow River; water discharge; sediment load; climate change; human activity; reservoir

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1. Introduction

The hydrologic cycle describes processes that contribute to the upland source, and the yield of water and sediment resources as they flow through the fluvial system (Julien, 2002). As a complicated, sensitive and fragile system, the hydrological cycle reflects the interaction of the hydrosphere, atmosphere, lithosphere and biosphere. In the hydrologic cycle, water discharge and sediment flux are the two most important components, whose changes directly affect the fluvial estuarine, and coastal shelf environment (Zhang et al., 2008). River morphology depends on temporal and spatial variations in water discharge, the relationship between sediment load and the sediment-transport capacity of the flow. Examples of rivers whose morphology is changing include the Burdekin River in Australia (Amos et al., 2004), Ben River in Bolivia (Gautier et al., 2007), Rhone River in France (Petit et al., 1996; Arnaud-Fassetta, 2003), Wisloka River in southern Poland (Wyżga, 1997), Cache Creek and Stony Creek in California, USA (Collins and Dunne, 1990; Kondolf, 1997) and the Yangtze and Yellow River in China (Chen et al., 2001a; Saito et al., 2001; Zhang et al., 2006a; Xu, 2006).

The water discharge and sediment flux from river systems provide humans with water resources, renewable energy, fertile soil, etc. However, excessive changes to the water discharge and sediment flux threaten the eco-environment and can have disastrous socio-economic consequences through more frequent and intense droughts and floods, water eutrophication, the raising of the riverbed, and spreading of the river delta. Researchers have come to view understanding both river flows and sediment transport as crucial, especially in relation to climate variability and human activities (e.g. Lettenmaier et al.,1994; Burn and Elnur, 2002; Kahya and Kalayci, 2004; Wang et al., 2006a; Zhang et al., 2006a). In the latter half of the 20th century, global change resulting from human activities has intensified at an increasing rate, gradually altering global river systems, such that hydrologic changes are receiving greater attention.

In ancient times, China's emperors attempted to control rivers, and dynasties were remembered as being "good" or "bad" depending on whether or not they succeeded in the struggle to harness water and sediment transport in large rivers (Julien, 2002). It is likely that large-scale water-sediment management commenced with the Chinese hero Yu (2205~2198 B.C.), who was selected to be the emperor of China because of his talent at constructing flood countermeasures such as dams, dikes, and river training (Dudgeon, 2000). The Yellow River is fundamentally important to Chinese civilization, due to the very long history of human activities along its middle and lower reaches (Xu and Ma, 2009). The Yellow River is notable for its relatively small water discharge and huge sediment load. Although its mean annual discharge is only about 0.7% that of the Amazon (the largest river in the world) and 4.5% of the Yangtze (the largest river in China), the annual sediment load of the Yellow River almost equals that of the Amazon and is more than twice that of the Yangtze. Wang et al. (2007) calculate that sediment from the Yellow River basin contributes about 6% of the total global river load to the oceans. Frequent changes in sediment flux have caused switches between recession and growth of deltaic coastlines (Ren and Shi, 1986), and in turn influence the form of river deltas. Figure 1 compares the Yellow River delta with the bird's foot delta of the Mississippi River. On the other hand, although the annual runoff of the Yellow River basin is only about 2% that of China's total runoff, the Yellow River directly supports 12% of the national population (mostly farmers and rural people) and supplies water to 15% of the irrigation area of China, and contributes to 9% of China's GDP (YRCC, 2009). In addition, catastrophic floods and droughts have occurred many times in the Yellow River basin throughout history, leading to enormous cumulative losses of life and damage to property (Hu et al., 1998). In the Yellow River, the sediment load and water discharge are characterized by large spatial and temporal variations, which are interpreted in the present paper in the context of global climate change and intensive regional human activity.

Previous studies have shown that the hydrologic cycle has changed over interannual and decadal scales (Hu and Feng, 2001), and that the discharges in the headwater of Yellow River (Zheng et al., 2009), middle Yellow River (Xu, 2005), lower Yellow River (Wu et al., 2008) and water fluxes to the sea (Wang et al., 2006a) have all declined significantly since the 1970s. This has resulted in a progressive increase in water stress along the downstream reaches of the Yellow River (Vörösmarty et al., 2000; Xu et al., 2008). Meanwhile, there has also been a decline in sediment load that can be correlated with a similar decline in water discharge (Wang et al., 2006b). Although many publications have discussed the changes of river delivery in the Yellow River (especially in the Chinese literature), these were based on limited hydrological data acquired over the latter half of the 20th Century from a few hydrologic gauging stations, mainly located along the lower Yellow River rather than the whole Yellow River. As a consequence, the factors that influence changes in water discharge and sediment load in the whole Yellow River were not fully discussed.

The goal of the present work is to examine recent changes, both gradual and abrupt, in water discharge and sediment load for the whole Yellow River basin from the 1950s to the 2000s (primarily 1956 to 2007). Natural and anthropogenic factors are identified and their potential impacts discussed.

2. The Yellow River basin

The Yellow River is the second-longest river in China, and is located between 96°~119° E longitude and 32°~42° N latitude. Its catchment area occupies about 753,000 km^2, and the length of the main river channel is about 5,464 km (Figure 2). The river originates in the Tibetan plateau. It then flows through the semi-arid region of north China, the Loess Plateau, and the eastern plain, before discharging into the Pacific Ocean (Xu and Ma, 2009). In 2000, the population within the drainage area was about 110 million. The catchment consists of 12.6 million ha of farmland, of which 40% is under irrigation, with the Yellow River supplying the water (Xia et al., 2002).

As indicated in Table 1, the Yellow River basin is usually divided by its physical characteristics into three water source areas: upper (above Hekou), middle (between Hekou and Huayuankou); and lower (below Huayuankou) reaches (see e.g. Yang et al., 2004; Wang et al., 2007) (Table 1).

Table 1

3. Data and methods

3.1 Data

In the present study, hydrologic data from the 15 gauging stations listed in Table 2 are analyzed to investigate changes in water discharge and sediment load. Ten stations (at Tangnaihai, Lanzhou, Shizuishan, Hekou, Longmen, Sanmenxia, Huayuankou, Gaocun, Aishan, and Lijin) are located along the main stem of the Yellow River. The remaining five stations (at Jingyuan, Huangfu, Baijiachuan, Zhuangtou, and Huaxian) are situated at major tributaries of the Yellow River basin. Being spatially well distributed, the data from these stations reflect hydrologic changes occurring in the upper, middle, and lower reaches of the Yellow River. The observed series cover the period from 1956 to 2007. Figure 2 and Table 2 provide information on the station locations, associated drainage area, annual mean water discharge, and annual mean sediment load over the entire period of observations. The Yellow River Water Conservancy Commission (YRCC) supplied the data acquired before 2000. The data since 2000 were extracted from the China Water Resources Bulletin (Ministry of Water Resources, MWR).

The precipitation data come from two sources. The annual regional precipitation series from 1956 to 2000 were interpolated from data from 175 meteorological stations, provided by the National Meteorological Information Center, China Meteorological Administration. Figure 2 shows the locations of these stations in and around the Yellow River basin. Data on annual regional precipitation after 2000 were taken from the China Water Resources Bulletin (Ministry of Water Resources, MWR). However, the Bulletin (2001~2007) only provides information on the annual precipitation in the drainage areas above Tangnaihai, Lanzhou, Hekou, Longmen, Sanmenxia, Huayuankou and Lijin stations, and so it is only possible to discuss the influence of precipitation (from 1956 to 2007) on the water discharge and sediment load in these areas.

Table 2

Figure 2

3.2 Methodology

The non-parametric Mann-Kendall test (MK), originally proposed by Mann (1945) and later reformulated by Kendall (1948), is used to detect changes in the data. This test has the advantage of not assuming any distribution form for the data and has similar order of accuracy as its parametric competitors (Serrano et al., 1999). Consequently, the MK test has been strongly recommended by the World Meteorological Organization for general use (Mitchell et al., 1966). Besides application to climatic time series, the MK test has been widely used to evaluate statistically monotonic trends (see e.g. Xu et al., 2004c; Zhang et al., 2008; Chen et al., 2009) and abrupt changes (see e.g. Zhang et al., 2006a, 2006b; Zhao et al., 2008) in hydrological series.

