

Stepwise decreases of the Huanghe (Yellow River) sediment load (1950–2005): Impacts of climate change and human activities

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Abstract

The sediment load delivered from the Huanghe (Yellow River) to the sea has decreased sharply to 0.15×10^9 metric tons per year (0.15 Gt/yr) between 2000 and 2005, and now represents only 14% of the widely cited estimate of 1.08 Gt/yr. The river seems to be reverting to the pristine levels characteristic of the middle Holocene, prior to human intervention. Datasets from 1950 to 2005 from four key gauging stations in the main stream reveal distinct stepwise decreases in sediment load, which are attributed to both natural and anthropogenic impacts over the past 56 yr. Completions of two reservoirs, Liujiaxia (1968) and Longyangxia (1985), in the upper reaches of the river and their joint operations have resulted in stepwise decreases in sediment load coming from the upper reaches. Effective soil conservation practices in the middle reaches since the late 1970s, combined with the operation of the Sanmenxia and Xiaolangdi reservoirs, have also caused stepwise decreases in sediment load at Huayuankou in the middle reaches, but the decrease differs from that observed in the upper reaches. Decrease in precipitation is responsible for 30% of the decrease in sediment load at Huayuankou, while the remaining 70% is ascribed to human activities in the river basin, of which soil conservation practices contribute 40% to the total decrease. Sediment retention within reservoirs accounts for 20% of the total sediment load decrease, although there was notable sediment retention within the Xiaolangdi reservoir from 2000 to 2005. The remaining 10% of the decrease in sediment load is a result of the operation of reservoirs in the upper reaches. In the lower reaches, 20% of the sediment passing Huayuankou has been lost as a result of channel deposition and water abstraction. Soil conservation practices and the operation of reservoirs have lowered the content of coarser sediment ($D > 0.05$ mm) at Huayuankou, and reduced channel deposition in the lower reaches. In contrast, sediment loss owing to water abstraction in the lower reaches has increased considerably as water consumption for agricultural needs has increased. Therefore, the combined effects of climate change and human activities in the upper, middle, and lower reaches have resulted in stepwise decreases in the sediment load delivered from the Huanghe to the sea. The Huanghe provides an excellent example of the altered river systems impacted by climate change and extensive human activities over the past 56 yr. Further dramatic decreases in sediment load and water discharge in the Huanghe will trigger profound geological, morphological, ecological, and biogeochemical responses in the estuary, delta, and coastal sea. © 2007 Elsevier B.V. All rights reserved.

Keywords: Huanghe (Yellow River); stepwise decrease; sediment load; climate change; human activity; dam and reservoir

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1. Introduction

Rivers represent the major link between continents and oceans within the global geochemical cycle and are major pathways for the delivery of terrestrial materials to the oceans (Milliman and Meade, 1983; Walling and Fang, 2003; Meybeck and Vörösmarty, 2005). Understanding the flux of these materials has been set as a goal of the International Geosphere Biosphere Programme and its core project, Land Ocean Interaction in the Coastal Zone (Syvitski, 2003; Syvitski et al., 2005). The river sediment-associated transport accounts for more than 90% of the total river-borne flux of elements such as P, Ni, Mn, Cr, Pb, Fe, and Al (Martin and Meybeck, 1979). Furthermore, 43% of the total transport of organic carbon from the land to the oceans by rivers is in particulate form (Ludwig et al., 1996) and is thus closely associated with river sediment transport. Milliman and Syvitski (1992) estimated global sediment flux to the ocean to be 20×10^9 metric tons (Gt/yr); this value has been widely cited in the scientific literatures. In recent years, studies of riverine sediment flux to the oceans, and the processes of sediment transport, have increasingly received more attention as variations of riverine sediment flux have become an important index for the effects of climate change and human activities in river basins (e.g., Yang et al., 2002; Walling and Fang, 2003; Meybeck and Vörösmarty, 2005; Nilsson et al., 2005; Syvitski et al., 2005; Walling, 2006; Yang et al., 2006). During the latter half of the 20th century, the global changes resulting from human activities, including population increases, water use, fertilizer consumption, and damming of rivers, have intensified at an increasing rate, and have altered the global river systems (Steffen, 2004). Recent studies have documented, on a global scale, many examples of rivers that have shown marked decreases in both water discharge and sediment load delivered to the sea; for example, the Colorado, Mississippi, Indus, Nile, Changjiang (Yangtze River) and Huanghe (Yellow River) (Meade and Parker, 1985; Yang et al., 1998; Stanley and Warne, 1998; Walling and Fang, 2003; Yang et al., 2006; Wang et al., 2006). Among these, the Huanghe provides an excellent illustration of the interaction between climate change, extensive implementation of soil and water conservation, and sediment control measures (Walling and Fang, 2003).

The Huanghe is regarded as the second largest river of the world in terms of sediment load over the last several thousand years, with a widely cited annual sediment load (Q_s) of 1.08 Gt/yr (Milliman and Meade, 1983), which represents 6% of the estimated global river sediment flux to the ocean. However, more recent data

(1990–2005) show that the annual sediment load reaching the sea is only 0.3 Gt/yr, less than one-third of that estimated by Milliman and Meade (1983). In particular, in the most recent 6 yr (2000–2005) the Huanghe discharged only 0.15 Gt/yr of sediment load to the Bohai Sea, reverting to its pristine levels of the middle Holocene, prior to human intervention (Milliman et al., 1987; Ren and Zhu, 1994; Saito et al., 2001). The decline of the Huanghe sediment load, as well as synchronous decreases in water discharge (Wang et al., 2006) and total dissolved solid flux (Chen et al., 2005), has had profound physical, ecological, and geomorphological effects on the lower reaches of the river, the coastal area near the river mouth, and the Bohai Sea (e.g., Deng and Jin, 2000; Jin and Deng, 2000; Lin et al., 2001; Huang and Fan, 2004).

Over thousands of years of Chinese history, frequent catastrophic floods in the Huanghe river basin have resulted in tremendous losses of life and property (Hu et al., 1998). The high sediment load, most of which is eroded from the Loess Plateau, has become a concern. This is because the annual water discharge of the Huanghe is only $49 \text{ km}^3/\text{yr}$, equivalent to approximately 5% of that of the Yangtze River ($900 \text{ km}^3/\text{yr}$), whereas the annual sediment load is more than twice that of the Yangtze River (Milliman and Meade, 1983). Since the 1950s, many dams and reservoirs have been constructed in the Huanghe river basin to intercept discharge and trap sediment, and soil conservation practices have been implemented in the middle reaches. Consequently, there have been no floods other than those caused by winter ice jams (Fuggle et al., 2000). Since the 1970s, water consumption in the river basin has accelerated because of increasing water demand by a growing population and extensive agricultural development. Over the same period, climatic changes have led to a reduction in precipitation in the river basin (Xu, 2003; Wang et al., 2006). As a result, the annual sediment load discharged from the Huanghe to the sea has decreased synchronously with the decrease in water discharge, as documented by Yang et al. (1998) and Walling and Fang (2003). Recent studies of the ecosystem and depositional systems of the Huanghe delta have revealed distinct responses to decreases in water and sediment flux (Jin and Deng, 2000; Huang and Fan, 2004; Wu et al., 2004). It is therefore important to make use of the most recently available data from the Huanghe to elucidate the causes of decreases in sediment load, which will provide a reference for consideration of the alteration of global river systems during the Anthropocene.

Although there have been many publications that discuss the decreases in sediment load of the Huanghe over the past 50 yr, especially in the Chinese literature

(e.g., Yang et al., 1998; Liu et al., 2005; Ru et al., 2005), most of them focus mainly on descriptive accounts of the decreases in sediment load recorded at Lijin, rather than quantitative analyses. Xu (2003) made estimates of the contributions of human activities and changes in precipitation to decreases in the amount of the Huanghe sediment discharged to the sea on the basis of data up to 1997 from the Lijin gauging station. However, it is not reasonable to evaluate the effect of precipitation changes on sediment load based on the relationship between the basin-wide precipitation and sediment load discharged to the sea for two reasons: (1) Precipitation in the lower reaches is higher than that in the upper and middle reaches; however, it has little effect on the sediment yield since the Huanghe sediment comes predominately from the loess region in the middle reaches. (2) Channel deposition and water abstraction in the lower reaches cause considerable sediment loss (as will be seen in this

study) that is not related to basin-wide precipitation. Only when the precipitation above Huayuankou and the sediment load at Huayuankou are examined together, the estimation become credible.

Our major interest is in the rapid changes of the Huanghe River; that is, which human activities (reservoir entrapment, soil conservation practices, and water abstraction) have the most influence on the decrease in sediment load? The goal of our study was to illustrate the interannual and seasonal variations of the Huanghe sediment load on the basis of an up-to-date dataset (1950–2005) recorded at four gauging stations in the upper, middle, and lower reaches of the river, to investigate the contributions of climate change (precipitation decrease) and basin-wide human activities (e.g., dams and reservoirs, soil conservation practices, and water abstraction) to the decreases in sediment load, and to elucidate the causes of such dramatic decreases.

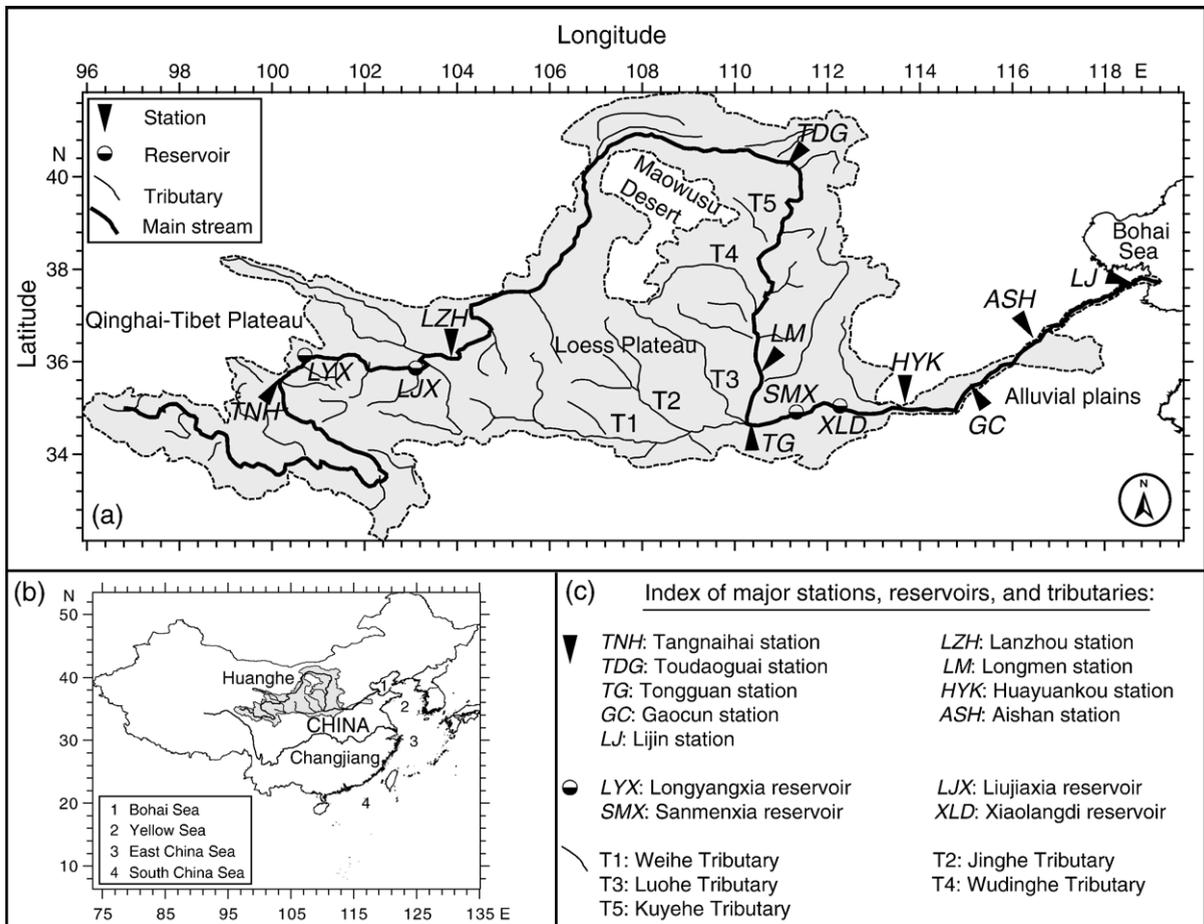


Fig. 1. The Huanghe (Yellow River): (a) extent of the drainage basin, (b) regional location map; and (c) index for locations of major gauging stations and tributaries. The source of the Huanghe is in the high Qinghai–Tibet Plateau. The river is a major contributor of fluvial sediment to the world’s oceans, and is characterized by low runoff and high sediment load (1.1 Gt/yr). Most of the sediment load is derived from erosion on the Loess Plateau surrounding the middle reaches of the river.

