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Global and Planetary Change 50 (2006) 212–225

GLOBAL AND PLANETARY CHANGE

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Interannual and seasonal variation of the Huanghe (Yellow River) water discharge over the past 50 years: Connections to impacts from ENSO events and dams

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Received 7 April 2005; accepted 27 January 2006
Available online 23 March 2006

Abstract

The Huanghe, the second largest river in China, is now under great pressure as a water resource. Using datasets of river water discharge, water consumption and regional precipitation for the past 50 years, we elucidate some connections between decreasing water discharges, global El Niño/Southern Oscillation (ENSO) events and anthropogenic impacts in the drainage basin. Global ENSO events, which directly affected the regional precipitation in the river basin, resulted in approximately 51% decrease in river water discharge to the sea. The degree of anthropogenic impacts on river water discharge is now as great as that of natural influences, accelerating the water losses in the hydrological cycle. The large dams and reservoirs regulated the water discharge and reduced the peak flows by storing the water in the flood season and releasing it in the dry season as needed for agricultural irrigation. Thus, as a result, large dams and reservoirs have shifted the seasonal distribution patterns of water discharge and water consumption and finally resulted in rapidly increasing water consumption. Meanwhile, the annual distribution pattern of water consumption also changed under the regulation of dams and reservoirs, indicating that the people living in the river basin consume the water more and more to suit actual agricultural schedule rather than depending upon natural pattern of annual precipitation. The combination of the increasing water consumption facilitated by the dams and reservoirs and the decreasing precipitation closely associated with the global ENSO events over the past half century has resulted in water scarcity in this world-famous river, as well as in a number of subsequent serious results for the river, delta and coastal ocean.

Keywords: Huanghe (Yellow River); water discharge; ENSO events; dams impacts

1. Introduction

The effect of anthropogenic global change on water resources is one of the most severe crises faced by humanity (Goudie, 2000). In recent decades, the global human demand for freshwater has increased rapidly due to the explosive growth of the world's population and the concurrent economic boom. A large proportion of the world's population is concurrently experiencing water stress (Vörösmarty et al., 2000). One-third of the world's renewable water resources (13,500 out of a total $42{,}700 \times 10^9$ m^3/year) are concentrated in Asia

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doi:10.1016/j.gloplacha.2006.01.005

(Shiklomanov, 2001). Water availability varies widely across the regions of Asia, however, from 77,000 m^3/year per capita to less than 1000 m^3/year per capita. The two largest river systems of Asia, the Ganges-Brahmaputra and the Changjiang (Yangtze), have water resources of 1389×10^9 m^3/year and 1003×10^9 m^3/year, respectively (McCarthy et al., 2001). In the past 20 years, China's rapid economic growth, industrialization and urbanization, accompanied by inadequate infrastructure investment and water management, have contributed to widespread problems of water scarcity throughout the country (UNDP, 1997). Of the 640 major cities in China, more than 300 are facing water shortages and 100 are facing severe scarcities.

In northern China, the Huanghe (Yellow River) is a major source of freshwater for about 107 million people within the river basin (Fig. 1), about 8.7% of the total population in China. Originating from the high Qinghai-Tibet Plateau in the far west of China, the Huanghe flows north, turns south and then bends east for a total of 5464 km before debouching into the Bohai Sea, draining a basin area of about 752,000 km^2 (Fig. 1). Downward to the Huayuankou gauge the Huanghe is confined to a narrow basin characterized by highly raised riverbed over the surrounding grounds caused by intensive siltation of large amount of sediments eroded from the Chinese Loess Plateau in the middle of the river basin. It delivered about 1060 million tons of sediment annually from the loess plateau to the Bohai Sea, which makes it well known in the world (Milliman and Meade, 1983). Since the 1950s the Huanghe's water discharge to the sea has steadily decreased (Yang et al., 1998), while populations and economic development in the drainage basin have grown rapidly. In the 10 years from 1990 through 1999, the average water discharge from the Huanghe to the sea decreased to 13.2×10^9 m^3/year, only 28.7% of its discharge in the 1950s (48.0×10^9 m^3/year) (Yang et al., submitted for publication). Since 1972, the number of no-flow days in the lower reaches has increased rapidly, peaking at 226 days in 1997 (Xu, 2004). In the years following 1997, this severe situation was improved through artificial manipulation of several large reservoirs in the river basin; however, the water discharge to the sea has continued to steadily decrease.

Such a dramatic decrease in water discharge from the Huanghe to the sea has also resulted in a steady decrease in sediment discharge to the sea. The average sediment discharge during the period from 1990 to 1999 was 389.9×10^6 tons/year, only 29.5% of that in the 1950s. The Huanghe, formerly the world's second largest river in terms of sediment discharge to the sea over millennial-scale historical time (Milliman and Meade, 1983),

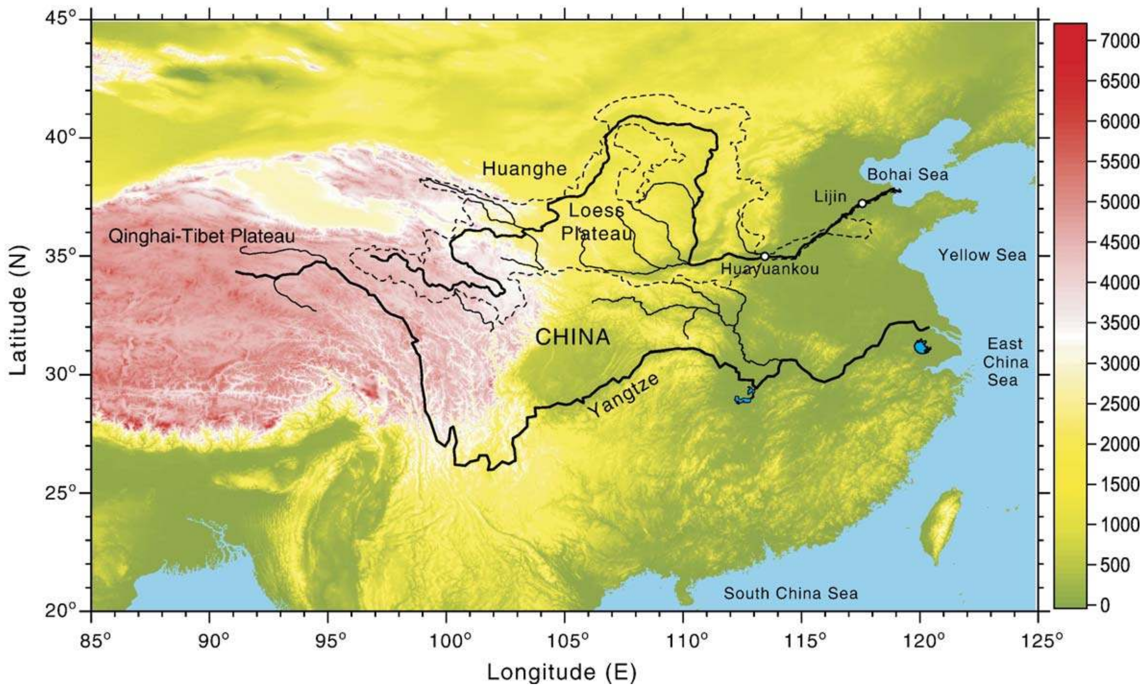

Fig. 1. Index map of China and the Huanghe river basin. The dashed outline shows the drainage basin of the Huanghe. The color scale of the relief map indicates the land elevation above the sea level in meter and the DEM data are available at http://www.ngdc.noaa.gov/mgg/.