(1) Mann-Kendall test for monotonic trend

The Mann-Kendall test for monotonic trend is given as follows:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}} & , S > 0 \\ 0 & , S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}} & , S < 0 \end{cases} \qquad (1)$$

where

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \qquad (2)$$

$$\mathrm{sgn}(\theta) = \begin{cases} 1 & , \theta > 0 \\ 0 & , \theta = 0 \\ -1 & , \theta < 0 \end{cases} \qquad (3)$$

$$\mathrm{Var}(S) = \frac{\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p (t_p - 1)(2t_p + 5) \right]}{18} \qquad (4)$$

in which x_i and x_j are the sequential data values at times i and j respectively, provided $j > i$, n is the length of the time series, q is the number of tied groups, t_p is the pth group and $\sum$ denotes summation over all ties (Gilbert, 1987; Xu et al., 2007). A positive (or negative) value of Z indicates an upward (or downward) trend. The magnitude of trend slope can be also calculated as:

$$Slope = \text{Median}(\frac{x_j - x_i}{j-i}) \quad (5)$$

where a positive (negative) value of *Slope* indicates an upward (downward) trend, i.e. increasing (decreasing) values with time.

The null hypothesis (H_0) is no trend (*Slope*=0). The H_0 is accepted if $-Z_{1-\alpha/2} \le Z \le Z_{1-\alpha/2}$, where α is the significance level of the test. Here, a typical confidence level of 95% (i.e. $p = 0.05$) was used.

(2) Mann-Kendall test for abrupt change

A sequential version of the original Mann-Kendall test (also called the Mann-Kendall-Sneyers test) proposed by Sneyers (1975), is used to determine abrupt changes in a data series. For a time series (x_1, x_2, …, x_n), the null hypothesis is as follows: the sample under investigation shows no evidence of a developing trend. The following test is performed to prove or disprove the hypothesis, based on the rank series r of the progressive and retrograde rows of the sample. First, the MK test statistic, d_k is calculated from:

$$d_k = \sum_{i=1}^{k} r_i (2 \le k \le n) \quad (6)$$

where

$$r_i = \begin{cases} +1 & \text{if } x_i > x_j \\ 0 & \text{otherwise} \end{cases} \quad (j=1,2,...,i) \quad (7)$$

Presuming that the series is random and independent, the statistic d_k is normally distributed with expected value $E[d_k]$ and variance $Var[d_k]$ given as follows:

$$E[d_k] = \frac{n(n-1)}{4} \quad (8)$$

and

$$Var[d_k] = \frac{n(n-1)(2n+5)}{72} \tag{9}$$

Hence, the statistical index Z_k is determined from:

$$Z_k = \frac{d_k - E[d_k]}{\sqrt{Var[d_k]}} \qquad (k = 1, 2, 3, ..., n) \tag{10}$$

Here, Z_k follows the standard normal distribution. Unlike the original MK test which calculates the above statistical variables only once for the whole sample, in the modified MK test the corresponding rank series for the retrograde rows are also obtained for the inverse series (x_n, x_{n-1},…, x_1). Using the same procedure as listed in Eqs. (6) ~ (10), the statistical variables, d_k, $E[d_k]$, $Var[d_k]$ and Z_k are calculated for the inverse series. The Z values calculated via progressive and retrograde series are named Z_1 and Z_2. If the intersection point of the two lines, Z_1 and Z_2 lies between the two confidence lines (with the confidence level set at 95% in the present research), it is judged that an abrupt change has taken place at that point (Demaree and Nicolis, 1990; Moraes et al., 1998).

3.3 Preliminary data analysis

The Mann-Kendall test assumes that the series is independent (Yue and Wang, 2004). However, hydrologic series are often autocorrelated due to coherence and inertial effects from their influence factors (such as precipitation and human activities). The effective sample size is reduced because of the existing autocorrelation, and this affects the outcomes of the MK test. The autocorrelation coefficient r_k between the hydrologic time series and the same series lagged by k time steps is given by:

$$r_k = \frac{\sum_{i=1}^{n-k}(x_i - \overline{x})(x_{i+k} - \overline{x})}{\sum_{i=1}^{n}(x_i - \overline{x})^2} \quad (11)$$

where k is the number of lagged time steps, n is the length of hydrologic series, x_i is the ith value in the series, and $\overline{x}$ is the overall average value . The critical value of r_k for a given significance level (e.g., 95%) is calculated as follows (Salas et al., 1980) :

$$r_k(95\%) = \frac{-1 \pm \sqrt{n-k-1}}{n-k} \quad (12)$$

Table 3 lists the results of the autocorrelation test. Free pre-whitening (Yue and Wang, 2002) was applied to the hydrologic series with significant autocorrelation in order to eliminate the effect of serial correlation.

Table 3

4. Results

4.1 Trend analysis

Table 4 summarizes the results obtained using the Mann-Kendall trend analysis test applied to the water discharge and sediment load series for the Yellow River basin. All the water discharge series present a downward trend. Except for the series at Tangnaihai, the downward trends of all the other water discharge series are significant at the 95% confidence level (with two series at the 95% level, and twelve series at the 99% level). For the sediment load series, although no trend was detected at Tangnaihai, all the other stations show significant downward trends with 95%

confidence level (again with two series at the 95% level, and twelve series at the 99% level).

The absolute value of slope during the MK test reflects the local rate of change of the variables being analyzed. Looking at the results in Table 4, it can be seen that the declining trend of water discharge series steepens in the downstream direction. The rate of decline (or slope) grows from about -0.07×10^9 m^3/yr at Tangnaihai to about -0.81×10^9 m^3/yr at Lijin. Although the changes in the sediment load series present relatively similar characteristic behaviour to that of the water discharge along the main course, the greatest reduction occurs at Huayuankou at a rate of -28×10^6 ton/yr. Figure 3 plots the slopes of water discharge change and sediment load change against drainage area. From Figure 3, it can be seen that for both water discharge and sediment transport in the Yellow River, there is a strong correlation with drainage area.

Table 4

Figure 3

Table 5 presents the decadal changes in the water discharge and sediment load. These are obtained by comparing the decadal mean values with reference mean values over the period from the start of the series in the mid 1950s (the exact date depending on the data availability) to 1969. Unlike the other stations, the annual mean water discharge series at Tangnaihai during the 1970s and 1980s increased in magnitude, with respect to the reference mean value. The annual sediment load series at Tangnaihai increased in the 1970s, 1980s, and 1990s, but fell in the 2000s. The maximum change at Tangnaihai occurred in the 1980s. Lijin (which is located close to the mouth of the Yellow River) experienced the greatest decline in water discharge, with the annual mean water discharges reducing by 70.74% during the period from 2000 to 2007 compared with the overall mean value for the period from 1956 to1969. The largest decline in sediment load occurred at Huayuankou, with its annual mean sediment load dropping by over 90% in the period from 2000 to 2007 compared with the reference value. This is mainly due to the Xiaolangdi reservoir becoming operational during the early 2000s. In terms of percentages, the proportional reduction in sediment load is generally larger than that of the water discharge from the 1980s onwards.

Table 5

4.2 Abrupt change analysis

Table 6 shows the results of the Mann-Kendall test for abrupt changes to the hydrologic series. Here, the single most abrupt change is identified, and the year in which it occurs denoted by T. No significant abrupt changes are detected in the water discharge series at Huangfu and in the sediment load series at Longmen. For the annual water discharge series at stations located along the main stem of the river, the MK test indicates that abrupt changes occurred in the late 1980s and early 1990s. These abrupt changes in annual water discharge follow an antedated trend in the downstream direction. However, the years during which abrupt changes occur in the annual sediment load series do not display any obvious correlation with the corresponding values for the water discharge series. At Lijin, abrupt changes in water discharge and sediment load occur at 1985 and 1990 respectively (Figure 4). In this case, the mean values of the annual water discharge and sediment load series averaged over the period before the abrupt changes occurred are 40.10×10^9 m^3/yr and 935×10^6 t/yr, respectively. The corresponding mean values of the annual water discharge and sediment load series averaged over the period after the abrupt changes occurred reduce to about 14.73×10^9 m^3/yr and 284×10^6 t/yr, respectively. Table 6 lists the differences between the pre-T and post-T series at all stations. Although most of the abrupt changes for the water discharge appear to have occurred during the late 1980s and early 1990s, this is not the case for the sediment load series. Of the 15 hydrologic series, the most significant difference in water discharge before and after the abrupt change occurs at Lijin where the mean annual value has reduced by 63.27%. The greatest difference in sediment load appears at Zhuangtou where the mean annual load has decreased by 82.41%. In general, the percentage change in the average sediment load over the pre-T and post-T is larger than that of corresponding annual water discharge series.

Figure 4

Table 6

5. Discussion

5.1 Influence of climate change

In general, climate change is mainly characterized by changing temperature and precipitation variability. Precipitation drives runoff, and hence directly influences both the discharge of a river and its sediment transport capacity. The recent decreasing trend of precipitation in the Yellow River basin (e.g. Liu et al., 2008) is consistent with the reduction of water discharge and sediment load of the Yellow River.