Yang et al. (2006) presented a thorough description of the dam impacts on decreases in sediment load of the Changjiang from 1950 to 2004 and considered in detail the budget and future trend of the sediment load. The present study on the Huanghe sediment load, in combination with that on the Changjiang, provides an integrated view of the considerable changes affecting the two major river systems of China.

2. An overview of the Huanghe River basin

2.1. Geography

The Huanghe originates on the eastern Qinghai–Tibet Plateau, and it flows eastward through northwestern China over a total length of 5464 km before debouching into the Bohai Sea (Fig. 1). It drains a wide basin that covers more than 750,000 km² and exhibits a variety of geological and climatic features. The river can be divided into three sections according to its geographical settings: (1) The upper reaches extend over a length of 3471 km from the river source to Toudaoguai and drain an area of 385,996 km²; (2) The middle reaches stretch 1206 km from Toudaoguai to Huayuankou and drain an area of 343,751 km². A considerable number of tributaries join the main stream in the middle reaches; And (3) the lower reaches extend over a length of 786 km from Huayuankou through the flat alluvial plains of Henan and Shandong provinces to the river mouth, and drain an area of 22,726 km² (Fig. 1, Table 1). The river descends from an altitude of approximately 4500 m at its source with variable gradient to 1000 m at Toudaoguai, and then with relatively continuous gradient to 110 m at Huayuankou (Table 1, Fig. 2a). Changes from steep to gentler gradients near Lanzhou and Huayuankou correspond to the boundaries between the Qinghai–Tibet Plateau (above Lanzhou), the Loess Plateau (below Lanzhou and including the middle reaches), and the flat alluvial plains of the lower reaches (Fig. 1).

2.2. Climatic conditions

There is considerable climatic variation within the Huanghe drainage basin. The annual mean temperature varies from 1 to 4 °C in the upper reaches, 8 to 14 °C in the middle reaches, and 12 to 14 °C in the lower reaches, with the highest temperatures occurring in July and the lowest in January (Chen et al., 2005). The mean annual precipitation is highly variable across the river basin, increasing from 368 mm in the upper reaches, to 530 mm in the middle reaches, and to 670 mm in the lower reaches (Table 1). The spatial distributions of

Items	Mainstream			Major tributaries in the middle reaches				
	Upper reaches: Above Toudaoguai	Middle reaches: Toudaoguai–Huayuankou	Lower reaches: Huayuankou–Lijin	T1: Weihe	T2: Jinghe	T3: Luohe	T4: Wudinghe	T5: Kuyehe
Length (km)	3471	1206	786	818	–	446.9	491.2	241.8
Basin Area (km ²)	385,996	343,751	22,726	106,500	43,200	25,600	29,700	8500
Altitude (m)	4480–1000	1000–110	110–0	–	–	–	–	–
P (mm/yr)	368	530	670	–	–	–	–	–
Qc (km ³ /yr)	10.4	5.3	7.3	–	–	–	–	–
Gauging station	Toudaoguai	Huayuankou	Lijin	Huaxian	Zhangjashan	Zhuangtuo	Baijiachuan	Wenjiachuan
D ₅₀ (mm)	0.015	0.019	0.018	0.017	0.028	0.032	0.033	0.057
Q (km ³ /yr)	22.0 (56.4%)	39.0 (100%)	32.0 (82.0%)	7.2	1.7	0.9	1.2	0.6
Qs (Gt/yr)	0.11 (11.1%)	0.97 (100%)	0.80 (82.5%)	0.36	0.25	0.09	0.12	0.1
SSC (kg/m ³)	4.4 (19.7%)	25.4 (100%)	24.8 (97.6%)	54.5	141	119	92	139

P—annual precipitation; Qc—Annual water consumption; D₅₀—median grain size of the suspended sediment; Q—annual water discharge; Qs—annual sediment load; SSC—suspended sediment concentration. The data are partly referred to IRTCES (2005). Cell with dash indicates there is no data available. Locations of stations are shown in Fig. 1.

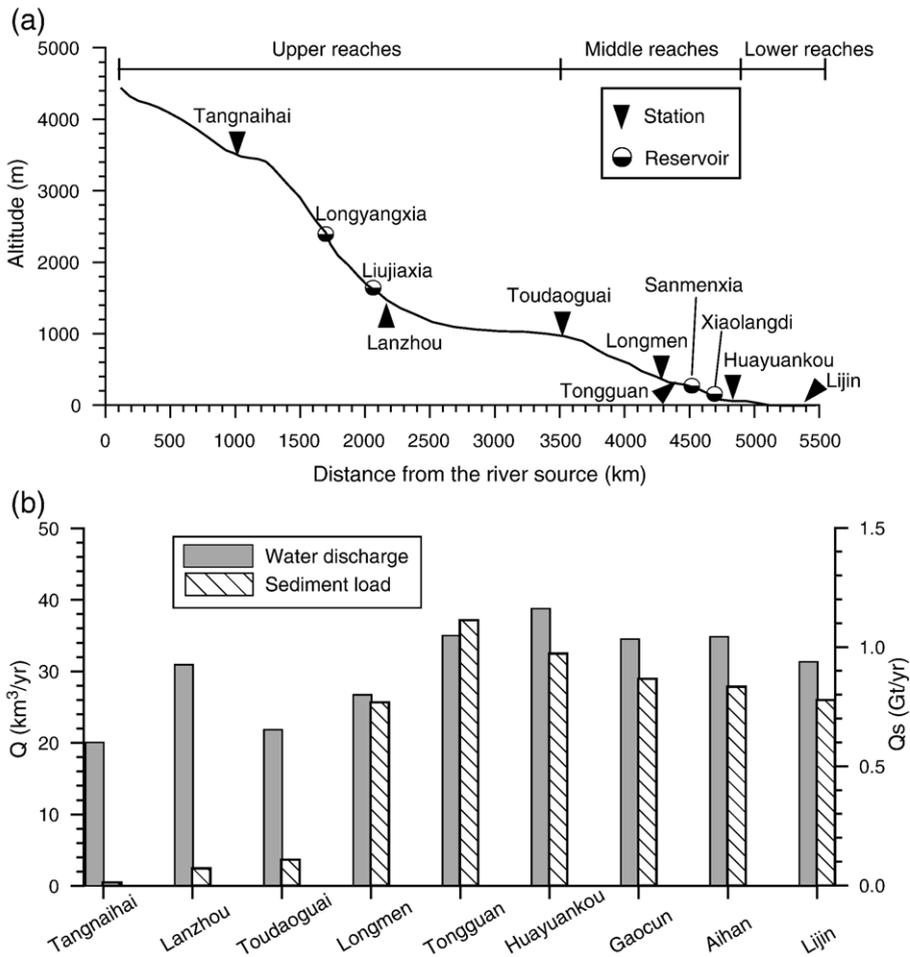


Fig. 2. (a) Longitudinal profile of the main stream of the Huanghe showing the locations of gauging stations and reservoirs, and their elevation relative to the Yellow Sea Datum. (b) Averages of annual water discharge and sediment load recorded at gauging stations along the main stream. Most of the sediment load of the river originates from the Loess Plateau in the region downstream from Toudaoguai gauging station. The annual water discharge and sediment load are averaged over the period from 1950 to 2005 for the major stations of Lanzhou, Toudaoguai, Huayuankou, and Lijin, and over the period from 1956 to 2005 for other stations. Station locations are shown in Fig. 1.

mean temperature and mean precipitation in the river basin indicate that the upper and middle reaches are situated in arid and semi-arid regions, respectively, whereas the lower reaches are in a humid area. These changes of climatic regions correspond with changes in the geology of the river basin.

Seasonal climatic changes are distinct. For example, winters are cold and dry with little rainfall, and summers are wet and warm and account for most of the annual rainfall. The summer season contributes approximately 85% of annual precipitation in the upper and middle reaches. Except in ice-covered upstream mountainous areas, where snowfall is significant, rainfall is the main source of river water; river flows in arid and semi-arid regions of northern China are sensitive to changes in precipitation, as noted by Lu (2004).

2.3. Water and sediment

Compared with other large rivers of the world, high sediment load and low water discharge are distinctive characteristics of the Huanghe. The average annual water discharge from the Huanghe to the sea between 1950 and 2005, as recorded at Lijin station, was 32.0 km³/yr, which represents only 5% of that of the Changjiang (Yang et al., 2006), or 0.5% of that of the Amazon (Milliman and Meade, 1983). Most of the river water of the Huanghe originates from the upper reaches, where ice melt and snowfall are the main contributors. The average annual water discharge (1950–2005) at Toudaoguai, near the boundary between the upper and middle reaches, is 22.0 km³/yr, and accounts for 56.4% of the annual discharge at Huayuankou (Table 1; Fig. 2b). The annual

discharge at Toudaoguai is somewhat lower than that at Lanzhou (Fig. 2b), because water is used for agricultural irrigation along the river between Lanzhou and Toudaoguai (Chen et al., 2005). Downstream from Toudaoguai the water discharge increases as several tributaries of considerable size join the main stream in the middle reaches. The highest annual discharge of the river ($39.0 \text{ km}^3/\text{yr}$) occurs at Huayuankou (Table 1; Fig. 2b). Downstream from Huayuankou the river is confined to a narrow basin characterized by a riverbed raised up to 10 m above the surrounding area by severe siltation. At Lijin, some 100 km upstream from the river mouth, the annual water discharge decreases to $32.0 \text{ km}^3/\text{yr}$, which is 82.0% of the discharge at Huayuankou, and is considered to represent the discharge from the Huanghe to the sea (Table 1). The decrease in discharge between Huayuankou and Lijin is caused mainly by water abstraction for agricultural irrigation and domestic use in the lower reaches. Because of climatic change (e.g., decrease in precipitation related to ENSO events) and increasing water consumption facilitated by dams and reservoirs, discharge from the Huanghe to the sea has decreased continuously over the past half century (Wang et al., 2006) and illustrates a complicated transformation of the river system as a result of both natural and human influences.