has now become the fourth largest after the Ganges-Brahmaputra, Amazon and Changjiang (Yangtze). The decreases of water and sediment discharge, as well as the declines of total dissolved solid flux (e.g. Chen et al., 2005), have resulted in profound physical, ecological and geomorphological impacts on the lower reaches of the river, the coastal area and the Bohai Sea (e.g. Deng and Jin, 2000; Jin and Deng, 2000; Lin et al., 2001; Huang and Fan, 2004).

The reduction in water discharge from the Huanghe can be basically attributed to two factors. One is the decreasing precipitation in the drainage basin, as the natural result under the global changes. The upper and middle reaches of the Huanghe are located in arid and semi-arid regions with low annual precipitation (<150 mm/year), whereas the lower reaches is more humid with an annual precipitation more than 900 mm/year (Chen et al., 2005). Except for the water supply by the melted ice-cover on the Qinghai-Tibet Plateau, precipitation is the major source for river runoff and controls the drought–flood cycles of the river. The average precipitation in the 1990s was about 8.8% less than that in the 1950s. The other factor is the intensifying impact of human activities, which also plays an important role in the hydrological cycle. The most widespread way of controlling water resources is the construction of dams and reservoirs. These structures facilitate improving agriculture, preventing floods, generating power and providing a reliable water resource. Meanwhile, these dams and reservoirs also facilitate water consumption by reducing peak flows during the flooding season and releasing the stored water during the dry season. Therefore, more and more water has been extracted from the river via the hydraulic facilities and used primarily for agricultural irrigation.

Previous studies on this topic mainly focused on increased water consumption and considered variations in regional precipitation to be slight fluctuations, but they did not reveal in detail how the dams and reservoirs facilitated water consumption and shifted the seasonal and annual variations in water consumption (Ren et al., 2002; Xu, 2004). Lu (2004) provided an overview of the water discharge changes occurring in major Chinese rivers and discussed their vulnerability to environmental changes. Therefore, the connections between decreasing water discharge and natural and anthropogenic impacts has not yet been extensively investigated. In this paper, we illustrate the decreasing Huanghe water discharge during the past 50 years with reference to natural and anthropogenic impacts, revealing how operations of the dams and reservoirs have shifted the seasonal and annual distributions of water consumption and finally facilitated increasing water consumption. The data sets (regional precipitation, water discharge and water consumption) we used in this paper are released from the Yellow River Water Conservancy Commission (YRCC) and partly obtained from the River Sediment Bulletin of China published by the Ministry of Hydrology, China.

2. Natural impacts on the decreasing Huanghe water discharge

2.1. ENSO events—regional precipitation

El Niño/Southern Oscillation (ENSO) events are closely linked to patterns of flood and drought in different areas of the world (Glantz et al., 1991) and have strongly affected local- and regional-scale climates through teleconnections affecting the coupled ocean–atmosphere and land systems. Based on the monthly sea surface temperature (SST) anomalies (JMA Index, data are available at ftp://www.coaps.fsu.edu/pub/JMA_SST_Index/) and the Southern Oscillation Index (SOI) (data are provided by Bureau of Meteorology, Australian Government, and are available at http://www.bom.gov.au/climate/glossary/soi.shtml), 13 ENSO events characterized by sustained positive values of SST anomalies and negative values of SOI have been identified over the past 50 years (Fig. 1) (Wang and Geng, 1999; Wang et al., 2001). Wang and Geng (1999) even classified those ENSO events into three categories according to their magnitudes, i.e., four weak, five moderate and four strong events. The annual precipitation over the whole Huanghe drainage basin and various source areas are area-weighted average values, calculated from the data recorded at 342 rain gauges in the whole river basin. When we compare the ENSO events to the regional precipitation from 1950 to 2000, it is clear that the ENSO events corresponded to low precipitation in the Huanghe river basin (Fig. 2). On the basis of a two-level atmospheric circulation model, Yang and Yuan (1994) hypothesized that the SST anomalies in 1985 were mostly responsible for the decreased precipitation in the Huanghe drainage basin in that year. Wang et al. (2001) confirmed that the ENSO events often resulted in decreased precipitation in the source regions of the Huanghe. Hu et al. (1998) also hypothesized that, during the ENSO event years, the river sediment discharge decreased owing to low water discharge. Since the mid-1980s, global ENSO events have become stronger and more frequent than ever, and most of the low-level precipitation years in the Huanghe river basin were closely associated with