We define the net water discharge and sediment load emanating from a given drainage area, as being the difference in water discharge and sediment load between two stations at the upstream and downstream boundaries of the sub-catchment. For example, the net water discharge in the Tangnaihai~Lanzhou area is given by the water discharge at Lanzhou minus that at Tangnaihai station. Figure 5 presents the correlation of regional annual precipitation with the net discharge data for seven sub-catchments. It can be seen that the annual precipitation and net water discharge are quite well correlated for most drainage areas, except Tangnaihai~Lanzhou. The positive correlation indicates that the reduction in precipitation causes an associated decrease in net water discharges along the Yellow River. By analyzing water discharge data from 1956 to 2000, Liu and Zhang (2004) found that the reduced precipitation was directly responsible for 75% and 43% of the reduction in river discharge in the upper and middle drainage basin respectively. Moreover, the present study shows that the annual net water discharge due to runoff from the Lanzhou~Hekou sub-catchment was negative, which means that runoff generated from the precipitation in this area did not compensate for the overall net water discharge loss due to infiltration, evapo-transpiration, and abstraction for domestic, agricultural, and industrial use. As the water discharge decreased so did the river's capacity for sediment transport.

Figure 6 presents the net sediment load as a function of precipitation for each of the sub-catchment. In all cases, the correlation between the net sediment load and precipitation is weaker than for the net water discharge (due to the greater sensitivity of net sediment load to human activities), but nevertheless invariably remains positive. Significant correlation is only apparent for data from the upper Tangnaihai, Tangnaihai~Lanzhou, Hekou~Longmen, and Huayuankou~Lijin sub-catchments. Wang et al. (2007) found that the decrease in precipitation was responsible for 30% of the decrease in sediment load at Huayuankou. In Figure 6, the net sediment loads in the Lanzhou~Hekou and Sanmenxia~Huayuankou sub-catchments are negative in certain years when sediment deposition exceeds entrainment. The sub-catchment most likely to have been influenced by climate change appears to be the drainage area upstream of Tangnaihai, where the correlations of both net water discharge and net sediment load with precipitation are maximum, with R = 0.79 and 0.74, respectively. The drainage area above Tangnaihai is located on the Southern Qinghai Plateau, and has an average altitude > 3,000 m above sea level and a low mean annual temperature of -0.87°C. Due to the relatively inhospitable natural conditions, the population is low, and so there is hardly any human impact, such as large reservoirs, in this area.

Figure 5

Figure 6

5.2 Influence of soil and water conservation practices

Recent population growth, economic development, reclamation, deforestation, and other human related activities have led to serious and widespread soil erosion in the Yellow River basin (Fu, 1989; Fu and Gulinck, 1994; Chen et al., 2001b). This severe soil loss, which can exceed 20000 t/km/yr in certain areas (Fu and Chen, 2000), has reduced land productivity, degraded the river ecosystem, and due to increased sediment concentrations and deposition caused a remarkable rise in the riverbed elevation along the lower reaches of Yellow River (Shi and Shao, 2000). Soil conservation practices (such as afforestation, grass-planting, creation of level terraces, contour plowing, non-tillage, ridge reconstruction, and building check dams) have been implemented since 1949, once the severity of soil loss was recognized (Liu, 2005). As the conservation area expanded, the measures against soil erosion became increasingly effective, particularly since the late 1970s.

The Normalized Difference Vegetation Index (NDVI) is effective at representing the vegetation cover and so is widely employed for monitoring purposes (Trishchenko et al., 2002). Figure 7 plots NDVI against time, from 1982 to 2006, showing the significant improvement in vegetation cover that occurred in the Yellow River basin due to the increased forest and grassland in that period. Figure 8 shows the expansion in different types of soil conservation area in the Yellow River basin from 1959 to 1989. According to Zhang et al. (2007), the increase in soil conservation area due to afforestation and grass-planting reached 11.57×10^6 ha at 2000, and is predicted by Chen et al. (2004) to reach 17.25×10^6 ha by 2010. Besides the absorption of water during the growth-phase, trees and grass intercept precipitation, enhance evaporation, improve soil structure, increase infiltration, and thus reduce runoff. Moreover, wooded areas and grasslands significantly increase terrain roughness, and thus slow the runoff speed (Xu, 2004b) reducing sediment entrainment and transport, thus lowering the sediment load.

Figure 7

Figure 8

Creation of level terraces can change the local micro-topography and greatly reduce the gradient of the hillsides. Chen et al. (2004) have estimated that the creation of level terraces decreased the runoff and sediment load by 86.70% and 95.00% in the middle Yellow River, where the most serious erosion occurs. Contour plowing and ridge reconstruction alter the direction of the flow of runoff and entrained sediment, while elongating its path.. Chen et al. (2004) observe that contour plowing and ridge reconstruction reduced runoff by 19~39% and 75% respectively, and reduced soil loss by 31~67% and 90% respectively in the Tianshui area of the upper Yellow River. Figure 8 also indicates the growth in soil conservation area due to the creation of terrace levels and the construction of check dams from 1959 to 1989. No-till is a way of growing crops that involves leaving crop stubble on the ground surface instead of plowing it under (Montgomery, 2007). No-till increases the water content of the soil and, because it does not disturb the soil, decreases erosion. Montgomery (2007) observed that no-till can reduce soil loss by a factor of more than 20 in comparison with that of conventional cultivation. In the Yellow River basin, no-till is an emerging agricultural practice that has only recently been introduced. Of the afore-mentioned measures for controlling soil loss, check dams have the greatest effect .

The soil and water conservation measures have not only decreased precipitation-induced runoff and sediment flow rates, but have also caused more runoff-sediment to deposited on the surface of hillsides instead of flowing into the river channel. Mou (1996) analyzed the changes to the sediment load contributed by the middle Yellow River basin due to the soil and water conservation measures in the 1980s; the results are summarized in Table 7. Wang et al. (2007) estimated the average decrease of sediment yield due to soil conservation practices from 1969 to 1999 to be 0.24×10^{9}t/yr in the Yellow River basin. In short, the conservation measures have played a major part in reducing water flow and sediment flux in the Yellow River basin.

Table 7

5.3 Abstraction and reservoir construction

Since 1952, the population of the Yellow River basin has grown at a rate of about 1.23 million/year, reaching 0.11 billion in 2000, and is estimated to reach 0.12 billion by 2030 (YRCC, 2002). Meanwhile, domestic, agricultural, and industrial water consumption has increased greatly. In order to meet the food requirements of the local population, the cultivated land area has expanded remarkably (Figure 9), with the irrigation area increasing by almost a factor of 10 during the last 50 years (Xi, 1996). In the Yellow River basin, irrigation-based agriculture with high grain yield is used to alleviate the potential food shortage, but at the cost of worsening the water shortage due to the low efficiency of water utilization. Li (2003) estimates that water diverted from the Yellow River for irrigation-based agriculture accounts for only 30 to 45% of the total irrigation water; the remainder is due to extensive floodwater irrigation. The irrigation water-use ratio (defined as annual gross water transfer to irrigation divided by annual runoff) has increased from 21% to 68% during the last 50 years (Yang et al., 2004). The Yellow River Conservancy Commission (YRCC) predicts that by 2010, the average annual water shortfall will be about 4 billion m^3 in the Yellow River basin (YRCC, 2009). Figures 5 and 6 show that the annual net water discharge and sediment load in the Lanzhou~Hekou area are negative, mainly because the Lanzhou~Hekou area is a major irrigation zone covering 116 ha. Most irrigation takes place in the lower Yellow River basin, causing the observed water discharge to exhibit the strong downward trend indicated in Table 5.

Figure 9

In order to generate electricity, store water, trap sediments, mitigate floods, and sluice sediment, more than 3147 reservoirs have been constructed in the Yellow River basin, with a combined storage capacity of 57.4 km^3 (Zhang et al., 2001). These include 24 large reservoirs whose individual storage capacity exceeds 0.1 km^3 (Wang et al., 2007). Along the main stem, the five major reservoirs listed in Table 8 make the greatest contribution to water regulation and sediment retention (Wang et al., 2006a). Most of the reservoirs adjust the water resource through storage in the wet season and discharge in the dry season each year, without having a significant influence on the annual water discharge. In fact, reservoir construction impacts on the water discharge eventually due to increasing evaporation and water losses from the system. Liu and Zhang (2004) estimated that reservoir construction has led to surface water evaporation of 1.05 billion m^3 along the upper and middle Yellow River, which is 0.42 billion m^3 higher than that under natural conditions (without the reservoir construction). All the reservoirs impact the annual sediment load greatly through sedimentation and flushing processes, though the former inevitably reduces the storage capacity of the reservoir (Table 8).