The spatial distribution of sediment load in the Huanghe differs from that of water discharge. Nearly 90% of the sediment load comes from the middle reaches, where the dominant geological feature is the wind-deposited Loess Plateau, which is acknowledged as the region of highest erodibility in the world (Ren and Shi, 1986; Huang and Zhang, 2004). In contrast, the upper reaches above Toudaoguai provide only 10% of the sediment load (Table 1). In the upper reaches of the river, sediment load increases from 0.07 Gt/yr at Lanzhou to 0.1 Gt/yr at Toudaoguai, and the average suspended sediment concentration (SSC) increases from 2.3 to 4.4 kg/m^3 along the same stretch of river (Fig. 2b; Table 1). In the middle reaches a surprisingly large increase in sediment load to 0.97 Gt/yr at Huayuankou is largely the contribution of major tributaries between Toudaoguai and Tongguan (Fig. 1, Table 1, and Fig. 2b). As the river flows over the flat alluvial plain, considerable quantities of suspended sediment fall from suspension, and the high level of channel deposition in the lower reaches has raised the riverbed 10 m above the surrounding areas to form a unique 'suspended river' that creates a high risk of catastrophic flooding in the surrounding area (Chen et al., 2005). Finally, the Huanghe discharges 0.8 Gt/yr (1950–2005) of sediment load to the sea, as recorded at Lijin (Table 1).

The loess region surrounding the middle reaches provides a high sediment yield. The 5 major tributaries in

the middle reaches, namely, the Weihe (T1), Jinghe (T2), Luohe (T3), Wudinghe (T4), and Kuyehe (T5) collectively contribute $\sim 0.92 \text{ Gt/yr}$ to the main stream, and account for 95% of the annual sediment load at Huayuankou (Fig. 1 and Table 1). Owing to the high erodibility of the Loess Plateau, 85% of the sediment from the major tributaries each year can be associated with only a few heavy rainfalls (Ye, 1992), and high SSC values of more than 100 kg/m^3 have been recorded (Table 1). The maximum SSC recorded for an individual tributary was surprisingly high at around 1700 kg/m^3 (Walling, 1981; Zhao, 1996). The maximum daily rainfall for the Wudinghe tributary (location shown in Fig. 1) was recorded in 1971 and accounted for 43% of the rainfall in that year (Zhang and Shao, 2001). Consequently, the median grain sizes of the suspended sediment (D_{50}) in the major tributaries of the middle reaches are significantly higher than those measured at stations in the main stream (Table 1), which indicates that the heavy rainfall has resulted in severe soil erosion in the area of the Loess Plateau.

2.4. Major hydrological events in the river basin since 1950

2.4.1. Dams and reservoirs

The impact of dams on large river systems has become a worldwide concern in recent years (Vörösmarty and Sahagian, 2000; Goudie, 2000; Nilsson et al., 2005; Syvitski et al., 2005; Yang et al., 2006; Wang et al., 2006). Several studies have included the Huanghe among examples of the impact of dams on river water and sediment flux to the ocean (e.g., Walling and Fang, 2003; Syvitski et al., 2005; Wang et al., 2006). Since the 1950s, the Huanghe has become a highly fragmented and regulated river as a result of the construction of more than 3147 reservoirs in the river basin, with a combined storage capacity of 57.4 km^3 (Zhang et al., 2001). These reservoirs can store approximately 1.5 times of the annual discharge recorded at Huayuankou. There are 24 large dams and reservoirs with individual storage capacities exceeding 0.1 km^3 scattered widely through the river basin. Four of these major reservoirs (Sanmenxia, Liujiaxia, Longyangxia, and Xiaolangdi) are on the main stream and make the greatest contribution to water regulation and sediment retention (Wang et al., 2006) (Fig. 1).

The Sanmenxia reservoir, the first largest reservoir built in the river basin, is in the middle reaches downstream from the Tongguan gauging station, where the Huanghe begins to bend eastward (Fig. 1). Construction started in 1957 and was completed in 1960 with a dam wall height of 106 m and a total capacity of 9.6 km^3 . There have been 3 stages in the operation of the

Table 2
Sediment retention within the Sanmenxia and Xiaolangdi reservoirs

Reservoirs	Time periods			
	1960–1973	1973–1986	1986–2000	2000–2005
Sanmenxia				
Retention (Gt)	7.71	0.06	1.97	–0.23
Average (Gt/yr)	0.55	0.005	0.13	–0.04
Xiaolangdi		2000–2005		
Retention (Gt)		2.37		
Average (Gt/yr)		0.40		

Reference: Data are from Zhao (1996), IRTCES (2001–2005) and E.J. (2006).

Sanmenxia reservoir: storing water and trapping sediment (1960–1964), flood mitigation and sediment release (1964–1973), and, because of severe siltation within the reservoir, storing only clear water since 1973 (Zhao, 1996). During the first two stages (1960–1973), total siltation in the Sanmenxia reservoir amounted to 7.7 Gt, accounting for 81% of the total siltation from 1960 to 2005 (Zhao, 1996; IRTCES, 2004; Table 2). From 1973 to 1986 there was little siltation within the reservoir. However, in recent years, severe siltation and floods in tributaries upstream from the reservoir (e.g., floods in Weihe tributary in 2004; Fig. 1) that were attributed to the presence of the reservoir have become a cause for concern (Zhang et al., 2004; Li et al., 2004).

The Liujiaxia and Longyangxia reservoirs were constructed in the upper reaches above Lanzhou in 1968 and 1985, respectively (Fig. 1). The Liujiaxia reservoir has a storage capacity of 5.7 km³ and a 147-m-high dam wall. It normally stores about 2.7 km³ of water and traps 0.06 Gt of sediment annually (Chen, 1997). The Longyangxia reservoir (27.6 km³ of storage capacity and 178-m-high dam wall) is a giant reservoir according to the criteria of Nilsson et al. (2005). Since its completion, it has operated jointly with the Liujiaxia reservoir to trap most of the sediment supplied from above Lanzhou. In addition, the combined operation of these two reservoirs after 1985 regulated the seasonal water discharge from the upper reaches to meet demands for agricultural irrigation (Wang et al., 2006), thus affecting the middle and lower reaches (Chen, 1997).

The Xiaolangdi reservoir, which has a storage capacity of 12.7 km³ and a 160-m-high dam wall, is in the middle reaches between the Sanmenxia reservoir and Huayuankou station. Construction was completed in October 1999, and regulation of water discharge from the middle reaches then commenced. Sediment entrapment in the reservoir is considerable; for example, siltation from 2000 to 2005 amounted to ~2.4 Gt at a rate of approximately 0.4 Gt/yr (Table 2). In 2002, the Yellow River Water Conservancy Commission (YRCC) initiated the Water–sediment Regulation Scheme, which

uses the controlled release of floodwaters from the Xiaolangdi reservoir and other small reservoirs to deliver the sediment retained within the Xiaolangdi and scour the lower reaches (Wang et al., 2005).

2.4.2. Soil conservation practices in the middle reaches

The loess region of the middle reaches covers an area of 640,000 km²; severe erosion of about 212,000 km² of this area supplies approximately 90% of the total river sediment (Table 1). The sediment yield from the loess region via tributaries (T3, T4, and T5 of Table 1) is coarser (median grain size of 0.03–0.05 mm) than that from the upper reaches owing to erosion associated with heavy rainfall (Table 1). The siltation in the lower reaches is caused mostly by deposition of coarser sediment ($D_{50} > 0.05$ mm) from the middle reaches (Xu, 2003). A series of soil conservation practices were implemented in the late 1950s to retard the erosive capacity of heavy rainfall in the loess region, to maintain the productivity of land, and to improve the quality of environment. These practices have included construction of terraces and sediment-retaining dams, reforestation and planting of grass to improve the land cover, and establishment of pasturelands. They have been notably effective since the late 1970s, as the sediment yield from the middle reaches has been reduced by 0.25–0.30 Gt/yr since then (Zhao, 1996; Walling and Fang, 2003; Huang and Zhang, 2004). Zhao (1996) compiled comprehensive datasets covering the period from 1950 to 1990 that included basin-wide precipitation, sediment yield, runoff, and soil conservation practices in the Huanghe drainage basin. Zhao (1996) described the decline of water discharge and sediment flux of the Huanghe before 1990 as well as erosion and deposition in the river channel of the lower reaches. He ascribed the decline of water discharge and sediment flux to fluctuations of precipitation, flow regulation by dams, agricultural irrigation, and soil conservation practices. Soil conservation measures had been applied to ~80 × 10⁹ ha in the middle reaches by 1990. Therefore, soil conservation practices have become a major human activity that, along with flow regulation by dams and agricultural irrigation, has played a major role in the decline of water flow and sediment flux within the river basin.

3. Data collection

The datasets used in this study, which presents the most up-to-date data available, consist of consecutive monthly and annual water discharge and sediment load records from 1950 to 2005 at several key gauging

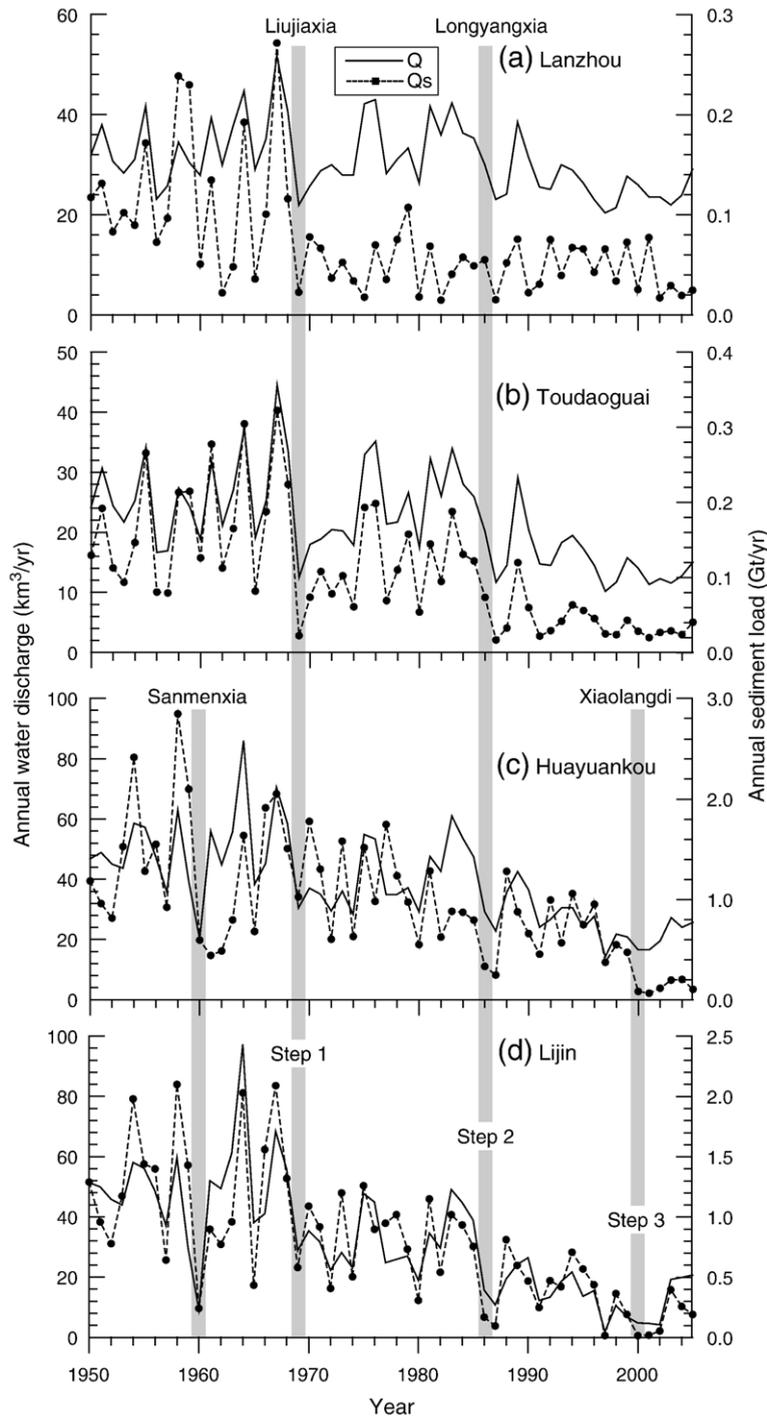


Fig. 3. Time series (1950–2005) of annual water discharge (Q) and sediment load (Q_s) at 4 major gauging stations along the mainstream: (a) Lanzhou, (b) Toudaoguai, (c) Huayuankou, and (d) Lijin. The construction of reservoirs and their combined operations have resulted in stepwise decreases of river water flow and sediment load over the past 56 yr.