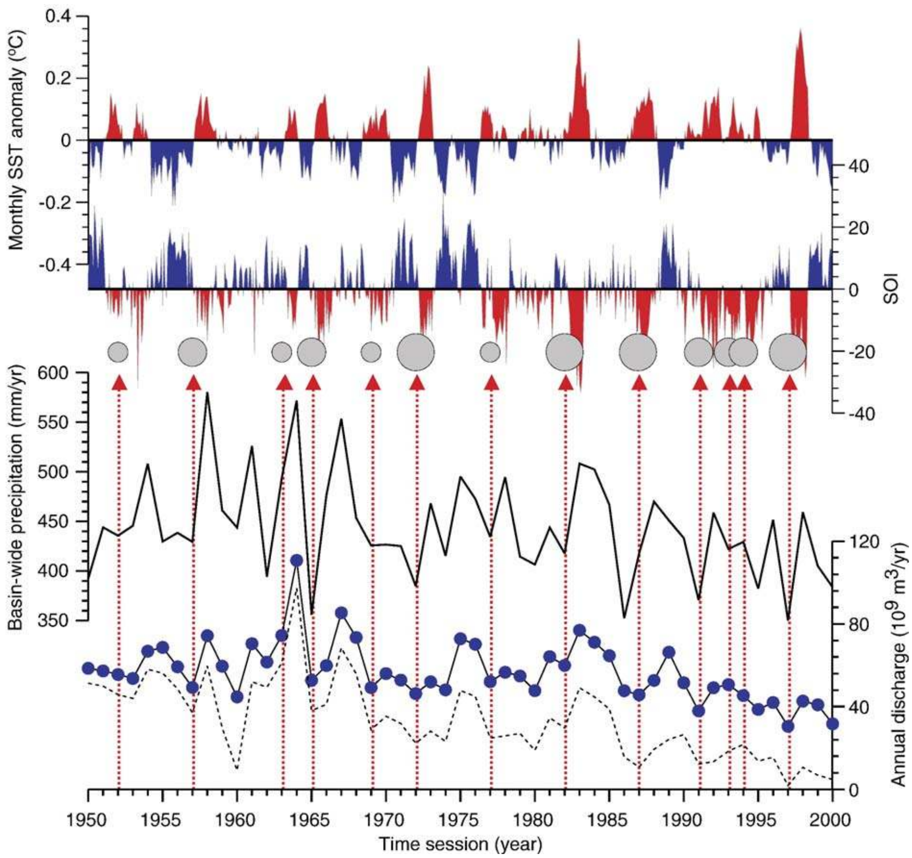

Fig. 2. Time series of monthly SST anomalies, SOI (South Oscillation Index), annual basin-wide precipitation (solid line) in the Huanghe drainage basin, natural water discharge (solid line with dots) and actual measured water discharge to the sea (dashed line) during the past 50 years. The ENSO events were identified based on sustained positive SST anomalies and negative SOI values (shaded areas). The bubbles indicate the years of ENSO events and their sizes correspond to the magnitudes of ENSO events.

moderate and strong ENSO events (Fig. 2). Before the 1970s, the precipitation in the Huanghe river basin had strong interannual variability (over 216 mm); however, interannual variation became mild as the strong ENSO events occurred frequently in subsequent years. The average annual precipitation in the river basin from 1985 to 2000 was only 427.8 mm, about 10% less than that before the 1960s. These correlations between ENSO events and lower regional precipitation indicated that regional precipitation was strongly affected by the global climate system. The changes in SST values resulted from the equatorial Pacific Ocean trade winds, which fed moisture back to the atmosphere, and finally shifted the pattern of regional precipitation in the Huanghe river basin. Lu (2004) also suggested that the water resources in the major rivers in north China are more vulnerable to climatic variations than those in south China. Therefore, the global climate change affected the Huanghe river water discharge by shifting the pattern of precipitation that was the major source for river water discharge.

2.2. Precipitation—water discharge

Precipitation is the main driver of variability in the water balance over space and time, and changes in precipitation have important implications for hydrology and water resources (McCarthy et al., 2001). We define the annual natural discharge (Q_n) as follows:

$$Q_n = Q_m + Q_c + Q_r$$

where Q_m is the actual annual water discharge to the sea measured at Lijin gauge that is the last hydrographical gauge some 100 km upward to the river mouth (location shown in Fig. 1), and Q_c is the officially recorded water discharge that is diverted from the river and consumed above the Lijin gauge. Q_r is the amount of water annually stored in the reservoirs (+) or released from the reservoirs (−). The annual natural discharge, approximately equal to the sum of actual measured water discharge (Q_m), the water consumption (Q_c) and reservoir regulation (Q_r), is roughly characterized as the water source transferred directly from regional precipitation without human disturbance, and this characterization made it possible to assess natural impacts on the initial water supply.

River flows in arid and semi-arid regions (e.g. northern China) are sensitive to changes in precipitation (e.g. Lu, 2004). The natural discharge of the Huanghe fluctuated synchronously with precipitation and both have shown a distinct decreasing trend during the past 50 years (Fig. 2). The natural discharge was closely related to the annual basin-wide precipitation with a coefficient of determination $R^2=0.60$, which indicated the natural discharge is quite sensitive to the regional precipitation (Fig. 3) and vulnerable to the climatic change (Lu, 2004). The actual measured discharge from the Huanghe to the sea at Lijin gauge also had a similar interannual variation pattern to that of the natural discharge; however, the decreasing rate has been accelerated, especially since the 1980s, as precipitation decreased rapidly owing to frequent strong ENSO events during this period. In 1997, the strong ENSO events led to the lowest precipitation in the drainage basin (350.3 mm) among the 50-year records, consequently resulting in the lowest natural river discharge (30.5×10^9 m^3) and the lowest water discharge to the sea (1.9×10^9 m^3) (Fig. 2). This effect was of great concerns because the lower reaches of Huanghe had no flow discharge to the sea for a surprising period of 226 days (Xu, 2004). The natural discharge, discounting water consumption in the drainage basin, reflected the natural impacts on the river hydrological cycle. The average annual natural discharge from 1990 to 2000 decreased by about 30.5% (18.4×10^9 m^3) from that in 1950s (from 60.3×10^9 m^3 to 41.9×10^9 m^3), while precipitation decreased by about 10% during the same time periods (Fig. 2, Table 1). The actual measured discharge at Lijin gauge decreased more sharply than the natural discharge and in 1990–2000 was only 25% of the natural discharge in 1950s. We attributed approximately 51% of the 35.8×10^9 m^3 decrease of the water discharge to the sea to the natural impacts represented by decreasing regional precipitation, and the remaining 49% should be mainly attributed to anthropogenic impacts in the river drainage basin, which indicated that the anthropogenic impacts are now becoming as great as natural influences.

3. Anthropogenic impacts on the decreasing Huanghe water discharge

The past 50 years were a period of dramatic and unprecedented change in human history, during which many aspects of human activities, including world population, water use and damming of rivers, have changed at an increasing rate, resulting in global-scale changes in the earth's system (Goudie, 2000). Any assessment of the impacts of global change on water resources must take into account the increasing anthropogenic impacts from human activities in the terrestrial part of the hydrological cycle. For the Huanghe in particular, operation of dams and reservoirs and related water consumption are the most important human activities affecting the river hydrological cycle.

3.1. Dams and reservoirs

Among the human activities in the river drainage basin, the construction of dams and reservoirs is the

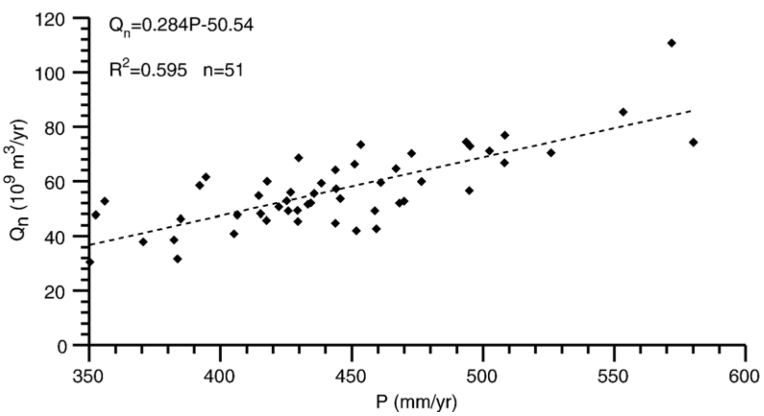

Fig. 3. Annual natural discharge (Q_n) versus annual basin-wide precipitation (P) shows good linear relationship between two variables, indicating that Q_n has high sensitivity to the basin-wide precipitation.