Table 8

Usually, the double mass curve between water discharge and sediment load is approximately linear if the sediment load is solely dependent on the transport capacity of water discharge. However, the double mass curves in Figure 10 for the Yellow River contain inflection points when the reservoir commences operation. There is no large-scale hydro-electric scheme in the drainage area upstream of Tangnaihai, and so the double mass curve does not present any obvious deflections in this case. In the drainage area related to Hekou, the Qingtongxia, Liujiaxia and Longyangxia upstream reservoirs respectively commenced operation in 1968, 1969 and 1986. The double mass curve at Hekou therefore contains two discrete changes in gradient corresponding to changes in the ratio of sediment load to water discharge. It is also evident that the hydrologic series observed at Sanmenxia and Huayuankou stations are affected by the operation of the reservoirs at Sanmenxia and Xiaolangdi.

Figure 10

Net water diversion is the amount of water used for reservoir storage, agricultural irrigation and domestic and industrial consumption. It is equal to the quantity of water diverted from the river minus that returned to the river after water use (Xu, 2005). Figure 11 shows that the net water diversion appears to have increased approximately linearly from 1955 to the mid 1980s and then saturated (allowing for fluctuations which are much more evident after the 1980s, except for a single large-scale event in 1960 associated with the initial operation of the reservoir at Sanmenxia). The trend in net water diversion may be linked to the decrease in annual water discharge, indicated in Table 5. In the Yellow River basin, the river flow at its farthest downstream station Lijin is usually regarded as the flux from the Yellow River to the sea. Table 9 shows that the increasing net water diversion at Lijin has a strong influence on the declining water discharge, given that the contribution ratio always exceeds 50% .

Figure 11

Table 9

6. Conclusions

In the Yellow River basin, except for the drainage area of the upper Tangnaihai station, the water discharge and sediment load have undergone distinct stepwise decreases from the 1950s to the 2000s, the downward trends being significant at the 95% confidence level. By interpreting the annual mean water discharge series, it has been found that the declining trend in water discharge is exacerbated in the downstream direction, and that the sub-catchment drainage area positively correlates with the rate of decrease in water discharge and sediment load. Precipitation, water consumption and anthropogenic activities (such as water conservation practices, and the construction and operation of reservoirs) have had a large impact on the variation of water discharge and sediment load. In particular, the reduction in precipitation due to climate change has had a direct influence on the decreasing water discharge in the Yellow River basin. Moreover, the steady rise in water consumption has severely worsened the water crisis. Given all that, the human consumption and the construction-operation of reservoirs should be chiefly responsible for the decreasing water discharge and sediment load respectively.

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Table captions

Table 1. Physical characteristics of the upper, middle and lower reaches in the Yellow River basin.

Table 2. Detailed information of hydrological stations in the Yellow River basin.

Table 3. The results of autocorrelation analysis [a]; ([a] Lag=0 means the series is independent, Lag≠0 means the series has significant autocorrelation with the corresponding lagged time steps.).

Table 4. Results of the trend analysis by use of the Mann-Kendall test.

Table 5. Percentage changes in water discharge and sediment load [a]. ([a] The reference value is the mean of the annual series during 1950s~1960s).

Table 6. Results of abrupt change analysis by use of the Mann-Kendall test. ([a] Time when the abrupt change occurs; [b] Mean value before the abrupt change; [c] Mean value after the abrupt change; [d] Change of the mean value between Pre-T and Post-T).

Table 7. Effects of soil and water conservation practices in the middle Yellow River basin during the 1980s[a]. ([a] Data from Mou (1996).).

Table 8. Summary information of 5 major reservoirs along Yellow River [a]. ([a] Data from Wang et al., (2007); Jiao (2004); Chen et al., (1999) and YRCC (2002); [b] Data in parentheses indicate the observation period).

Table 9. The change in water discharge and net water diversion at Lijin station [a]. ([a] The reference value is the mean of the annual series over the period from 1956 to 1969; Symbol "-" means decrease and "+" means increase.)

Figure Captions

Figure 1. Comparison between (a)Yellow River delta and (b) Mississippi river delta. The images are derived from NASA's Landsat 7 satellite.

Figure 2. Yellow River Basin: location of hydrological and meteorological stations, and major reservoirs.

Figure 3. Correlation between the drainage area and the slope calculated by the MK test

Figure 4. Changes in water discharge and sediment load at Lijin before and after the change point

Figure 5. Correlation between precipitation and net water discharge

Figure 6. Correlation between precipitation and net sediment load

Figure 7. Variation of annual average NDVI in the Yellow River basin from 1982 to 2006. The NDVI data are derived from Global Inventory Monitoring and Modeling Studies (GIMMS) dataset.

Figure 8. Growth of soil conservation area in the Yellow River basin (after Xu, 2004a)

Figure 9. Growth of irrigation area in the Yellow River basin.

Figure 10. Double mass plots relating cumulative annual sediment load to cumulative annual water discharge at Tangnaihai, Hekou, Sanmenxia, and Xiaolangdi.

Figure 11. Temporal variation of net water diversion in the Yellow River basin. The public data from 1955 to 1989 is supplied by the Yellow River Water Conservancy Commission (YRCC). The interpolated data is generated by net water diversion at Lijin (the correlation r = 0.98, $p = 0.000$).

Table 1

	Length (km)	Drainage area (km^2)	Altitude range (m)	Annual mean precipitation (mm)	Annual mean temperature range (℃)
Upper reaches (above Toudaoguai)	3471	385,996	4480~1000	368	1~4
Middle reaches (Toudaoguai~Huayuankou)	1206	343,751	1000~106	530	8~14
Lower reaches (below Huayuankou)	787	22,726	106~0	670	12~14

Table 2

No.	Location	Station	Data period	Drainage area (10^3 km^2)	Mean water discharge (10^9m^3/a)	Mean sediment load (10^6t/a)
1	mainstream	Tangnaihai	1956~2007	122.0	19.9	12.3
2	mainstream	Lanzhou	1956~2007	222.6	30.6	63.8
3	tributary	Jingyuan	1955~2002	10.7	0.11	48.9
4	mainstream	Shizuishan	1956~2003	309.1	27.5	114.5
5	mainstream	Hekou	1956~2007	367.9	21.1	101.2
6	tributary	Huangfu	1954~2007	3.2	0.14	43.9
7	tributary	Baijiachuan	1956~2007	29.7	1.15	114.5
8	mainstream	Longmen	1956~2007	497.6	25.9	711.2
9	tributary	Zhuangtou	1956~2007	25.6	0.84	73.4
10	tributary	Huaxian	1956~2007	106.5	6.75	329.4
11	mainstream	Sanmenxia	1956~2007	688.4	33.6	1035.8
12	mainstream	Huayuankou	1956~2007	730.0	37.1	890.4
13	mainstream	Gaocun	1956~2007	734.1	34.5	803.2
14	mainstream	Aishan	1956~2007	749.1	33.2	767.5
15	mainstream	Lijin	1956~2007	751.9	29.4	709.7

Table 3

Station No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Water discharge series															
Lag=	1	1	0	1	3	0	9	9	0	1	9	6	1	1	6
Sediment load series															
Lag=	0	3	0	3	8	0	3	3	2	0	1	1	3	3	9

Table 4

No.	Location	Station name	Length (yr)	Water discharge			Sediment load		
				Slope	Sig.	Trend	Slope	Sig.	Trend
1	mainstream	Tangnaihai	52	-0.07	0.140	↓	0.0	0.893	—
2	mainstream	Lanzhou	52	-0.15	0.006	↓	-1.70	0.000	↓
4	mainstream	Shizuishan	48	-0.24	0.000	↓	-1.60	0.003	↓
5	mainstream	Hekou	52	-0.23	0.000	↓	-3.00	0.000	↓
8	mainstream	Longmen	52	-0.34	0.000	↓	-21.10	0.000	↓
11	mainstream	Sanmenxia	52	-0.55	0.000	↓	-24.80	0.000	↓
12	mainstream	Huayuankou	52	-0.56	0.000	↓	-28.00	0.000	↓
13	mainstream	Gaocun	52	-0.60	0.000	↓	-27.90	0.000	↓
14	mainstream	Aishan	52	-0.65	0.000	↓	-24.40	0.000	↓
15	mainstream	Lijin	52	-0.81	0.000	↓	-27.40	0.000	↓
3	tributary	Jingyuan	48	-0.002	0.020	↓	-0.80	0.026	↓
6	tributary	Huangfu	54	-0.003	0.000	↓	-0.90	0.000	↓
7	tributary	Baijiachuan	52	-0.018	0.000	↓	-2.90	0.000	↓
9	tributary	Zhuangtou	53	-0.005	0.018	↓	-1.10	0.005	↓
10	tributary	Huaxian	54	-0.107	0.000	↓	-5.10	0.000	↓