stations along the main stream (Lanzhou, Toudaoguai, Sanmenxia, Huayuankou, and Lijin), as well as similar data for a few tributaries. The records of siltation within

the major reservoirs (Sanmenxia and Xiaolangdi) and in the lower reaches used in this study are available from publications by the YRCC (e.g., Ye, 1992; Zhao, 1996)

Table 3

Stepwise decreases in annual water discharge (Q), sediment load (Q_s), and suspended sediment concentration (SSC) at three gauging stations, and major hydrological events in the river basin. The average annual sediment loads (1950–1968) are used as the reference levels (100%)

Time periods	Toudaoguai				Huayuankou				Lijin			
	Q (km ³ /yr)	Q_s (Gt/yr)	%	SSC (kg/m ³)	Q (km ³ /yr)	Q_s (Gt/yr)	%	SSC (kg/m ³)	Q (km ³ /yr)	Q_s (Gt/yr)	%	SSC (kg/m ³)
1950–1968: reference level ^a	26.54	0.18	100.0	6.8	49.88	1.55	100.0	31.1	48.85	1.33	100.0	27.2
1969–1985: after the 1st step ^b	24.07	0.11	61.1	4.6	40.79	1.08	69.7	26.5	32.70	0.84	63.2	25.7
1986–1999: after the 2nd step ^c	16.59	0.05	27.8	3.0	27.65	0.68	43.9	24.6	15.06	0.40	30.1	26.6
2000–2005: after the 3rd step ^d	12.83	0.03	16.7	2.2	21.61	0.13	8.4	5.8	12.24	0.16	12.0	10.5

Major hydrological events in the river basin

^a The Sanmenxia reservoir was completed and began to store water and sediment in 1960. It was forced to release the water and sediment from 1962 to 1964 due to severe siltation in the reservoir. In 1968 the Liujiaxia reservoir was completed and trapped ~39% of the sediment from the upper reaches.

^b The Longyangxia reservoir was completed in 1985 and led to the retention of a further 35% of sediment from the upper reaches, as well as a decrease of water discharge. In the middle reaches the soil conservation practices that started in the late 1950s were effective by the late 1970s.

^c The Xiaolangdi reservoir was completed in 1999, resulting in sharp decreases of water discharge and sediment load through Huayuankou and Lijin from 2000 to 2005.

^d The Water–sediment Regulation Scheme was initiated in 2002 by the YRCC to release the sediment previously retained in the Xiaolangdi reservoir and to scour the lower reaches. As a result of channel scouring in the lower reaches, the annual sediment loads and SSC at Lijin became remarkably higher than those at Huayuankou.

and in Bulletins of Chinese River Sediment compiled by the International Research and Training Center on Erosion and Sedimentation (IRTCES, 2001, 2002, 2003, 2004, 2005) and published recently by the Ministry of Water Resources of China (E.J., 2006).

The measurement of river sediment load was carried out according to the Chinese national standard criteria. At each gauging station, successive samples and flow readings were always taken at the same section of river. Water samples were taken at different depths through the water column for measurement of sediment concentrations and the flow was recorded at the same time. Daily, monthly, and annual sediment loads were calculated by multiplying the sediment concentrations by the water discharge. Annual precipitation over the whole Huanghe drainage basin was determined from area-weighted average values from records at 342 rain gauges spread throughout the river basin.

4. Stepwise decreases of annual sediment load (Q_s) from 1950 to 2005

Over the past 56 yr (1950–2005) the annual sediment loads at gauging stations in the upper reaches (e.g., Lanzhou and Toudaoguai), the middle reaches (e.g., Huayuankou), and the lower reaches (Lijin) showed distinct stepwise decreases (Fig. 3). Sediment load was maintained at relatively consistent levels from 1950 to 1968 before completion of the Liujiaxia reservoir in the upper reaches. A marked step down in sediment load was observed in 1969, and the load

then remained relatively stable until 1985. The completion of the Longyangxia reservoir in 1985 marked another step down, followed by another period of little change from 1986 to 1999. A final step down was marked by the completion of the Xiaolangdi reservoir in 1999 in the middle reaches. If the average sediment loads during the period from 1950 to 1968 are taken as the reference levels for each station, the sediment load coming from the upper reaches at Toudaoguai decreased to 0.11 Gt/yr after the first step down, approximately 60% of the reference level, but the decrease in water discharge was small (2.5 km³/yr). The sediment load at Huayuankou after the first step down decreased to approximately 70% of the reference level, and that at Lijin to approximately 63% (Table 3). After the second step down, the sediment loads at the three gauging stations decreased to around 30–40% of the reference levels, together with significant decreases of water discharge (Fig. 3, Table 3). After the third step down the decreases in sediment load at Huayuankou and Lijin were accelerated; for example, at Huayuankou and Lijin they were only 0.13 Gt/yr and 0.16 Gt/yr, respectively, accounting for 8.4% and 12%, respectively, of the reference levels (Table 3). The statistical parameters of annual sediment loads at the three stations in the upper, middle, and lower reaches (Toudaoguai, Huayuankou, and Lijin, respectively) during the four periods between stepwise decreases are shown in a box-whisker plot (Fig. 4). The medians, 25th percentiles, 75th percentiles, and maximum values show distinct stepwise decreases corresponding

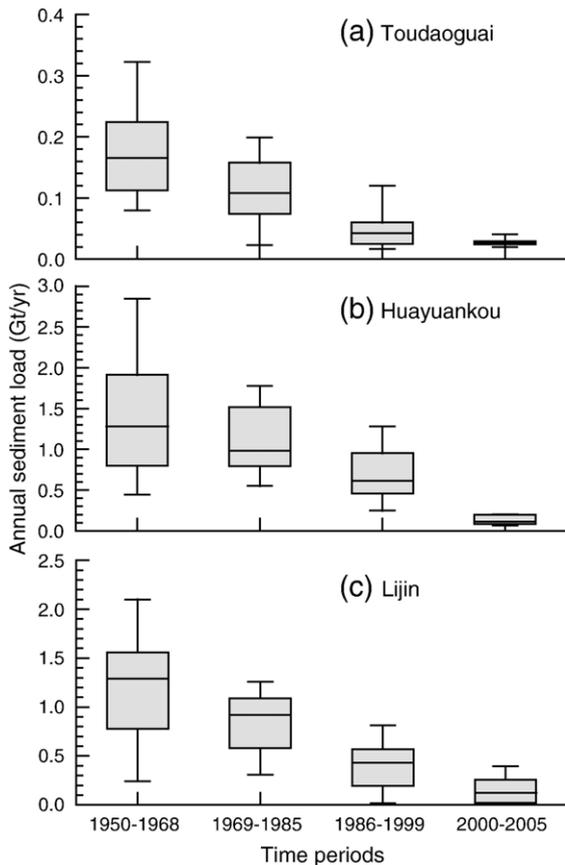


Fig. 4. Box-whisker plots of annual sediment load at gauging stations of (a) Toudaoguai, (b) Huayuankou, and (c) Lijin over 4 time periods: 1950–1968 ($n=19$), 1969–1985 ($n=17$), 1986–1999 ($n=14$), and 2000–2005 ($n=6$). The median, 25th percentile, 75th percentile, and maximum values show distinct stepwise decreases in sediment load at the major gauging stations in the upper, middle, and lower reaches.

to the times when the reservoirs were commissioned. In particular, the stepwise decrease in the annual sediment load at Lijin station (Fig. 4c) well illustrates the impact of natural and anthropogenic processes on the sediment load delivered to the sea. Although the variations of sediment load at the four stations between 1950 and 2005 show stepwise decreases, the patterns for the upper reaches, middle reaches, and lower reaches are quite different, as discussed below.

The upper reaches provide 60% of the water discharge and 10% of the sediment load that are sensitive to the operations of the two reservoirs constructed in the upper reaches (Liujiaxia and Longyangxia). As illustrated in Fig. 5, the annual mean SSC recorded at Toudaoguai shows distinct stepwise decreases in response to the commissioning of the Liujiaxia and Longyangxia reservoirs. For example, the annual mean SSC at Toudaoguai decreased from the

reference level of 6.8 kg/m^3 to 4.6 kg/m^3 after operations of the Liujiaxia reservoir started in 1968, and decreased further to 3.0 kg/m^3 after operations of Longyangxia reservoir started at 1985 (Fig. 5a, Table 3). Such stepwise decreases can also be identified in the monthly sediment load recorded at Toudaoguai from 1950 to 2000 (Fig. 5b). Prior to construction of the Liujiaxia reservoir in 1968, the sediment loads during the flood seasons (July–October) are clearly visible in the records; however, this seasonal pattern changed after 1968, especially after the commencement of joint operations of the Liujiaxia and Longyangxia reservoirs in 1985. After 1986 the peaks of sediment load during the flood season were sharply reduced due to the entrapment of sediment by the two reservoirs (Fig. 5b).

The variation of annual mean SSC at Huayuankou demonstrates a different and more complicated pattern than that at Toudaoguai, which can be attributed to both the commissioning of the Sanmenxia reservoir in 1960 and the soil conservation practices employed in the middle reaches (Fig. 6). The period of high SSC (average 32 kg/m^3) extends from 1950 to 1978, except for a decrease from 1960 to 1965 when a considerable amount of sediment was trapped within the Sanmenxia reservoir (Fig. 6a). There was an abrupt decrease in the late 1970s when the annual mean SSC decreased to 17.4 kg/m^3 . It recovered slightly to 25 kg/m^3 after 1987 (Fig. 6a). A more abrupt decrease occurred after the completion of Xiaolangdi reservoir in 1999, when the annual mean SSC decreased to 6 kg/m^3 , 19% of that from 1950 to 1978. The monthly distribution of sediment load also illustrates a complicated pattern, including the impact of the Sanmenxia reservoir (1960–1964), as well as abrupt decreases in the late 1970s and after the completion of Xiaolangdi reservoir in 1999 (Figs. 4b and 6b). The abrupt decreases in sediment load from the late 1970s to the late 1980s are attributed mainly to a decrease in precipitation and the implementation of effective soil conservation practices (Zhao, 1996; Walling and Fang, 2003) that together decreased the sediment yield from the tributaries in the middle reaches. It appears that the two reservoirs built in the upper reaches (Liujiaxia and Longyangxia) have had little impact on the sediment load at Huayuankou (Fig. 5). Therefore, the operations of the Sanmenxia and Xiaolangdi reservoirs, the soil conservation practices in the middle reaches, and climatic change combined to produce the complicated pattern of sediment load recorded at Huayuankou over the past 56 yr.