Table 1
ENSO events, decadal variation of precipitation, natural discharge, actual measured discharge to the sea, reservoir regulations and major hydrologic events of the Huanghe over the past 50 years

	1950–1959	1960–1969	1970–1979	1980–1989	1990–2000
ENSO events					
Weak	1	2	1	0	0
Moderate/strong	1	1	1	2	4
Average annual precipitation (mm)	456.4	469.4	443.2	443.7	413.3
Natural discharge Q_n (10^9 m^3/yr)	60.3	68.3	56.2	59.7	41.9
Actual measured water discharge at Lijin gauge Q_m (10^9 m^3/yr)	48.0	50.1	31.1	28.6	13.2
Annual basin-wide water consumption					
Q_c (10^9 m^3/yr)	12.3	17.8	25.0	29.6	28.5
Ratio to natural discharge	20%	26%	44%	50%	68%
Water storing/releasing in the reservoirs Q_r (10^9 m^3/yr)					
Storing	+0.00	+0.99	+0.40	+1.55	+1.63
Releasing	−0.00	−0.63	−0.34	−0.05	−1.42
Hydrologic events [a]	–	SMX/LJX	–	LYX	XLD

[a] Completions of reservoirs. SMX—Sanmenxia Reservoir, LJX—Liujiaxia Reservoir, LYX—Longyangxia Reservoir, XLD—Xiaolangdi Reservoir. Detailed information is shown in Table 2.

most direct way to manipulate river water resources. Dams and reservoirs are globally essential to the river fragmentation, and thus having significant impacts on the water regulation and sediment retention in the reservoirs (Nilsson et al., 2005; Syvitski et al., 2005). One of the most striking features of the dams and reservoirs constructed in the river drainage basin is that they have become so large that they can regulate the streams and reduce their peak flows. For example, the Aswan High Dam in Egypt can store 1.5 times the average annual flow of the Nile River and has provided a high degree of protection to the lower Nile River

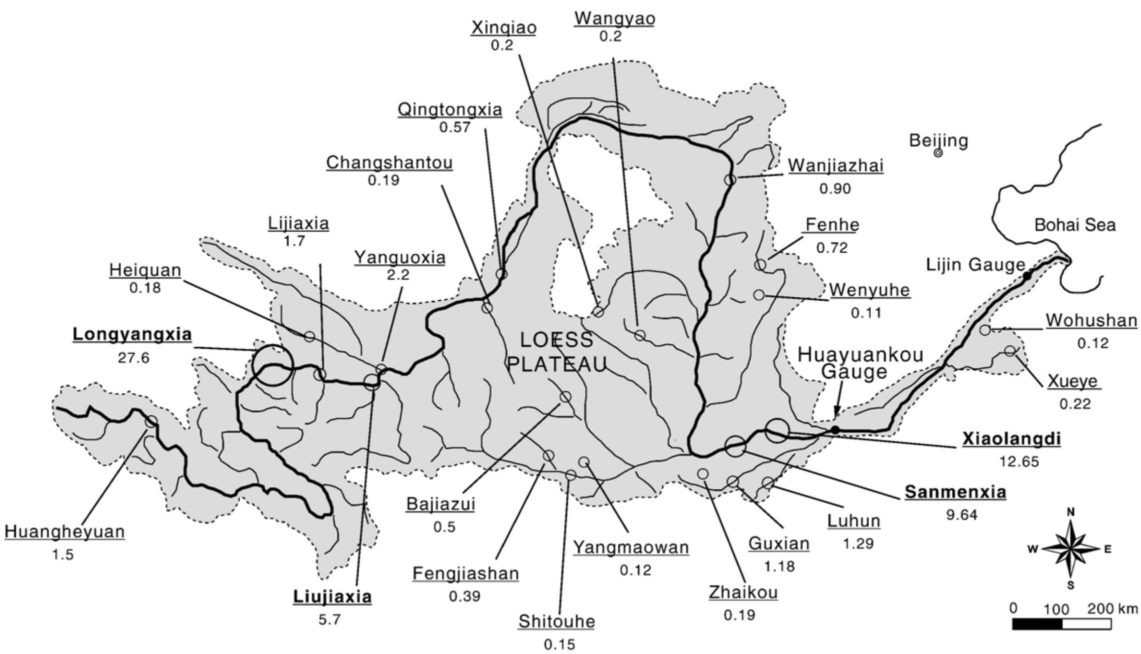

Fig. 4. The reservoirs with storage capacity exceeding 0.1×10^9 m^3 in the Huanghe river basin and the four most influential reservoirs along the main stream: Longyangxia, Liujiaxia, Sanmenxia and Xiaolangdi (see Table 2). The Longyangxia and Liujiaxia reservoirs control the water from the source of upper reaches, and the other two, locating at the end of middle reaches, control the water from the middle reaches. The numbers underlying the reservoir names indicate the storage capacities in 10^9 m^3.