Table 5

No.	Station	Change in Water discharge (%)				Change in Sediment load (%)			
		1970s	1980s	1990s	2000s	1970s	1980s	1990s	2000s
1	Tangnaihai	1.55%	20.03%	-12.34%	-18.70%	16.70%	89.76%	4.12%	-26.49%
2	Lanzhou	-5.61%	-1.00%	-22.90%	-22.59%	-45.84%	-65.22%	-57.78%	-79.26%
4	Shizuishan	-6.61%	-3.11%	-28.33%	-40.19%	-30.16%	-37.85%	-44.54%	-63.80%
5	Hekou	-8.36%	-6.04%	-38.39%	-44.29%	-33.61%	-43.49%	-76.24%	-78.12%
8	Longmen	-12.07%	-14.67%	-38.77%	-47.91%	-27.47%	-60.73%	-56.61%	-82.72%
11	Sanmenxia	-19.50%	-16.64%	-45.55%	-57.05%	-2.07%	-39.85%	-43.18%	-72.03%
12	Huayuankou	-22.71%	-16.41%	-47.96%	-53.22%	-6.31%	-40.86%	-48.13%	-91.14%
13	Gaocun	-25.14%	-22.27%	-53.89%	-56.78%	-13.91%	-44.42%	-61.03%	-87.61%
14	Aishan	-29.57%	-29.65%	-60.09%	-59.45%	-18.31%	-40.59%	-57.92%	-85.36%
15	Lijin	-35.62%	-40.84%	-70.87%	-70.74%	-23.44%	-45.52%	-66.73%	-87.10%
3	Jingyuan	-25.86%	-37.21%	-33.33%	-61.03%	-31.17%	-49.13%	-42.80%	-77.42%
6	Huangfu	-16.16%	-38.73%	-55.84%	-79.84%	0.81%	-31.17%	-59.36%	-80.83%
7	Baijiachuan	-21.02%	-32.25%	-38.97%	-51.48%	-46.30%	-75.59%	-61.26%	-80.12%
9	Zhuangtou	-12.55%	-3.51%	-21.45%	-29.78%	-23.96%	-53.97%	-15.42%	-73.44%
10	Huaxian	-36.78%	-15.75%	-53.39%	-50.63%	-18.79%	-41.56%	-43.35%	-66.61%

Table 6

		Water discharge				Sediment load			
No.	Station name	Time[a]	Pre-T[b] (10^9 m^3/a)	Post-T[c] (10^9 m^3/a)	Change[d] (%)	Time[a]	Pre-T[b] ($10^6 t/a$)	Post-T[c] ($10^6 t/a$)	Change[d] (%)
1	Tangnaihai	1994	20.84	16.66	-20.06	2005	12.60	3.80	-69.84
2	Lanzhou	1990	32.99	25.70	-22.10	1973	105.40	63.70	-39.56
4	Shizuishan	1995	29.26	18.87	-35.51	1982	137.80	87.00	-36.87
5	Hekou	1990	24.25	14.69	-39.42	1986	141.20	42.10	-70.18
8	Longmen	1991	29.66	18.16	-38.77	No significant abrupt change			
11	Sanmenxia	1991	39.57	21.29	-46.20	1996	1190.00	458.00	-61.51
12	Huayuankou	1990	43.48	23.83	-45.19	1996	1073.00	211.00	-80.34
13	Gaocun	1988	41.40	21.56	-47.92	1993	1003.00	310.00	-69.09
14	Aishan	1985	42.53	20.55	-51.68	1991	972.30	346.00	-64.41
15	Lijin	1985	40.10	14.73	-63.27	1990	921.80	273.00	-70.38
3	Jingyuan	1968	0.16	0.10	-38.10	1965	84.30	40.00	-52.55
6	Huangfu	No significant abrupt change				1992	54.10	18.00	-66.73
7	Baijiachuan	1983	1.37	0.91	-33.53	1971	215.50	70.00	-67.52
9	Zhuangtou	2003	0.87	0.55	-36.69	2002	79.60	14.00	-82.41
10	Huaxian	1988	7.98	4.61	-42.30	1996	372.80	168.00	-54.94

Table 7

Soil and water conservation practices	Intercepting sediment yield (10^6 t)	Percentage of overall change (%)
Level Terrace	42	16.60
Afforestation	43	17.10
Grass-planting	12	4.80
Check dam	79	31.30

Table 8

Reservoir	Longyangxia	Liujiaxia	Qingtongxia	Sanmenxia	Xiaolangdi
Commencement of operation	1986	1969	1968	1960	2000
Storage capacity ($10^9\times m^3$)	24.70	5.70	0.61	35.40	12.65
Siltation capacity[b] ($10^9\times m^3$)	0.30 (1999)	1.50 (2006)	0.58 (2005)	9.51 (2005)	2.40 (2008)

Table 9

	1970s	1980s	1990s	2000s
Change in water discharge ($10^9m^3/a$)	-17.21	-19.73	-34.24	-34.13
Change in net water diversion ($10^9m^3/a$)	+9.44	+18.47	+20.84	+18.14
Contribution Ratio of net water diversion (%)	54.89%	-93.64%	60.87%	53.14%