The data from Lijin represent water discharge (average $32 \text{ km}^3/\text{yr}$) and sediment load (average

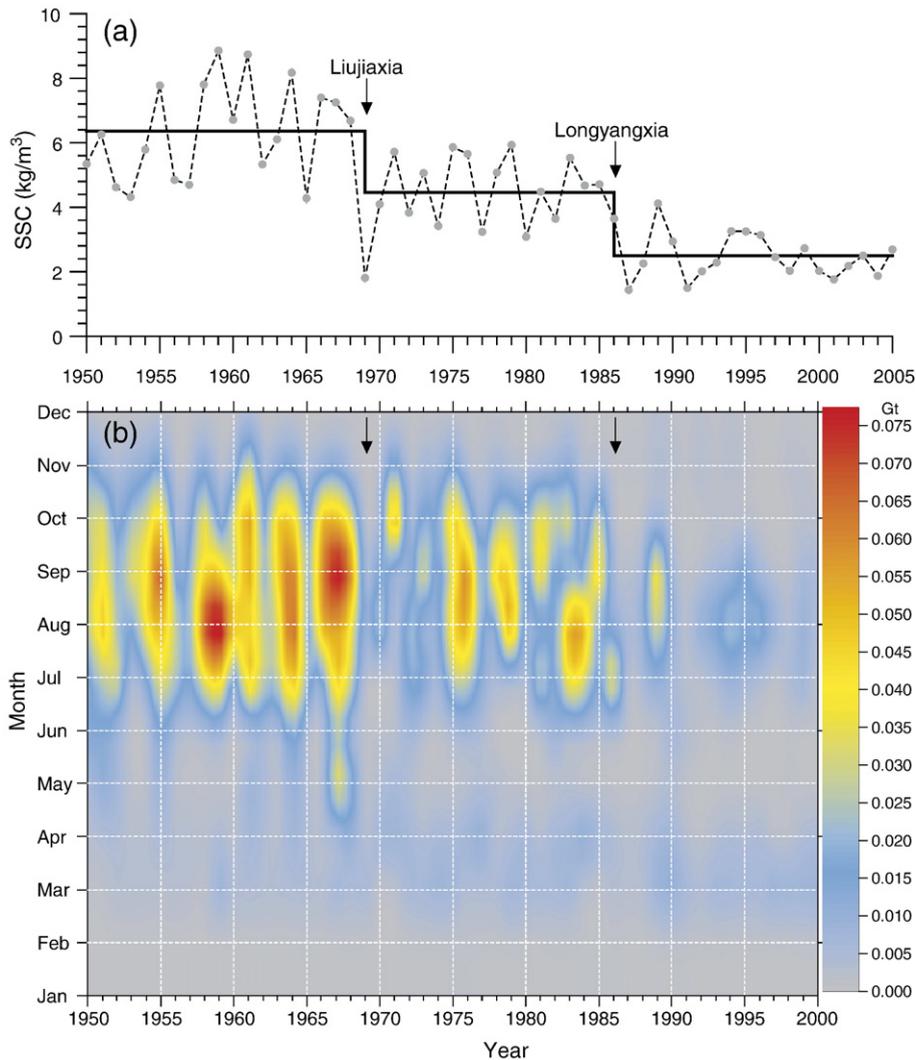


Fig. 5. (a) Annual suspended sediment concentration (SSC), 1950–2005; and (b) monthly distribution of sediment load (Gt), 1950–2000, at the Toudaoguai gauging station. Both SSC and monthly sediment load illustrate distinct stepwise decreases in response to the commencement of operations at the Liujiaxia and Longyangxia reservoirs in the upper reaches.

0.8 Gt/yr) delivered by the Huanghe to the sea over the last 56 yr. The stepwise decreasing pattern of sediment load at Lijin (Fig. 3d) reflects a combination of those at Toudaoguai and Huayuankou and more clearly illustrates the stepwise nature of the decreases than observations from the other two stations. For example, the average sediment load at Lijin prior to 1969 was 1.33 Gt/yr, but it decreased abruptly in 1969 to 0.58 Gt/yr (Fig. 3d and Table 3). In the following 17 yr the maximum sediment load was 1.26 Gt/yr (record in 1975), whereas the average was only 0.84 Gt/yr. After 1985 the sediment load decreased abruptly to a lower level (0.40 Gt/yr from 1986 to 1999), with a maximum value of 0.81 Gt/yr in 1988 (Table 3, Fig. 4c). After

completion of the Xiaolangdi reservoir in 1999, the average sediment load at Lijin decreased dramatically to 0.15 Gt/yr, a level slightly higher than at Huayuankou (Table 3, Figs. 3c and d, 4c and d), which implies that channel scouring has taken place in the lower reaches. From 2002 the sediment load at Lijin recovered markedly to 0.24 Gt/yr, owing mainly to the Water–sediment Regulation Scheme introduced by the YRCC. Therefore, fluctuations of water discharge or sediment load that occurred in the upper and middle reaches influenced the annual sediment load at Lijin and resulted in distinctive stepwise decreases in sediment load recorded there. Some examples of this influence are the transitory decreases around 1960 as a result of the

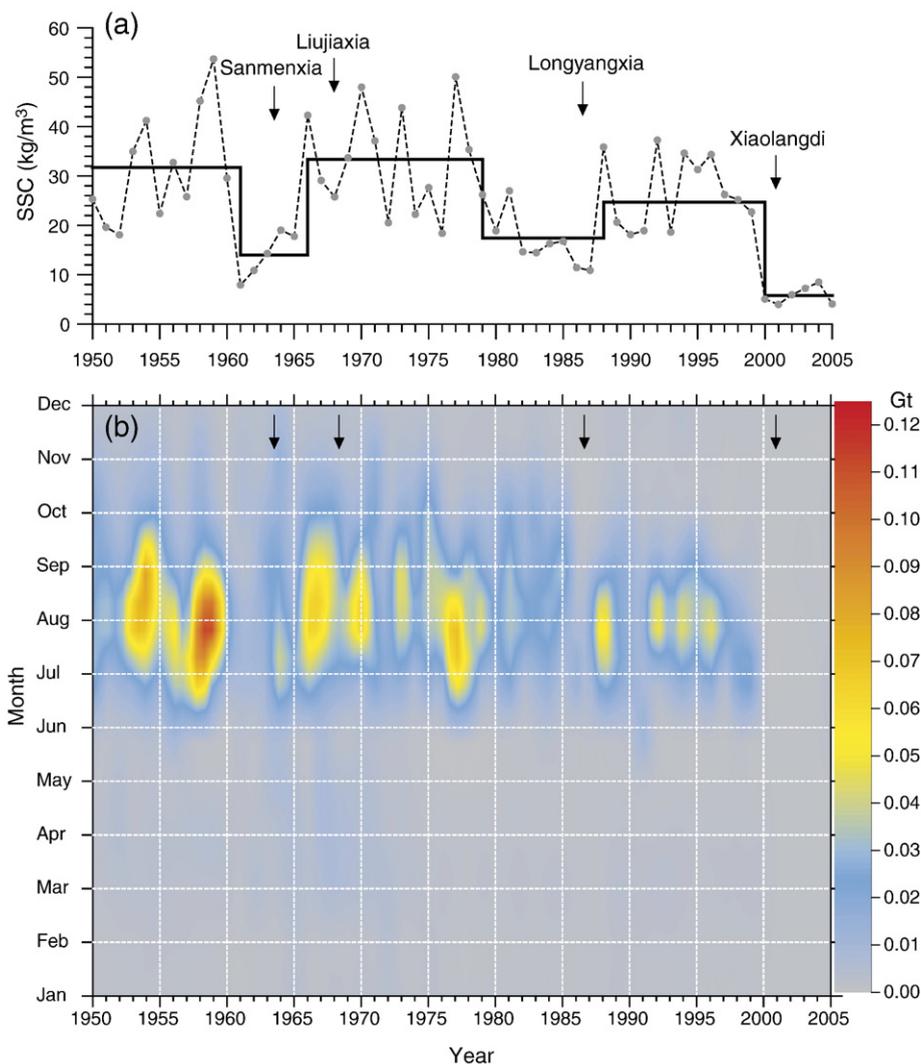


Fig. 6. (a) Annual suspended sediment concentration (SSC), 1950–2005; and (b) monthly distribution of sediment load (Gt), 1950–2000, at the Huayuankou gauging station. These illustrate a different mode of stepwise decreases from those at Toudaoguai (Fig. 5) as they show a response to both soil conservation practices and the commencement of operations at two reservoirs (Sanmenxia and Xiaolangdi).

commissioning of the Sanmenxia reservoir, the stepwise decreases in 1968, 1985, and 1999 after completions of the Liujiaxia, Longyangxia and Xiaolangdi reservoirs, and the slight recovery after the implementation of the Water–sediment Regulation Scheme in 2002 (Fig. 3d).

5. Causes of sediment load decreases at Huayuankou

5.1. Interannual variability of precipitation upstream from Huayuankou and sediment load at Huayuankou

Walling and Webb (1983) reviewed attempts to relate sediment yield to climatic factors on a global scale and concluded that there is no such relationship. However,

for river basins that include areas of highly erosive loess, such as the Huanghe river basin, sediment yield is controlled mostly by the magnitude and frequency of heavy rainfall events in the loess region, and is therefore likely to be sensitive to regional precipitation. At Huayuankou, when the effects of anthropogenic disturbances such as the reservoirs at Sanmenxia and Xiaolangdi and soil conservation practices are excluded, there is significant relationship between precipitation and sediment load (Fig. 7). Prior to 1978, when soil conservation practices in the middle reaches became effective, the cumulative sediment load at Huayuankou was well related to the cumulative precipitation upstream of Huayuankou, except for slight disturbances

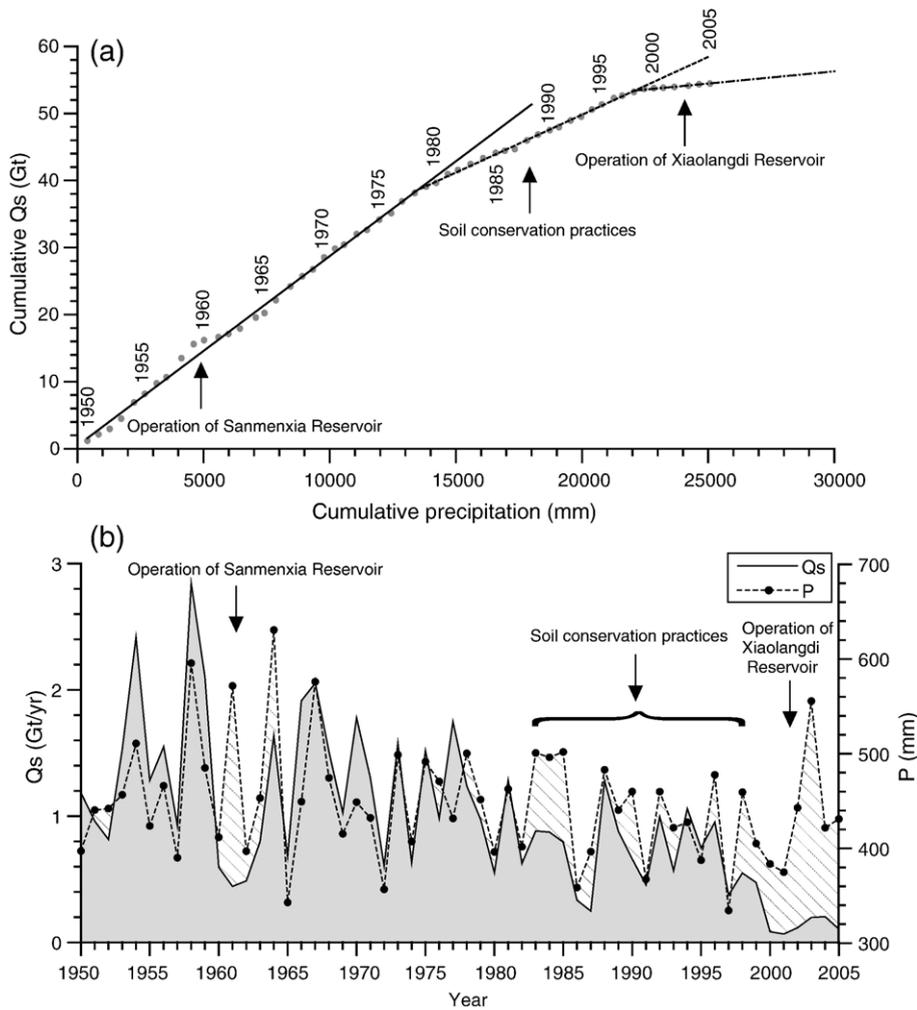


Fig. 7. Relationship between cumulative sediment load (Qs) at Huayuankou and cumulative precipitation above Huayuankou (a), and time series (1950–2005) of Qs at Huayuankou and precipitation above Huayuankou. These data show that the stepwise decreases of the Huanghe sediment load are mostly the result of soil conservation practices, operation of reservoirs (Sanmenxia and Xiaolangdi), and decreases of precipitation. The data also suggest that the Liujiaxia and Longyangxia reservoirs constructed in the upper reaches had little impact on the decreases of sediment load recorded at Huayuankou gauging station.