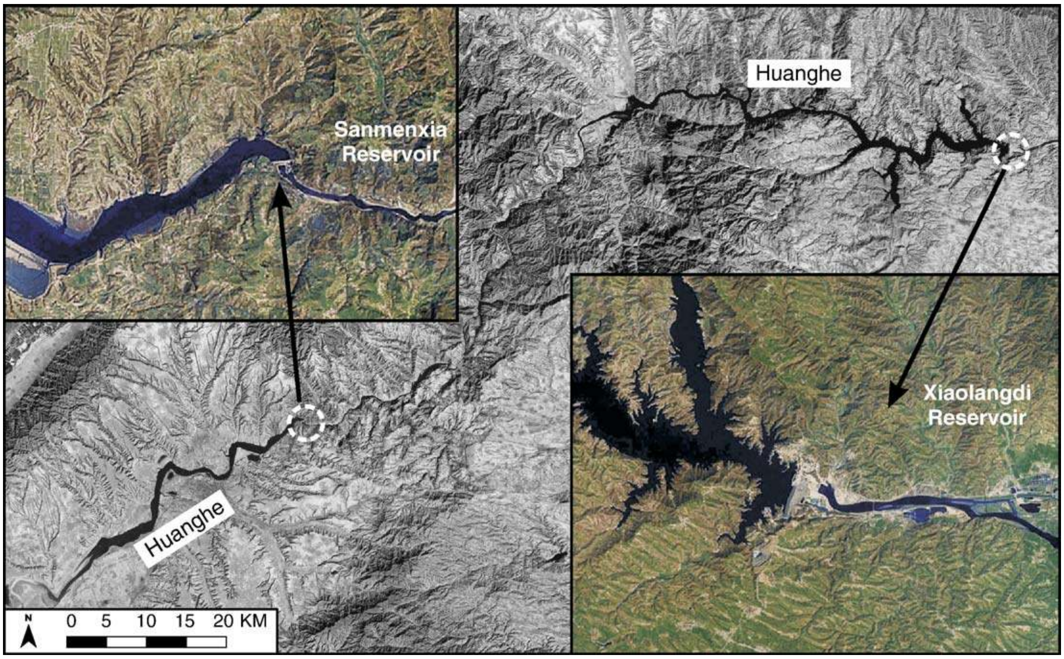

Fig. 5. Locations of the Sanmenxia and Xiaolangdi reservoirs illustrated on the Landsat 7 image on December 22, 1999 (processed by INSTAAR's Environmental Computation and Imaging Facility, made available by the U. Maryland Global Land Cover Facility, NASA and U.S. Forest Service. Courtesy of James P.M. Syvitski, INSTAAR, University of Colorado at Boulder) and close views of the two reservoirs (color images, available at http://maps.google.com/).

valley simply by reducing overall discharge, truncating the peak flows and shifting the seasonal distribution of natural water discharge (Goudie, 2000; Vörösmarty and Sahagian, 2000). By 2001, more than 3147 reservoirs had been built in the Huanghe river basin, with a total storage capacity of 57.4×10^9 m^3 (Zhang et al., 2001) that virtually equals to the annual natural discharge of 57.0×10^9 m^3 in the basin (average of 1950–2000).

There are 24 reservoirs scattering widely in the river basin with storage capacities exceeding 0.10×10^9 m^3, among which four major reservoirs along the Huanghe mainstream are most influential: the Sanmenxia, Liujiaxia, Longyangxia and Xiaolangdi reservoirs (Fuggle et al., 2000) (Fig. 4). The Sanmenxia reservoir, the first large one built on the mainstream, with a storage capacity of 9.7×10^9 m^3 at a water level of 335 m (Figs. 4 and 5, Table 2), began to store water in 1960, resulting in a dramatic reduction in discharge below the reservoir during 1960–1962 and very serious siltation within the reservoir, which has been forced to release the stored water in 1961 and 1962 (Fig. 2). The Xiaolangdi reservoir, located downward to the Sanmenxia (Figs. 4 and 5), was completed in 1999, resulting in a further decrease of the water discharge at Lijin gauge (Fig. 2). Since 2002, the Xiaolangdi reservoir has become a major regulator for the water-sediment-regulation scheme conducted by the YRCC to manage the Huanghe water resource (Wang et al., 2005). The Huanghe caused many problems over the millennia of the Chinese long history due to frequent flooding events in the river basin that resulted in tremendous losses of life and property (Hu et al., 1998). Since the founding of the People's Republic

Table 2
Information of four most influential reservoirs along the mainstream of Huanghe

Reservoirs	Location	Height (m)	Storage (10^9 m^3)	Time of completion
Sanmenxia	Middle reaches	335	9.7	September 1960
Liujiaxia	Upper reaches	147	5.7	October 1968
Longyangxia	Upper reaches	178	27.6	October 1986
Xiaolangdi	Middle reaches	160	12.7	October 1999

of China in 1949, numerous dams and reservoirs have been built as the most effective facilities to control floods by reducing the peak flows, and consequently there have been no breaches of the Huanghe levees except those caused by ice jams in the winter seasons (Fuggle et al., 2000).

As a direct result of construction of dams and reservoirs in the Huanghe river basin, the seasonal variability of the river discharge has been weakened. The measured water discharge in flood seasons accounted for more than 60% of the annual water discharge in the 1950s, but decreased to 43% in the 1990s (Fig. 6(a)), because the dams and reservoirs reduced the peak flows drastically by retaining the floodwater inside them and releasing it in the dry season to satisfy the demands of agricultural irrigation. As recorded at Huayuankou gauge, located at the end of the middle reaches (Figs. 1 and 4), the number of days with daily runoff exceeding 4000 m^3/s was reduced sharply in response to the operation of dams and reservoirs (Fig. 6(a)). Review of the monthly average water discharge from 1950 to 2000 shows that the annual distribution pattern of water discharge has been totally changed during the period of 1985–2000 with removal of seasonal peak of water discharge, mainly because of the operations of large dams and reservoirs (Fig. 6(b)). The discharge decreases in 1960, 1969–1974, 1986–1987 and 1999–2000 were undoubtedly caused by the operations of the Sanmenxia, Liujiaxia, Longyangxia and Xiaolangdi reservoirs, respectively (Table 2). And