Figure 1

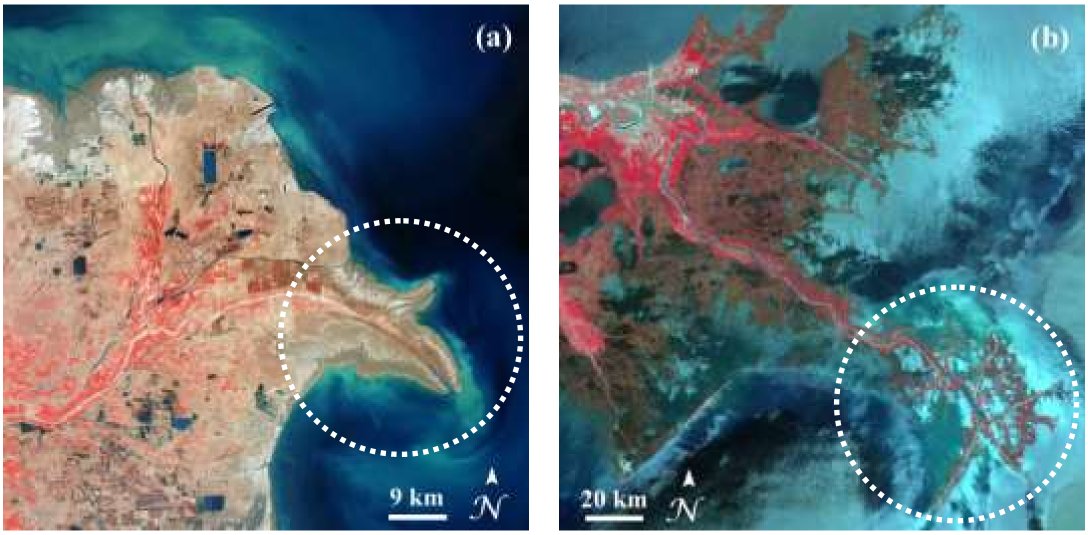


Figure 2

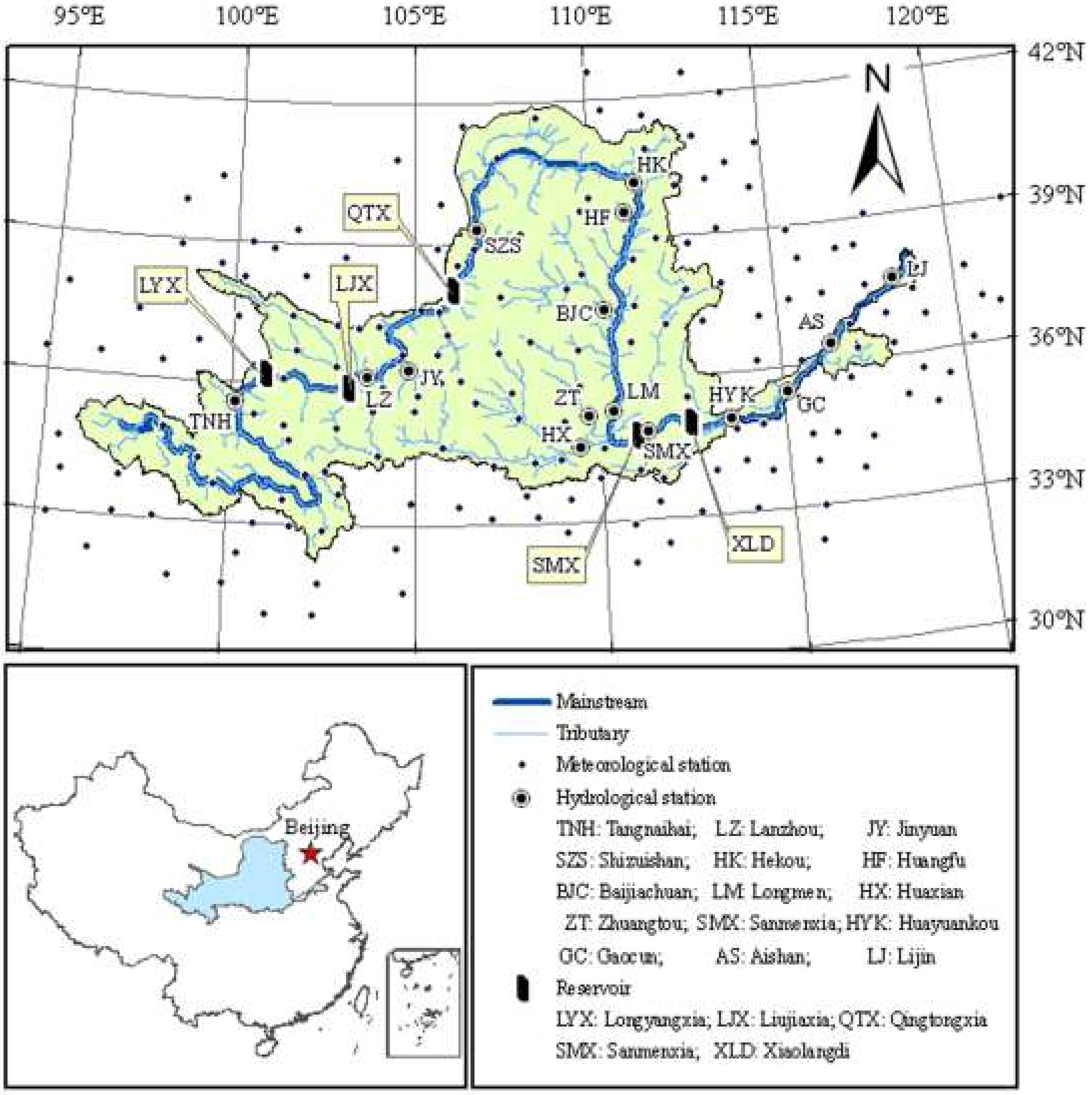
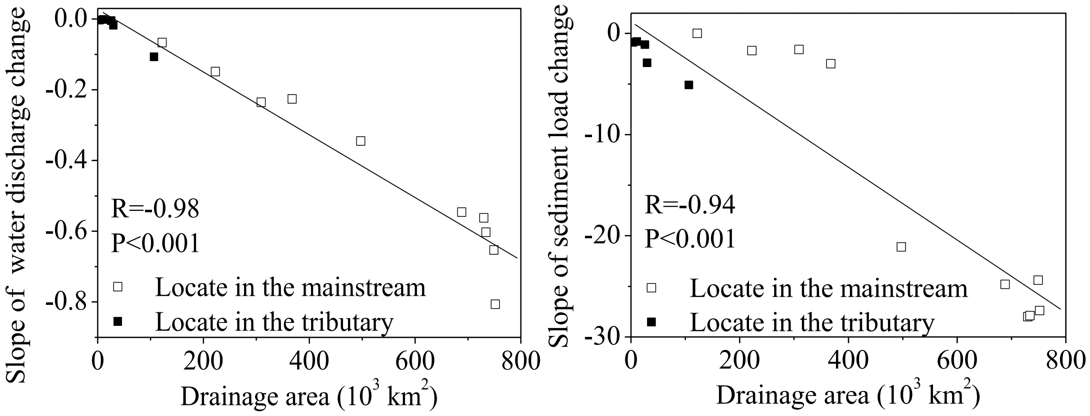
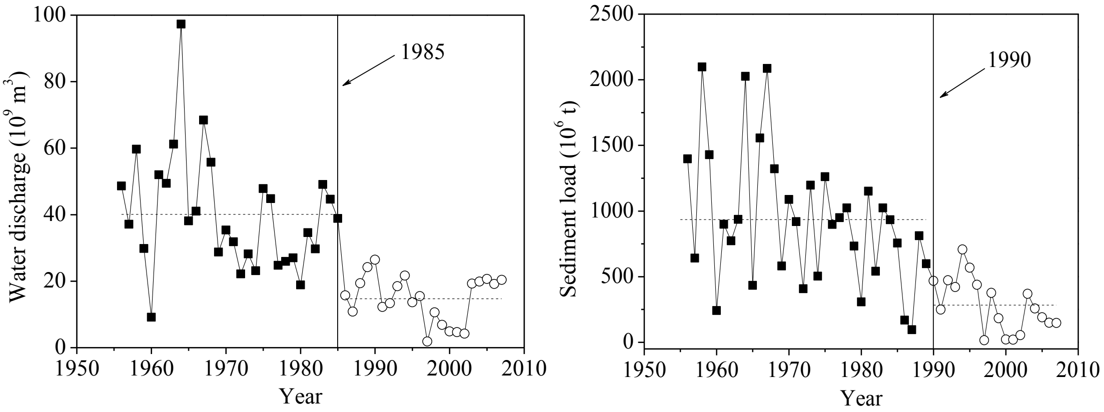

95°E
100°E
105°E
110°E
115°E
120°E
42°N
39°N
36°N
33°N
30°N
N
QTX
SZS
HK
HF
LYX
LJX
LJ
BJC
AS
JY
LZ
TNH
ZT
LM
HYK
GC
HX
SMX
SMX
XLD
Beijing
Mainstream
Tributary
Meteorological station
Hydrological station
TNH: Tangnaihai; LZ: Lanzhou; JY: Jinyuan
SZS: Shizuishan; HK: Hekou; HF: Huangfu
BJC: Baijiachuan; LM: Longmen; HX: Huaxian
ZT: Zhuangtou; SMX: Sanmenxia; HYK: Huayuankou
GC: Gaocun; AS: Aishan; LJ: Lijin
Reservoir
LYX: Longyangxia; LJX: Liujiaxia; QTX: Qingtongxia
SMX: Sanmenxia; XLD: Xiaolangdi

Figure 3



Slope of water discharge change
0.0
-0.2
-0.4
-0.6
-0.8
R=-0.98
P<0.001
□ Locate in the mainstream
■ Locate in the tributary
0
200
400
600
800
Drainage area (10^3 km^2)
Slope of sediment load change
0
-10
-20
-30
R=-0.94
P<0.001
□ Locate in the mainstream
■ Locate in the tributary
0
200
400
600
800
Drainage area (10^3 km^2)

Figure 4



100
80
60
40
20
0
Water discharge (10^9 m^3)
1985
1950
1960
1970
1980
1990
2000
2010
Year
2500
2000
1500
1000
500
0
Sediment load (10^6 t)
1990
1950
1960
1970
1980
1990
2000
2010
Year