when the Sanmenxia reservoir started operating around 1960 (Fig. 7a). After 1978 there was a distinct decrease in the amount of sediment mobilized by a given amount of precipitation upstream from Huayuankou, owing to the soil conservation practices in the middle reaches. For instance, 432 mm of precipitation above Huayuankou in 1971 produced 1.3 Gt of sediment load at Huayuankou, whereas the same level of precipitation in 1989 produced only 0.9 Gt. After 1999, the operation of Xiaolangdi reservoir caused further decreases in both annual mean SSC and sediment load at Huayuankou (Figs. 6 and 7). The annual variability of sediment load at Huayuankou demonstrates similar responses to variations of precipitation upstream of Huayuankou

(Fig. 7b); however, a given amount of precipitation produced less sediment at Huayuankou after the 1980s, which implies that the stepwise decreases in sediment load at Huayuankou were caused by the combined effects of precipitation changes, soil conservation practices, and the operation of Sanmenxia and Xiaolangdi reservoirs. Especially since 2000, the decrease in sediment load at Huayuankou has accelerated in response to the combined effects of natural and anthropogenic phenomena (Fig. 7).

When the interannual variability of precipitation above Huayuankou (ΔP) and the sediment load (ΔQ_s) at Huayuankou are examined, a linear relationship is revealed that allows evaluation of the impacts of

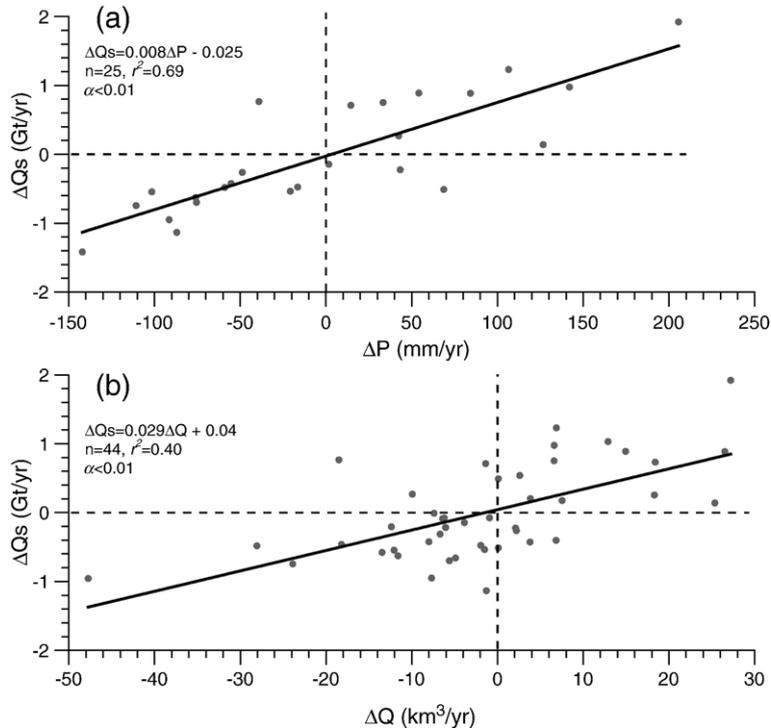


Fig. 8. The relationships between interannual variability of (a) precipitation above Huayuankou (ΔP) and sediment load (ΔQ_s) at Huayuankou (1950–1980), and (b) water discharge (ΔQ) and ΔQ_s (1950–1999). Data from 1960 to 1964 were excluded to eliminate the impact of the Sanmenxia reservoir. Linear relationships between ΔP and ΔQ_s , and ΔQ and ΔQ_s are evident, which indicate that annual sediment loads originating from the middle reaches were sensitive to the interannual variations of water discharge that resulted from variations of annual precipitation above Huayuankou.

precipitation changes on sediment load. This relationship can be expressed as follows:

$$\Delta Q_s = 0.008\Delta P - 0.025 \quad (1)$$

where ΔP and ΔQ_s are the increases or decreases in consecutive years of annual precipitation and annual sediment load, respectively. The data used to determine this relationship extend from 1950 to 1978, but data from 1960 to 1964 were excluded to eliminate the effects of anthropogenic disturbances from the Sanmenxia reservoir and soil conservation practices in the middle reaches (Figs. 7 and 8a). The data can be considered in two categories: decreasing sediment load associated with decreasing precipitation, and increasing sediment load associated with increasing precipitation (Fig. 8a), which suggests that the interannual change of sediment load is quite sensitive to precipitation. However, there are 3 anomalous data points in 1951, 1977, and 1978, and we suppose that these anomalies might be the result of spatial variation of precipitation within the river basin such that it was not coincident with regions of high sediment yield. For example, heavy rainfall outside the loess area may have

resulted in high annual precipitation but low sediment yield.

5.2. Interannual variability of water discharge and sediment load at Huayuankou

Prior to the completion of Xiaolangdi reservoir in 1999, the annual sediment load and water discharge at Huayuankou fluctuated in distinct steps, apart from the impact of the Sanmenxia reservoir at around 1960 (Fig. 3c). The annual SSC at Huayuankou fluctuated slightly, but maintained a relatively stable level of $\sim 30 \text{ kg/m}^3$ from 1950 to 1999 (Fig. 6a), which means that the annual sediment load at Huayuankou was also affected to a considerable extent by the annual water discharge. To examine the relationship between the interannual variability of sediment load and water discharge at Huayuankou we used the data from 1950 to 1999, but excluding 1960 to 1964 so that the impacts of the Sanmenxia and Xiaolangdi reservoirs were eliminated. The trends of decreasing water discharge with decreasing sediment load, and increasing water discharge with increasing sediment load are

Table 4
Stepwise decreases in annual sediment load, and their causes, at Huayuankou gauging station for different time periods

	After 1st step (1969–1985)	After 2nd step (1986–1999)	After 3rd step (2000–2005)	Reference
Decrease of annual precipitation above Huayuankou from the reference level: ΔP (mm/yr)	469–451	469–420	469–435	Wang et al. (2006), IRTCES (2001, 2002, 2003, 2004, 2005), E. J. (2006)
	18	49	34	
Decrease of annual water discharge from the reference level: ΔQ (km ³ /yr)	49.88–40.79	49.88–27.65	49.88–21.61	See Table 3
	9.09	22.23	28.27	
Decrease of annual sediment load from the reference level: ΔQ_s (Gt/yr)	1.55–1.08	1.55–0.68	1.55–0.13	See Table 3
	0.47	0.87	1.42	

Causes of sediment decrease	(Gt/yr)	% of ΔQ_s	(Gt/yr)	% of ΔQ_s	(Gt/yr)	% of ΔQ_s	Reference
1) Decrease from upper reaches	0.07	15	0.13	15	0.15	11	See Table 3
2) Contribution from water decrease	0.30	65	0.68	79	0.86	60	From Eq. (2): $\Delta Q_s = 0.029\Delta Q + 0.04$
Due to decrease of precipitation	0.12	25	0.37	42	0.25	17	From Eq. (1): $\Delta Q_s = 0.008\Delta P - 0.025$
Due to soil conservation practices	0.18	40	0.31	37	0.61	43	Derived from: $(0.029\Delta Q + 0.04) - (0.008\Delta P - 0.025)$
3) Sediment retention within Sanmenxia	0.12	25	0.13	15	-0.04	-3	Zhao (1996), IRTCES (2005)
4) Sediment retention within Xiaolangdi	-	-	-	-	0.40	28	IRTCES (2005), E. J. (2006)
Total decrease	0.49	105	0.94	109	1.37	96	

pronounced (Fig. 8b). Although there are several anomalous data points, the following linear relationship between the interannual variability of water discharge (ΔQ) and sediment load (ΔQ_s) at Huayuankou is evident.

$$\Delta Q_s = 0.029\Delta Q + 0.04 \quad (2)$$

with a coefficient of determination $r^2=0.4$. It is important to note that the interannual variability of water discharge is caused by both precipitation change (ΔP) and human activities (e.g., soil conservation practices, water abstraction from the tributaries). Therefore, the decreases of sediment load induced by the decreases of water discharge can be considered in 2 components: (1) decreases caused by decreases in precipitation, which can be estimated from Eq. (1); and (2) decreases caused by human activities, mostly soil conservation practices in the middle reaches. We assume that the second category approximates the effect of soil conservation practices, although it may be partly ascribed to other factors such as channel scour, deposition, or other anthropogenic disturbances (e.g., Walling and Fang, 2003). Eqs. (1) and (2) make it possible to assess the contributions of precipitation changes and soil conservation practices to the decreases of sediment load at Huayuankou over different periods.

5.3. Natural and anthropogenic impacts on the decreases of sediment load

We used the data on siltation at Sanmenxia and Xiaolangdi reservoirs published by Zhao (1996), IRTCES (2001, 2002, 2003, 2004, 2005) and E.J. (2006) and Eqs. (1) and (2) to estimate the natural and anthropogenic influences on the decreases of sediment load in the Huanghe over the past 56 yr. The average sediment loads from 1950 to 1968 were used as reference levels for comparison with those of the following years (Table 4).

During 1969–1985 the average annual precipitation above Huayuankou was 451 mm/yr, 18 mm/yr lower than the reference level and annual water discharge at Huayuankou was 9.09 km³/yr lower than the reference level. Eq. (2) gives a decrease in sediment load of 0.30 Gt/yr due to lower discharge, including 0.12 Gt/yr caused by lower precipitation, as estimated from Eq. (1). During this period, the sediment load from the upper reaches (records at Toudaoguai) was 0.07 Gt/yr lower than reference level (Table 3), and 0.12 Gt/yr of sediment was trapped by the Sanmenxia reservoir. Collectively, the total decrease in sediment load was estimated as 0.49 Gt/yr, and was quite close to the measured decrease at Huayuankou (0.47 Gt/yr) (Table 4). The sediment load reduction due to soil conservation

practices (effective since the late 1970s) was estimated as ~ 0.18 Gt/yr, accounting for 40% of the total decrease at Huayuankou. Changes in precipitation contributed only 25% of the total decrease and appear to be of secondary importance.