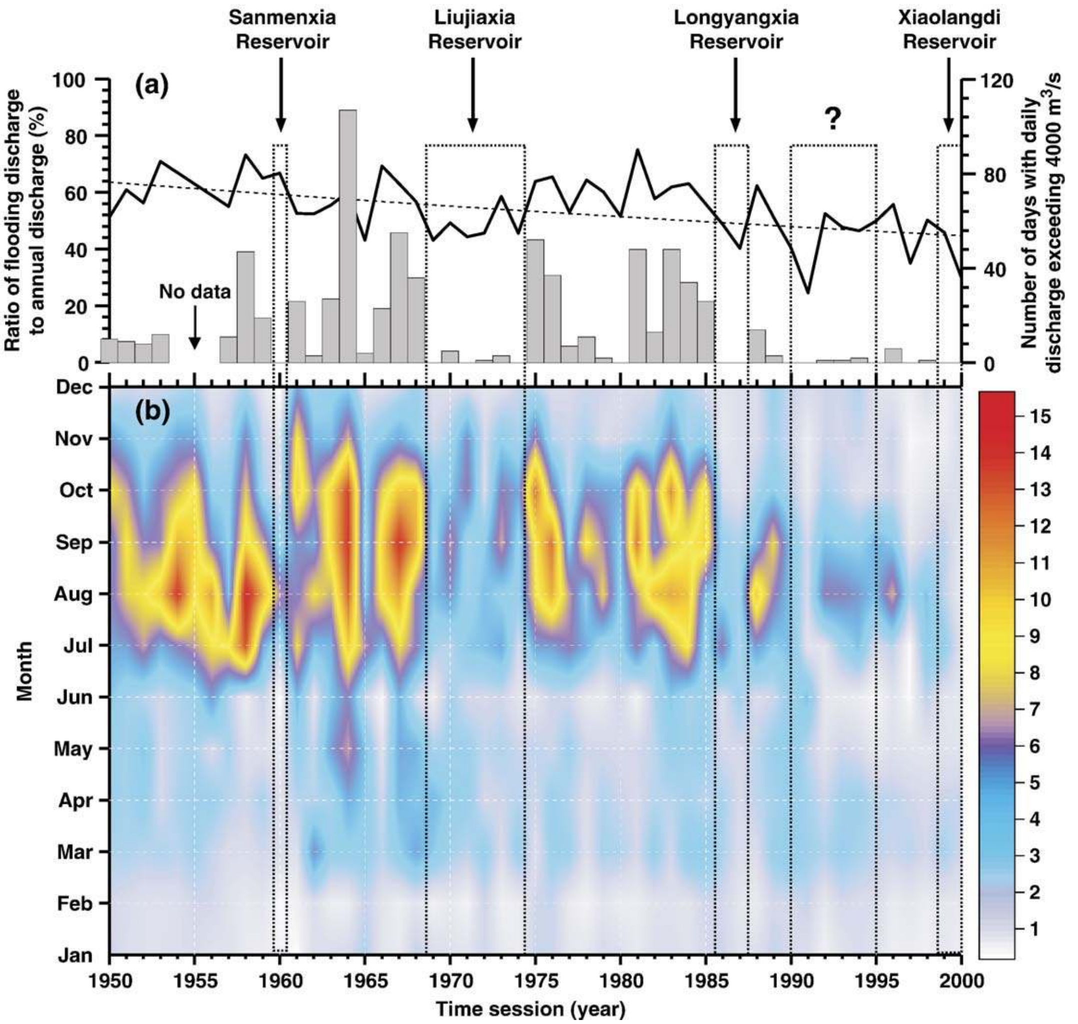

Fig. 6. (a) The ratio of flooding discharge to the annual water discharge and the number of days with daily discharge exceeding 4000 m^3/s at Huayuankou gauge (location shown in Fig. 4) over the past 50 years; (b) the monthly average water discharge measured at Huayuankou gauge from 1950 to 2000.

the decreases during 1990–1995 may have been caused by the joint regulation of the Sanmenxia, Liujiaxia and Longyangxia reservoirs (Fig. 6).

3.2. Water consumption

Besides regulating river discharge, the dams and reservoirs are also critical for the surrounding communities: millions of people depend upon them for survival. The basin includes approximately 3.1 million hectares of irrigation area for agriculture, making up 12.5% of the total agricultural irrigation area in China. Because the cities in the river basin are less industrialized than those in the coastal areas of China, agricultural irrigation is the dominant part (more than 92%) of water consumption (e.g. Wang et al., 1997; Chen and Zhang, 2001; Zhang et al., 2001).

The total water consumption within the whole river basin (Q_c) became larger and larger during the past 50 years (Table 1). The increased water consumption in the river basin was also closely associated with the operation of dams and reservoirs; for example, the

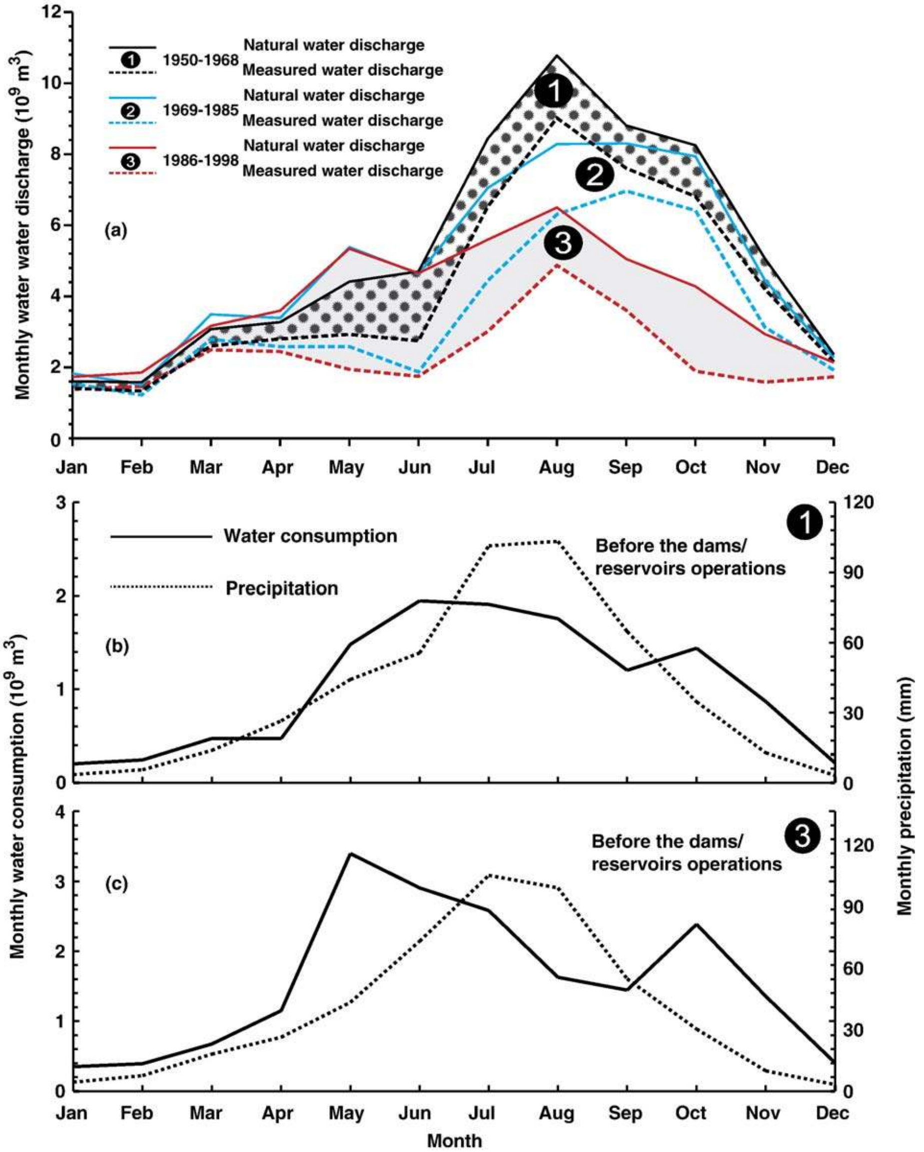

Fig. 7. (a) The monthly average natural water discharge Q_n and actual measured water discharge Q_m at Huayuankou gauge in three periods related to the operation of the Liujiaxia (1968) and Longyangxia (1986) reservoirs; (b) the monthly distribution patterns of basin-wide precipitation (P) and water consumption (Q_c) above Huayuankou gauge before; and (c) after the operations of dams and reservoirs.

average water consumption before the operation of Liujiaxia reservoir (1968) was 14.8×10^9 m^3/year, but consumption increased dramatically to 25.7×10^9 m^3/year before the operation of the Longyangxia reservoir (1986) and thereafter continued to increase to 29.4×10^9 m^3/year (1986–2000). Although the water consumption in 1990–2000 decreased slightly, the ratio of water consumption to the natural discharge still increased to 68% from 50% (1989–1990), while it was only 20% during the period of 1950–1959. Since the 1980s, more than 50% of the natural discharge has been consumed, indicating water consumption within the river basin has exceeded the water discharge to the sea (Table 1). The large water consumption rates around 1960, averaging 27.2×10^9 m^3/year, which were distinctly larger than any of the others before 1969, were caused by water storage in the Sanmenxia reservoir during that period (Fig. 2). The Sanmenxia reservoir was not capable of storing a large amount of water in subsequent years because a large amount of sediment was trapped inside it, resulting in serious siltation within the reservoir.