Figure 5

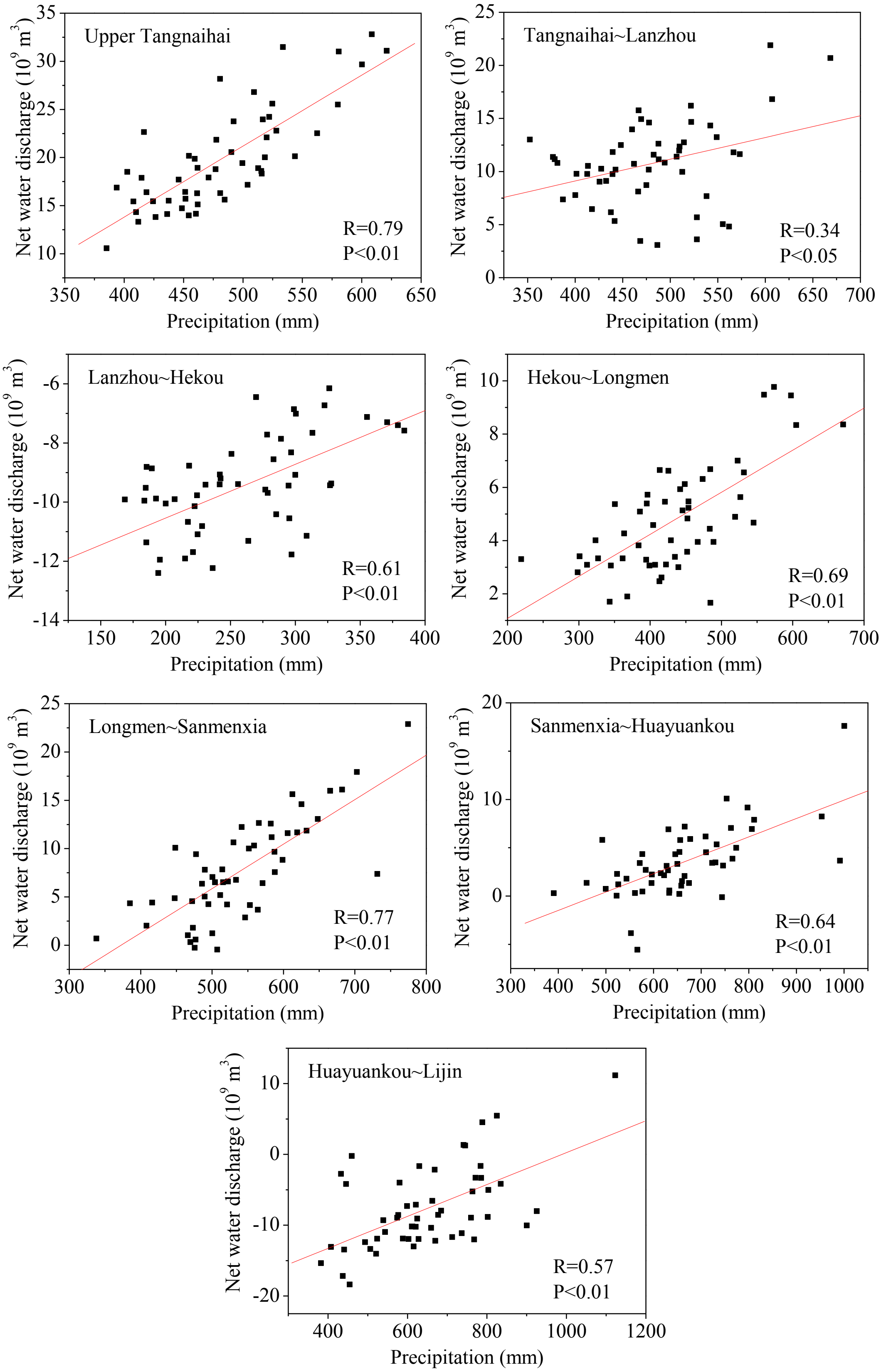

Upper Tangnaihai
R=0.79
P<0.01
Net water discharge (10^9 m^3)
10
15
20
25
30
35
350
400
450
500
550
600
650
Precipitation (mm)
Tangnaihai~Lanzhou
R=0.34
P<0.05
Net water discharge (10^9 m^3)
0
5
10
15
20
25
350
400
450
500
550
600
650
700
Precipitation (mm)
Lanzhou~Hekou
R=0.61
P<0.01
Net water discharge (10^9 m^3)
-14
-12
-10
-8
-6
150
200
250
300
350
400
Precipitation (mm)
Hekou~Longmen
R=0.69
P<0.01
Net water discharge (10^9 m^3)
2
4
6
8
10
200
300
400
500
600
700
Precipitation (mm)
Longmen~Sanmenxia
R=0.77
P<0.01
Net water discharge (10^9 m^3)
0
5
10
15
20
25
300
400
500
600
700
800
Precipitation (mm)
Sanmenxia~Huayuankou
R=0.64
P<0.01
Net water discharge (10^9 m^3)
0
10
20
300
400
500
600
700
800
900
1000
Precipitation (mm)
Huayuankou~Lijin
R=0.57
P<0.01
Net water discharge (10^9 m^3)
-20
-10
0
10
400
600
800
1000
1200
Precipitation (mm)

Figure 6

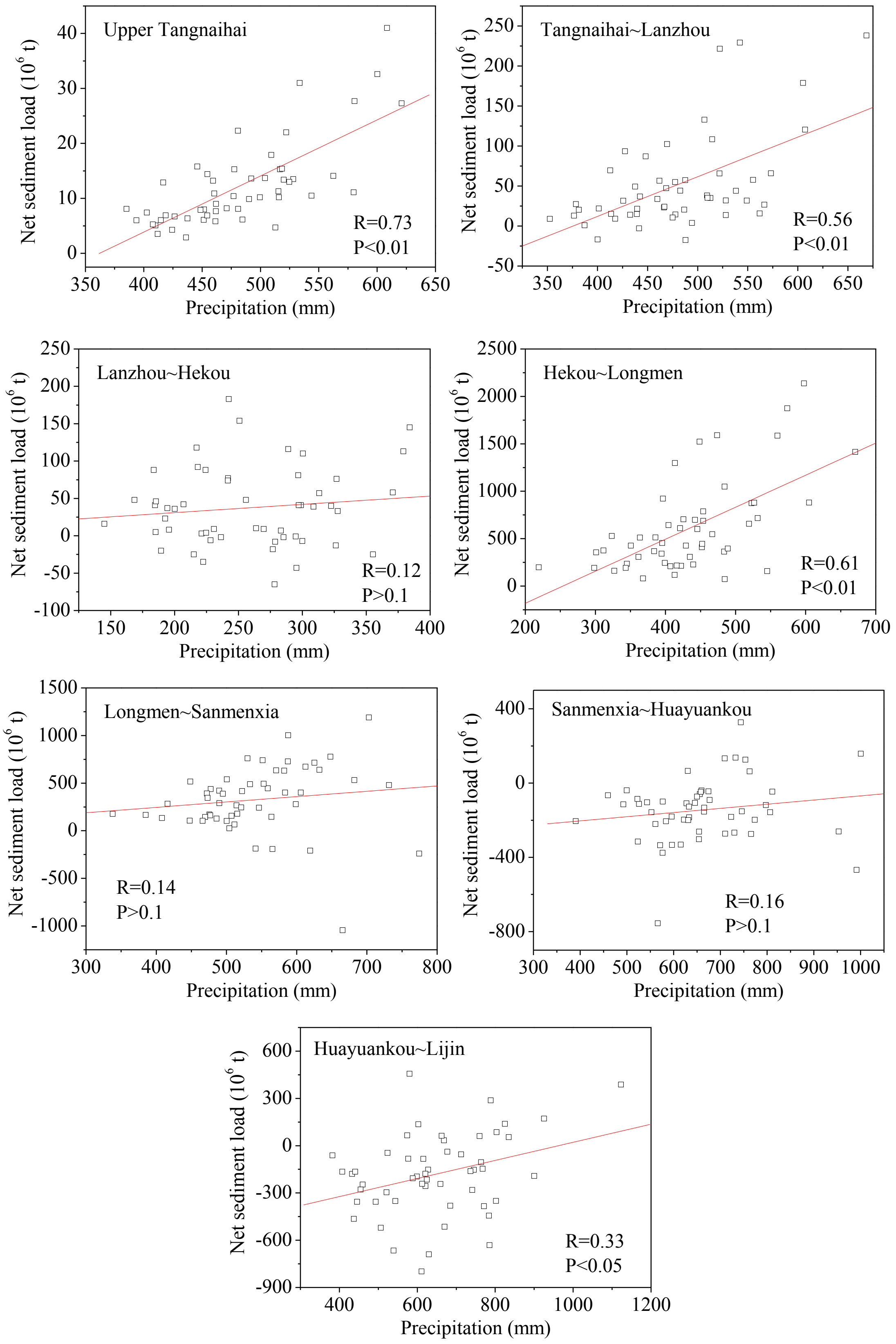

Upper Tangnaihai
R=0.73
P<0.01
Net sediment load (10^6 t)
0
10
20
30
40
350
400
450
500
550
600
650
Precipitation (mm)
Tangnaihai~Lanzhou
R=0.56
P<0.01
Net sediment load (10^6 t)
-50
0
50
100
150
200
250
350
400
450
500
550
600
650
Precipitation (mm)
Lanzhou~Hekou
R=0.12
P>0.1
Net sediment load (10^6 t)
-100
-50
0
50
100
150
200
250
150
200
250
300
350
400
Precipitation (mm)
Hekou~Longmen
R=0.61
P<0.01
Net sediment load (10^6 t)
0
500
1000
1500
2000
2500
200
300
400
500
600
700
Precipitation (mm)
Longmen~Sanmenxia
R=0.14
P>0.1
Net sediment load (10^6 t)
-1000
-500
0
500
1000
1500
300
400
500
600
700
800
Precipitation (mm)
Sanmenxia~Huayuankou
R=0.16
P>0.1
Net sediment load (10^6 t)
-800
-400
0
400
300
400
500
600
700
800
900
1000
Precipitation (mm)
Huayuankou~Lijin
R=0.33
P<0.05
Net sediment load (10^6 t)
-900
-600
-300
0
300
600
400
600
800
1000
1200
Precipitation (mm)