During the period from 1986 to 1999, the average annual precipitation decreased sharply to 49 mm/yr below reference level, and water discharge was $22.23 \text{ km}^3/\text{yr}$ lower, mainly caused by lower precipitation and greater water consumption in the middle reaches (Walling and Fang, 2003). Therefore, the estimated decrease in sediment load as a result of less precipitation was 0.37 Gt/yr, accounting for 42% of the total decrease at Huayuankou (Table 4). The contribution of the soil conservation practices was 0.31 Gt/yr, close to that from lower precipitation. This estimate is in reasonable agreement with the suggestion by Zhao (1996) and Walling and Fang (2003) that soil conservation practices reduced sediment yield by 0.25–0.30 Gt/yr in the 1980s. From 1986 to 1999, the contributions from the upper reaches and the Sanmenxia reservoir to the lower sediment load were 0.26 Gt/yr in total, and each accounted for 15% of the total decrease at Huayuankou (Table 4). Collectively, we estimated the average decrease of sediment yield due to soil conservation practices from 1969 to 1999 to be 0.24 Gt/yr, which is close to estimates by Walling and Fang (2003) and Ran (2006).

From 2000 to 2005 the Xiaolangdi reservoir trapped 0.4 Gt/yr of sediment (Table 2; IRTCES, 2001, 2002, 2003, 2004, 2005; E.J., 2006), accounting for 28% of the total decrease below reference level at Huayuankou. The estimated decrease resulting from lower precipitation was 0.25 Gt/yr, while the contribution from soil conservation practices amounted to 0.61 Gt/yr, and accounted for 43% of the total decrease at Huayuankou (Table 4). The collective total of the decreases in sediment load attributed to decreases in the upper reaches, precipitation changes, soil conservation practices, entrapment by the Xiaolangdi reservoir, and some slight scouring at the Sanmenxia reservoir was 1.37 Gt/yr, which agrees well with the measured decrease at Huayuankou during this period (Table 4). A notable observation is the surprising enhancement of sediment reduction in 2003 when soil conservation practices significantly reduced the sediment yield from heavy rainfalls in October. The annual mean precipitation above Huayuankou in 2003 was 556 mm, the highest since 1968, whereas the total amount of sediment supplied from the major tributaries in the middle reaches was only 0.61 Gt (IRTCES, 2004). Before soil conservation practices were effective, precipitation of the same level yielded much more sediment from the

tributaries than was the case in 2003. For example, in 1967 annual mean precipitation was 575 mm, and 2.05 Gt of sediment passed Huayuankou (Figs. 3c and 7b). If we assume that 90% of the sediment came from the loess region, this suggests that at least 1.85 Gt of sediment was yielded from the tributaries of the middle reaches in 1967. Therefore, it can be inferred that 1.24 Gt of sediment reduction in 2003 should be ascribed to soil conservation practices, which increased the contributions of soil conservation practices to the decrease in sediment load at Huayuankou during the period from 2000 to 2005 (Table 4).

Over the past 56 yr, soil conservation practices and lower precipitation are the main factors that caused the decreases in sediment load recorded at Huayuankou, rather than sediment retention in reservoirs, although considerable quantities of sediment were trapped in the Xiaolangdi reservoir between 2000 and 2005 (Table 4). We expect that sediment load of the Huanghe will decrease further in the future, and the anthropogenic impacts (soil conservation practices and sediment retention in reservoirs) will be greater than natural impacts such as reduced precipitation.

6. Sediment budget in the lower reaches

The river segment between Huayuankou and Lijin has been subjected to frequent flooding in historical time (Hu et al., 1998). Downstream from Huayuankou the suspended river phenomenon has developed with the riverbed raised considerably above the surrounding area. Most of the coarser sediment ($D > 0.05 \text{ mm}$) provided by the tributaries in the middle reaches has been deposited in this segment of the river (Xu, 2003). Over the past 56 yr the sediment load at Lijin has shown stepwise decreases due mainly to decreases at Huayuankou, which are mostly ascribed to soil conservation practices and lower precipitation in the middle reaches (Fig. 3, Table 4). The

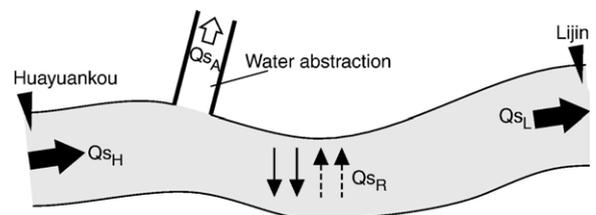


Fig. 9. Schematic plan view illustrating the sediment budget in the lower reaches between Huayuankou and Lijin gauging stations. Q_{sH} , sediment load at Huayuankou; Q_{sA} , sediment loss due to water abstraction; Q_{sR} , sediment loss due to channel erosion (–) or deposition (+); Q_{sL} , sediment load at Lijin. The sediment budget in the lower reaches is expressed by Eq. (3).

Table 5
Sediment budget in the lower reaches of the Huanghe

Period		1950–1964	1964–1973	1973–1980	1980–1993	2000–2005
Huayuankou	Q_H (km ³ /yr)	49.90	46.70	38.64	37.82	21.61
	Q_{S_H} (Gt/yr)	1.30	1.41	1.15	0.75	0.13
	SSC_H (kg/m ³)	26.13	30.16	29.83	19.70	5.79
Lijin	Q_L (km ³ /yr)	49.97	44.71	30.08	25.47	12.24
	Q_{S_L} (Gt/yr)	1.21	1.16	0.86	0.57	0.15
	SSC_L (kg/m ³)	24.15	26.02	28.56	22.44	10.53
Channel scour (–) or deposition(+) ^a	Q_{S_R} (Gt/yr)	0.10	0.34	0.20	0.07	–0.15
Water consumption in the lower reaches	Q_c (km ³ /yr)	2.46	4.22	8.32	11.12	9.00
SSC for water abstraction ^b	SSC_A (kg/m ³)	23.0	17.7	19.6	11.6	13.0 ^c
Sediment loss ^d	Q_{S_A} (Gt/yr)	0.06	0.07	0.16	0.12	0.12
$Q_{S_L} = Q_{S_H} - Q_{S_R} - Q_{S_A}$ ^e		1.14	1.00	0.79	0.56	0.16

^a Data are from Zhao (1996), IRTCES (2001, 2002, 2003, 2004, 2005) and E.J. (2006).
^b Data are from Cheng et al. (2000).
^c The average SSC_A during 2000–2005 was approximately estimated from $(Q_{S_H} - Q_{S_R})/Q_H * 1000$.
^d The sediment loss due to water abstraction is calculated from Eq. (4).
^e The derived sediment load at Lijin is calculated from Eq. (3).

processes of sediment delivery in the lower reaches, including both deposition and channel scour, appear to have an important influence on the sediment load that enters into the sea. However, it seems that there are some processes other than the channel scour or deposition that play an important role in the sediment budget in the lower reaches. For example, from 1980 to 1993 the total sediment loads at Huayuankou and Lijin were 10.4 and 8.0 Gt, respectively, indicating that 2.4 Gt of sediment was lost in the lower reaches, whereas channel deposition in the lower reaches amounted to only 1.3 Gt during the same period (Zhao, 1996). There was a similar situation from 2000 to 2005, when average channel scour in the lower reaches was 0.15 Gt/yr (IRTCES, 2001, 2002,

2003, 2004, 2005; E.J., 2006). However, the average sediment load at Lijin increased only slightly to 0.15 Gt/yr as a result of the input of 0.13 Gt/yr at Huayuankou. This was far less than would be expected if the sediment load supplied additionally from channel scour was also accounted for, which would be a total sediment load of 0.28 Gt/yr at Lijin.

Since the 1970s, water consumption in the lower reaches has increased at a surprising rate, facilitated mostly by the operations of reservoirs in the river basin (Wang et al., 2006). Many hydraulic works have also been constructed in the lower reaches to abstract water from the river channel to meet the increasing demands for agricultural irrigation and domestic use. Therefore, a

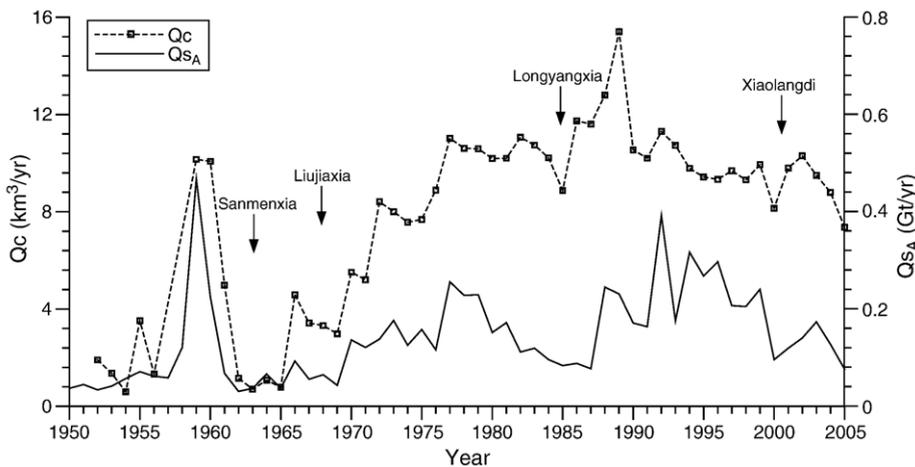


Fig. 10. Time series (1950–2005) of water consumption (Q_c) in the lower reaches and sediment loss from water abstraction (Q_{S_A}) between Huayuankou and Lijin gauging stations.

considerable amount of sediment would have been lost during water abstraction; however, the effect of abstraction on the sediment budget in the lower reaches has not been acknowledged in early studies (e.g., Zhao, 1996; Chen, 1997; Xu, 2003).

Since there are no tributary in the lower reaches (Fig. 1), the sediment load at Lijin (Q_{S_L}) can be considered to be made up of 3 basic components (Fig. 9): the sediment input at Huayuankou (Q_{S_H}), channel scour or deposition (Q_{S_R}), and sediment loss due to water abstraction (Q_{S_A}). The sediment budget in the lower reaches can then be described by the following equation.

$$Q_{S_L} = Q_{S_H} - Q_{S_R} - Q_{S_A} \quad (3)$$

The data for channel scour ($Q_{S_R} < 0$) or deposition ($Q_{S_R} > 0$) in the lower reaches were taken from Zhao (1996), IRTCES (2001, 2002, 2003, 2004, 2005) and E.J. (2006). The lower reaches are characterized by the suspended river phenomenon, which means that water abstracted from the river is totally consumed, because it is difficult to return surplus abstracted water to the river. Therefore, the sediment loss due to water abstraction (Q_{S_A}) can be approximated by multiplying water consumption by the average SSC of the water abstracted:

$$Q_{S_A} = Q_c \times SSC_A / 1000 \quad (4)$$

where Q_c is the average water consumption between Huayuankou and Lijin, and SSC_A (kg/m^3) is the average SSC of water abstracted.