The dams and reservoirs were built to change the natural seasonal distribution of water discharge to meet the demands of agricultural irrigation, as well as to prevent flooding. In the Huanghe drainage basin, precipitation events are mainly concentrated in a narrow band from July through August, whereas agricultural irrigation is often conducted in the early summer (May–June) for crops to mature before harvest and again in the late autumn (October) for planting seeds, respectively (Wei et al., 1996). Thus, a phasic shift is evident between the precipitation peak and the water consumption peak. The water regulation of the dams and reservoirs is the most effective way to resolve the conflict between natural

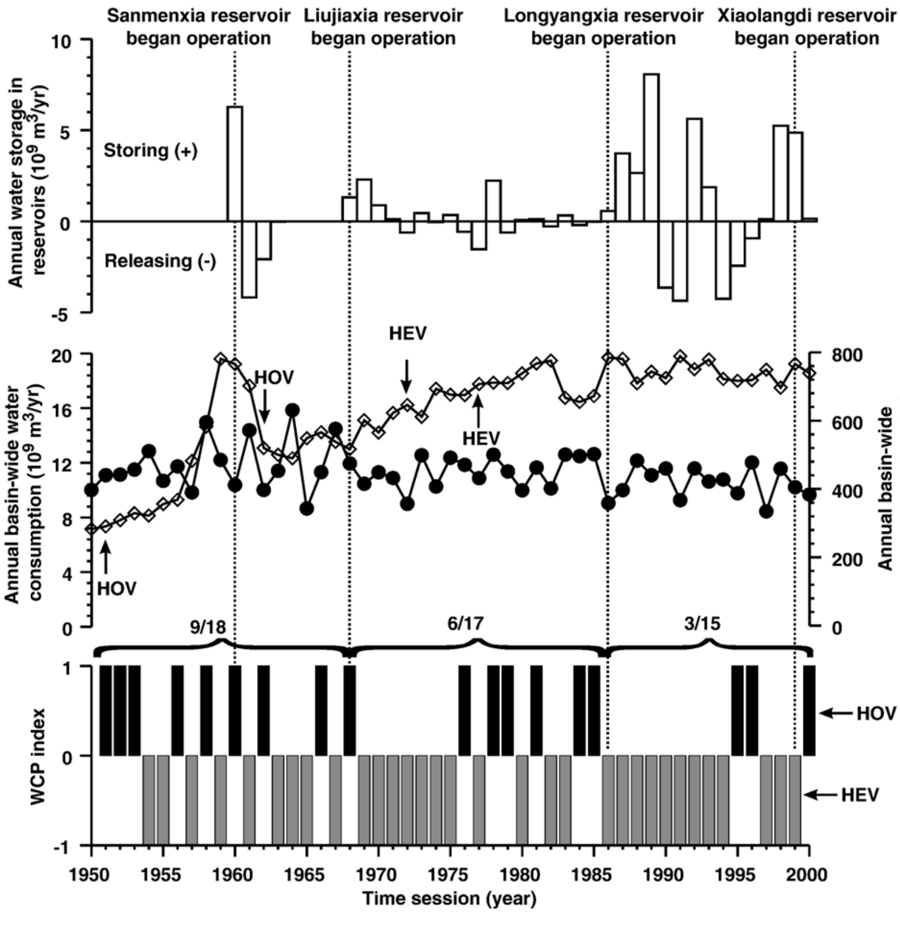

Fig. 8. Annual water storage/release of the reservoirs in the river basin (Q_r) (upper panel), interannual fluctuations of precipitation and water consumption (middle panel), and the index of water consumption–precipitation (WCP) (lower panel) over the past 50 years. The occurrence of HOV trends of annual water consumption decreased to three times over 15 years (1986–2000) from nine times over 18 years (1951–1968), corresponding to the more and more active regulations of large dams and reservoirs in the river basin.

precipitation and human demands for agricultural irrigation, as illustrated in Fig. 7. During the first period (1950–1968), before the operation of the Liujiaxia reservoir, the seasonal distribution patterns of both natural discharge and the measured water discharge at Huayuankou gauge had same steep modes with peaks in August. However, during the other two periods (1969–1985 and 1986–1998), the regulation of the Liujiaxia and Longyangxia reservoirs somewhat flattened the seasonal distribution patterns of natural discharge, which were characterized by continuous decreases of peaks in August and increases of sub-peaks in May (Fig. 7(a)). Particularly from 1986 to 1998, the natural river discharge in May was 5.3×10^9 m^3, quite close to that in August (6.5×10^9 m^3), demonstrating a dramatically different mode of seasonal distribution from that in the first period (Fig. 7(a)). Moreover, when water consumption was discounted from the natural discharge, the seasonal distribution patterns of measured water discharge during the later two periods resumed steep modes similar to that in the first period (Fig. 7 (a)).

The processes can be summarized as follows. Firstly, to modulate the natural water discharge process to an artificial pattern meeting the demands for agricultural irrigation, the dams and reservoirs stored the floodwater in the flood season (July–September), and then released the stored water in the late autumn (October) and in the late spring and early summer (May–June) of the next year, resulting in a more flat mode of the seasonal distribution of natural discharge. Secondly, the large water consumption for agricultural irrigation at these stages reshaped the distributional pattern of measured water discharge into a steep mode. Before the operation of the dams and reservoirs began, water consumption was mainly concentrated in June through August as well as the precipitation, but after the operation of dams and reservoirs, two distinct peaks of water consumption appeared in May and October, when `large amounts of water were consumed for agricultural irrigation, while the precipitation distribution had little change compared with that before the operation of dams and reservoirs began (Fig. 7(b) and (c)). Therefore, the regulation of dams and reservoirs made the water consumption more controllable and optional.