Figure 7

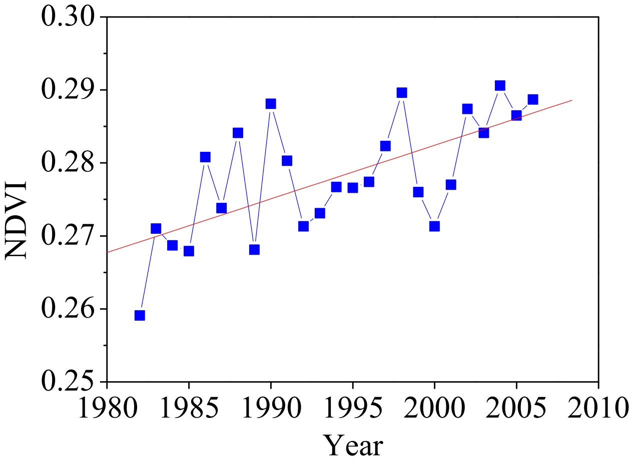

0.30
0.29
0.28
0.27
0.26
0.25
NDVI
1980
1985
1990
1995
2000
2005
2010
Year

Figure 8

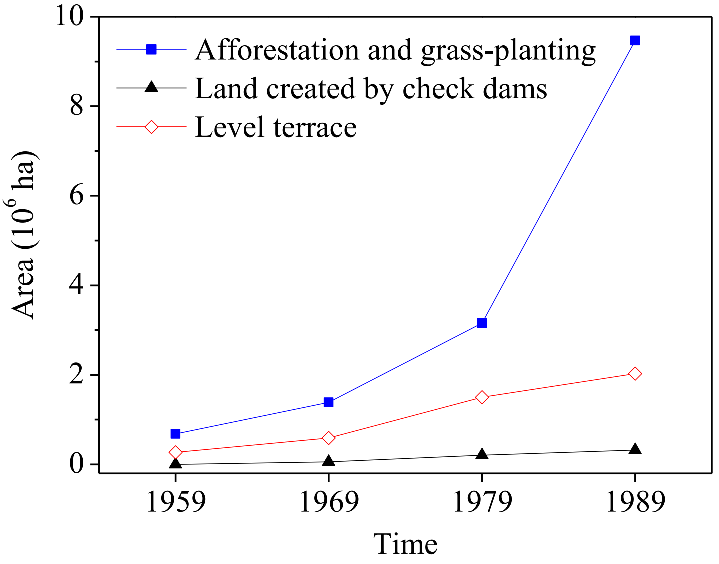

10
8
6
4
2
0
Area (10^6 ha)
1959
1969
1979
1989
Time
■ Afforestation and grass-planting
▲ Land created by check dams
◇ Level terrace

Figure 9

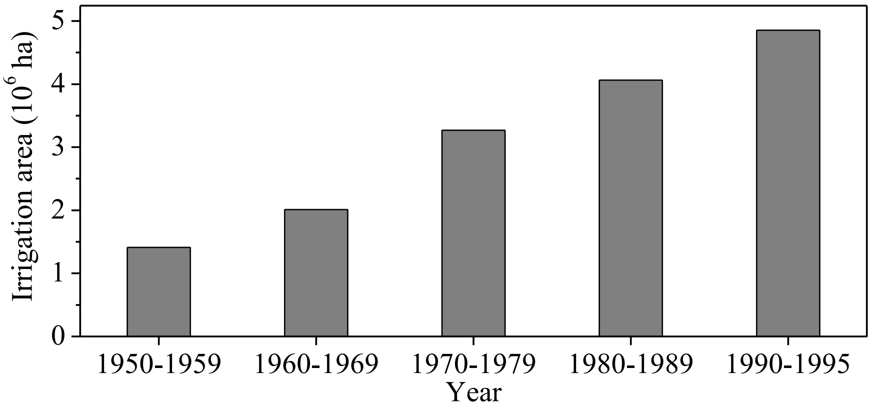
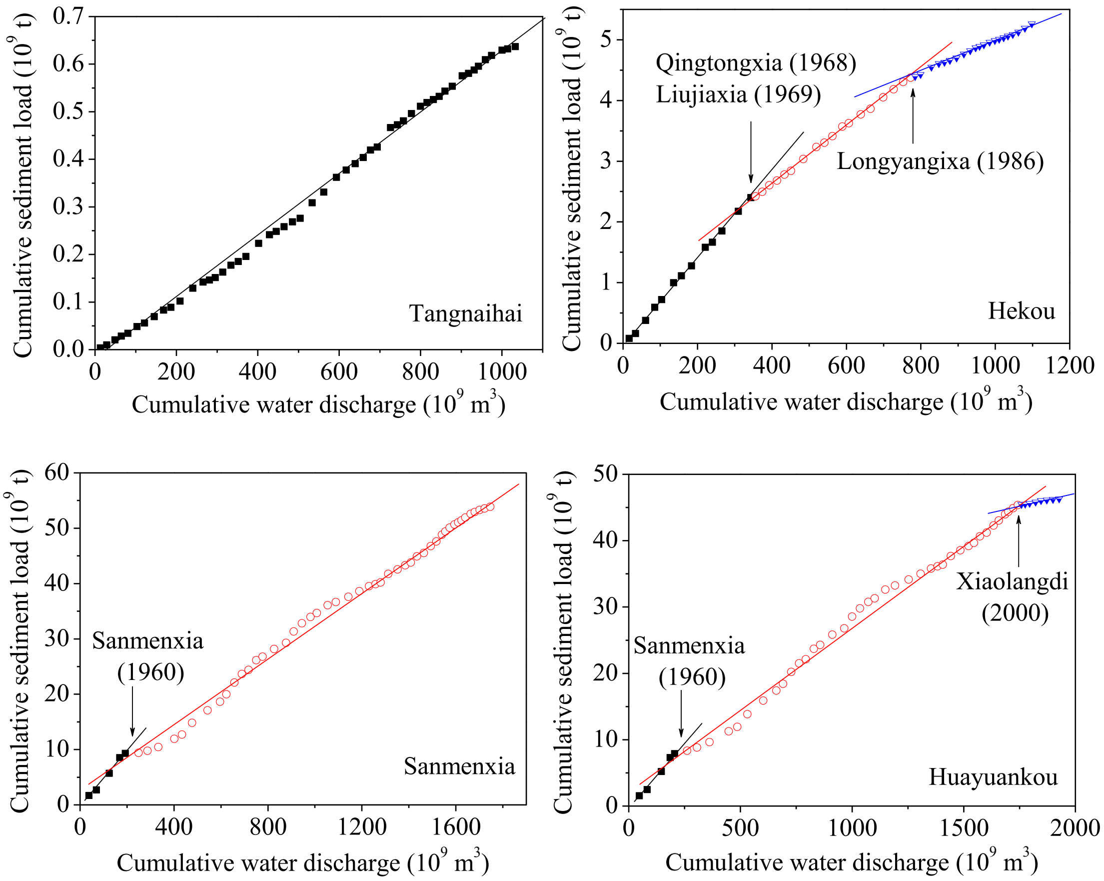
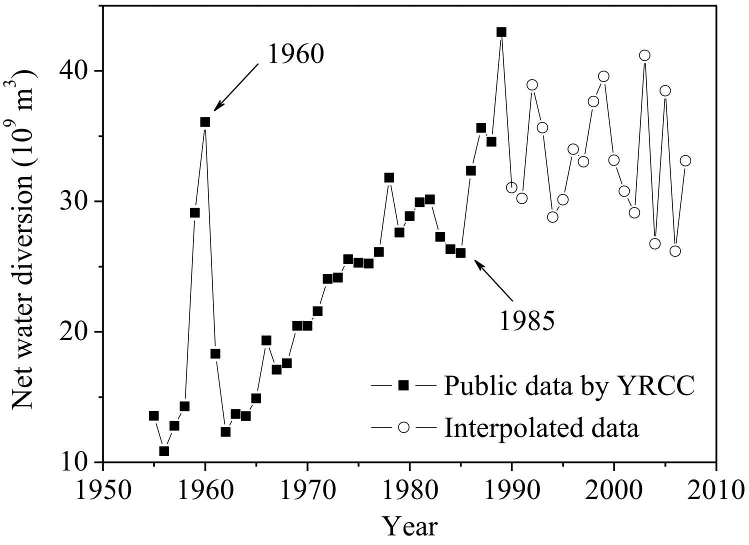

Irrigation area (10^6 ha)
0
1
2
3
4
5
1950-1959
1960-1969
1970-1979
1980-1989
1990-1995
Year

Figure 10



Cumulative sediment load (10^9 t)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
200
400
600
800
1000
Cumulative water discharge (10^9 m^3)
Tangnaihai
Cumulative sediment load (10^9 t)
0
1
2
3
4
5
0
200
400
600
800
1000
1200
Cumulative water discharge (10^9 m^3)
Qingtongxia (1968)
Liujiaxia (1969)
Longyangixa (1986)
Hekou
Cumulative sediment load (10^9 t)
0
10
20
30
40
50
60
0
400
800
1200
1600
Cumulative water discharge (10^9 m^3)
Sanmenxia
(1960)
Sanmenxia
Cumulative sediment load (10^9 t)
0
10
20
30
40
50
0
500
1000
1500
2000
Cumulative water discharge (10^9 m^3)
Sanmenxia
(1960)
Xiaolangdi
(2000)
Huayuankou

Figure 11


1960
1985
Public data by YRCC
Interpolated data
Net water diversion (10^9 m^3)
Year
10
20
30
40
1950
1960
1970
1980
1990
2000
2010