Besides changing the seasonal distribution pattern of water consumption, the dams and reservoirs shifted the annual distribution pattern of water consumption. Before 1968 only the Sanmenxia Reservoir stored the water discharge around 1960 and released the stored water in 1961 and 1962 due to serious siltation inside the reservoir. Since 1968, the water regulations by the reservoirs have become more and more active and intensive along with the completions of the other three reservoirs (Fig. 8, upper panel). When comparing the annual precipitation dataset with annual water consumption from 1950 to 2000, we classified the interannual variations of water consumption into two types (Fig. 8, middle panel). One is the homo-variation (HOV), in which increasing or decreasing annual water consumption corresponded to increasing or decreasing precipitation in the same year, respectively; the other is the hetero-variation (HEV), in which the increasing or decreasing annual water consumption corresponded to decreasing or increasing precipitation in the same year, respectively. The HOV trend of annual water consumption indicated that the water was consumed in a natural way, mostly depending upon natural precipitation, while the HEV trend implied that the water was consumed based on actual agricultural schedule rather than depending on precipitation. The HEV trend of annual water consumption is likely caused by the dams and reservoirs that stored the water in the flooding years and released it in the drought years, resulting in increasing or decreasing annual water consumption independent of annual precipitation. We defined the indexes of annual water consumption trend and annual precipitation trend, respectively, in the following equations:

$$I_i^{\mathrm{c}} = (Q_{\mathrm{c}_i} - Q_{\mathrm{c}_{i-1}})/|Q_{\mathrm{c}_i} - Q_{\mathrm{c}_{i-1}}|$$

$$I_i^{\mathrm{p}} = (P_i - P_{i-1})/|P_i - P_{i-1}|$$

where i was the time series ranging from 1951 to 2000. The indexes of annual water consumption (I_i^{c}) and annual precipitation (I_i^{p}) trends were normalized to -1 or 1, indicating decreasing or increasing trends, respectively. The water consumption–precipitation (WCP) index was defined as:

$$\mathrm{WCP}_i = I_i^{\mathrm{c}} \cdot I_i^{\mathrm{p}}$$

The value of WCP_i equals 1 or -1, corresponding with the HOV or HEV trend of annual water consumption, respectively. From 1951 to 2000, the occurrence of HOV trends in annual water consumption decreased apparently concurrently with operations of dams and reservoirs in the river basin (Fig. 8). Before the Liujiaxia reservoir began operation in 1968, the HOV trend occurred nine times over 18 years and the water consumption during this period was not very great except for that facilitated by the Sanmenxia reservoir around 1960 (Fig. 8). However, the HOV trend occurred six times over 17 years during the period from 1969 to 1985 before the Longyangxia reservoir began operation, and then decreased to only three times over 15 years after the Longyangxia reservoir began operation (Fig. 8, lower panel). The decrease of HOV trends in annual water consumption from 1950 to 2000 reflected that the people in the drainage basin consumed the water more and more to suit the actual agricultural schedules, facilitated by the active water regulations by dams and reservoirs, rather than depending upon the direct supply of natural precipitation. As results of these human activities, the seasonal distribution patterns of water consumption (Q_c) and actual measured discharge to the sea (Q_m) have changed significantly (see Fig. 7).

4. Discussion

Besides the strong ENSO events that have significant impacts on the regional precipitation in the Huanghe drainage basin, other global climate changes such as global warming also influence the hydrological cycle of this river. In particular, global warming has increased air temperatures in the river basin, causing increased evapotranspiration (Zhang et al., 2004), decreased river water discharge, and increasing water demand for agricultural irrigation. Since 1970, average annual air temperature over the river basin increased from 16.5 °C to 17.5 °C (Xu, 2005), while the regional precipitation decreased in reverse. Thus, climate of the Huanghe river basin has become warmer and drier. As a result, the evapotranspiration from agriculture and evaporation within the reservoirs will increase, as well as the water withdrawal from the river. In addition, the ice-cover on the Qinghai-Tibet Plateau (see Fig. 1), the source of the Huanghe, would melt more rapidly (Lai, 1996), increasing the river discharge of the upper reaches to some extent. Therefore, increasing evapotranspiration from global warming would be partly offset by the increasing melt water from the Huanghe's source area (e.g. Cao et al., 2005).

Anthropogenic impacts, especially referring to the regulation of dams and reservoirs and increasing water consumption, have been as great as natural impacts on the decreased water discharge to the sea. The large dams and reservoirs in the river basin have controlled extreme floods and thus prevented natural disasters; however, they have also facilitated the large amount of water consumption. Through regulation and reduction of peak flow, these structures have shifted the modes of seasonal and annual water consumption, accelerating the decrease of the river water discharge to the sea. Therefore, we do not know whether we should "bless the dams or damn the dams" (Milliman, 1997).

Since the late 1950s, a series of soil conservation practices have been implemented in the Chinese loess plateau, including biological measures (e.g. trees and pasture) and structural works (e.g. terrace and dams) (Huang and Zhang, 2004). Tang (2004) presented that the decrease of surface runoff in the upper and middle reaches owing to the improvement of soil conservation was approximately 0.63×10^9 m^3/year over a period of 1980–1997, only accounting 1.2% of the natural discharge during the same period. It seemed that soil conservation has little impact on the decreasing discharge.

It is undisputed that the Huanghe river mouth and delta and its receiving basin, the Bohai Sea, have responded dramatically to the rapid decrease of the water discharge to the sea. Since 1950, the structure of the coastal ecosystem has changed and fish catches have decreased drastically, corresponding to the declining freshwater input to the coastal sea (Deng and Jin, 2000; Jin and Deng, 2000). The average sea surface salinity (SSS) of the Bohai Sea has increased by 2‰ and by as much as 15‰ in Laizhou Bay, south of the Huanghe delta (Lin et al., 2001). The sediment discharge to the sea also decreased at the same rate as the water discharge owing to the low transport capability and the trapping effect of dams and reservoirs, resulting in significant changes to delta geomorphology such as retreating shorelines, coastal erosion and delta degradation (Huang and Fan, 2004).

5. Conclusion

Using the consecutive records of Huanghe for the past 50 years, here we elucidate some connections between decreasing water discharges, global ENSO events and anthropogenic impacts. Global ENSO events, which directly affected the regional annual precipitation in the river basin, resulted in approximately 51% decrease in river discharge to the sea. Anthropogenic impacts on river water discharge (49%) seemed to be as great as natural influences, accelerating the water losses in the hydrological cycle. The functioning of large dams and reservoirs in the river basin shifted the seasonal and annual distribution patterns of water discharge and water consumption, resulted in rapidly increasing water consumption and made it possible for the people living in the river basin to consume the water more and more to suit the actual agricultural schedules rather than depending upon the natural pattern of precipitation. The combination of large dams and reservoirs in the river basin and the global ENSO events over the past half-century has resulted in water scarcity in this world-famous river, as well as in a number of subsequent serious results for the river, river mouth, delta and coastal ocean.

Acknowledgements

This work was supported by National Science Foundation of China (NSFC) with grant numbers of 40306008 and 90211022. We gratefully appreciated Dr. James P.M. Syvitski and the anonymous reviewer for their critical comments on improving the original manuscript. Thanks are also extended to Mr. K. Wang and D. Li from the YRCC for their kind help and fruitful discussions.

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