The sediment loads at Lijin derived from Eq. (3) for several different time periods are similar to the sediment loads recorded at Lijin (Table 5), with differences of less than 15%. These results also imply that sediment losses due to water abstraction in the lower reaches (Q_{S_A}) have increased rapidly since the 1970s, and reached a level of around 20% of the total sediment load delivered by the Huanghe to the sea (Q_{S_L}). In particular, during the period from 2000 to 2005, sediment lost due to abstraction was almost equivalent to the total sediment load observed at Lijin (Table 5). This was due in part to severe channel scour below Huayuankou, which increased the average SSC in abstracted water. Over the past 56 yr the demand for agricultural irrigation in the lower reaches has increased rapidly in parallel with the constructions and regulations of reservoirs, dams, and other hydraulic facilities in the river basin (Wang et al., 2006). Water demand in the lower reaches has increased rapidly since the 1970s and become stable (approximately $10 \text{ km}^3/\text{yr}$ in average) during the last 30 yr (Fig. 10), and Q_{S_A} remained relatively stable at around $0.1\text{--}0.2 \text{ Gt}/\text{yr}$ (Table 3, Fig. 10). Clearly, the effect

Table 6

Composition of sediment load at Huayuankou gauging station (Q_{S_H}) and channel deposition in the lower reaches at different time periods (data from Zhao, 1996)

1950–1960				
Sediment class (mm)	Huayuankou		Channel deposition in the lower reaches	
	Q_{S_H} (Gt/yr)	%	Deposition (Gt/yr)	%
$d > 0.10$	0.07	4	0.05	13
0.05–0.10	0.30	16	0.14	36
0.025–0.05	0.46	26	0.13	33
$d < 0.025$	0.97	54	0.07	18
Total	1.8	100	0.39	100
1964–1973				
Sediment class (mm)	Huayuankou		Channel deposition in the lower reaches	
	Q_{S_H} (Gt/yr)	%	Deposition (Gt/yr)	%
$d > 0.10$	0.07	4	0.06	15
0.05–0.10	0.37	22	0.22	53
0.025–0.05	0.41	25	0.10	23
$d < 0.025$	0.80	48	0.04	9
Total	1.65	100	0.42	100
1973–1990				
Sediment class (mm)	Huayuankou		Channel deposition in the lower reaches	
	Q_{S_H} (Gt/yr)	%	Deposition (Gt/yr)	%
$d > 0.10$	0.04	3	0.03	26
0.05–0.10	0.18	17	0.03	23
0.025–0.05	0.27	27	0.03	25
$d < 0.025$	0.53	52	0.03	25
Total	1.02	100	0.12	100

of sediment loss due to water abstraction on the sediment budget cannot, therefore, be negligible.

In contrast with the increase of Q_{S_A} , channel deposition has been significantly reduced since the 1970s. Lower channel deposition in the lower reaches from 1950 to 1964 was mainly the result of severe channel scouring in the middle reaches due to the operation of the Sanmenxia reservoir around 1960 (Table 5). Of the total sediment passing Huayuankou from 1950 to 1960, 80% was fine sediment ($D < 0.05 \text{ mm}$). The coarser fraction ($D > 0.05 \text{ mm}$), or 20% of the total sediment load passing Huayuankou, however, accounted for 49% of deposition in the lower reaches (Table 6). Therefore, the fine sediment at Lijin probably accounts for more than 80% of the total sediment load at Huayuankou since only 14% (fine fraction) is lost in the lower

reaches. And during 1960–1973 the coarser fraction ($D > 0.05$ mm), or 26% of the total sediment load passing Huayuankou, accounted for 68% of deposition in the lower reaches. During period from 1973 to 1990 the contribution of the coarser sediment passing Huayuankou to the total deposition in the lower reaches was similar to that between 1960 and 1973 (Table 6). This implies that channel deposition in the lower reaches is dominated by the coarser fraction of sediment passing Huayuankou.

Since the late 1970s, soil conservation practices in the middle reaches have significantly reduced the yield of both the coarser and fine sediments from the loess region. As a result, the calculated channel deposition in the lower reaches is lower than that of the historical records (Tables 5 and 6). The Xiaolangdi reservoir, completed in 1999, has trapped a considerable amount of the coarser sediment. For example, the average median grain sizes (D_{50}) of the sediment load at the Tongguan and Huayuankou gauging stations during the period from 1961 to 2000 (IRTCES, 2001, 2002, 2003, 2004, 2005) were very similar, at 0.023

and 0.019 mm, respectively. After the operations of the Xiaolangdi reservoir, the median grain size at Huayuankou (2002–2005) decreased significantly to 0.01 mm, whereas that at Tongguan was almost unchanged (IRTCES, 2001, 2002, 2003, 2004, 2005; E.J., 2006). We expect channel deposition in the lower reaches to decrease further in the future. In addition, the Water–sediment Regulation Scheme implemented by YRCC from 2002 has resulted in marked channel scour in the lower reaches that offsets sediment losses due to water abstraction, causing the sediment load at Lijin to be slightly higher than that at Huayuankou (Table 5).

7. Discussion

7.1. Comparison of pristine and present sediment loads to the sea

The pristine sediment load delivered by the Huanghe to the sea during the middle Holocene, when there was negligible human intervention, has been estimated as ca.

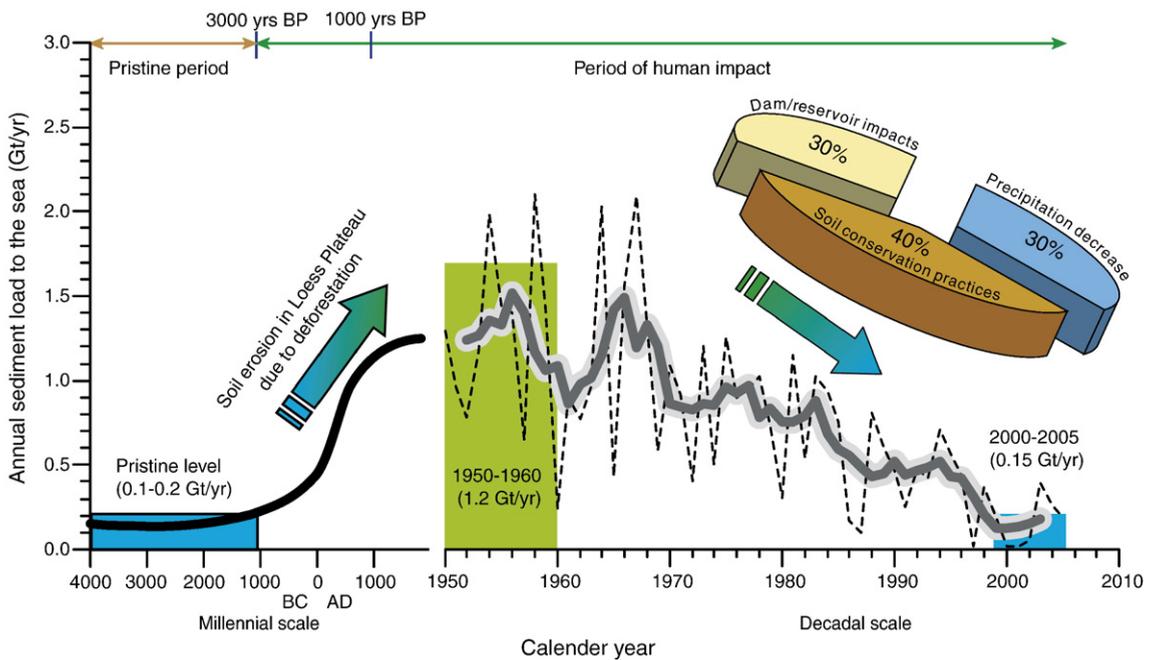


Fig. 11. Past and present sediment load discharged from the Huanghe to the sea. The pristine sediment load discharging to the sea during the middle Holocene was estimated from the volume of deltaic and marine deposition to be 0.1–0.2 Gt/yr (Milliman et al., 1987; Ren and Zhu, 1994; Saito et al., 2001; Liu et al., 2002, 2004). However, the sediment discharge to the sea increased gradually from the levels of 2000 to 3000 yr ago and then abruptly increased to ten times the pristine level around 1000 yr ago owing to soil erosion on the Loess Plateau as a result of deforestation (Milliman et al., 1987; Xue, 1993; Ren and Zhu, 1994; Saito et al., 2001). Since the 1950s the sediment discharging from the Huanghe to the sea (as observed at Lijin gauging station) has decreased drastically owing to the combined impacts of climate change (precipitation decrease, which represents 30% of the decrease) and extensive human activities (soil conservation practices and dam operations in the drainage basin, which represent 70% of the decrease). The present annual sediment load discharged to the sea (2000–2005) seems to be reverting to the pristine level (0.1–0.2 Gt/yr) of the middle Holocene. The past and present changes of sediment discharge to the sea indicate that human activities play a strikingly important role in changes to this large river system.

0.1 Gt/yr from the volume of deltaic sediments (Saito et al., 2001), and 0.1–0.2 Gt/yr and 0.17 Gt/yr from the volume of marine sediments during the Holocene (Milliman et al., 1987; Ren and Zhu, 1994, respectively). These values are an order of magnitude lower than the sediment load discharged to the sea during the last 1000 yr (Milliman et al., 1987; Xue, 1993; Ren and Zhu, 1994; Saito et al., 2001; Liu et al., 2002; Liu et al., 2004). However, these values are close to the present sediment discharge to the sea as presented in this study (ca. 0.15 Gt/yr from 2000 to 2005) (Fig. 11).

The sediment load discharged to the sea by the Huanghe increased gradually to ca. 0.5 Gt/yr in the early anthropogenic phase (3000–2000 yr BP) from the pristine level of the middle Holocene. During the period from 2000 to 1000 yr BP, the sediment load increased abruptly to 1.0–1.2 Gt/yr, owing particularly to enhanced cultivation and deforestation on the Loess Plateau (Milliman et al., 1987; Ren and Zhu, 1994; Liu et al., 2002). Over most of the past 1000 yr the Huanghe sediment discharge remained at a level of 1.2–1.3 Gt/yr as the delta prograded rapidly with a land growth rate of 20–25 km²/yr (Cheng and Xue, 1997) (Fig. 11). But the annual sediment load discharge as recorded at Lijin station has decreased rapidly during the past 56 yr (1950–2005). We estimate that 30% of the decrease in sediment load has resulted from climate change (decrease of precipitation) and 70% from human activities. Consequently, the present annual sediment discharge (2000–2005) appears to be reverting to the pristine

levels of the middle Holocene, when human intervention was negligible, but as a response to both climate change and human activities in the river basin (Fig. 11).

Sediment load at Huayuankou (which lies at the entry point of the Huanghe to the North China Plain) during the pristine period of the middle Holocene (6000–3000 yr BP) has been estimated at approximately 0.3–0.36 Gt/yr, varying with the dry bulk density used (Saito et al., 2001), 0.5 Gt/yr (Ren and Zhu, 1994), and 0.7 Gt/yr (Shi et al., 2002). However, estimates based on the volume of marine deposition suggest that only 0.1–0.2 Gt/yr of the total sediment load was delivered to the sea (Liu et al., 2002; Fig. 12), which implies that during the pristine period most of the Huanghe sediment was deposited by floods across the breadth of the North China Plain as the river meandered over the broad flood plain without confining systems such as dikes and levees (Milliman et al., 1987). At approximately 1000 yr BP (during the Song Dynasty) the sediment yield of the Huanghe increased abruptly to 1.5–1.6 Gt/yr, of which 1.2–1.3 Gt/yr discharged to the sea. This was one order of magnitude higher than the pristine level (Fig. 11). Sediment deposition on the North China Plain in the early part of the last 1000 yr was much heavier than the average of 1000 yr BP to the 1960s (0.3–0.4 Gt/yr) because of a lack of human intervention on the natural flood plain. In the 1950s and 1960s, most of the sediments were delivered to the coastal zone and into the ocean because man-made levee systems confined the river. At present (2000–2005), the sediment load

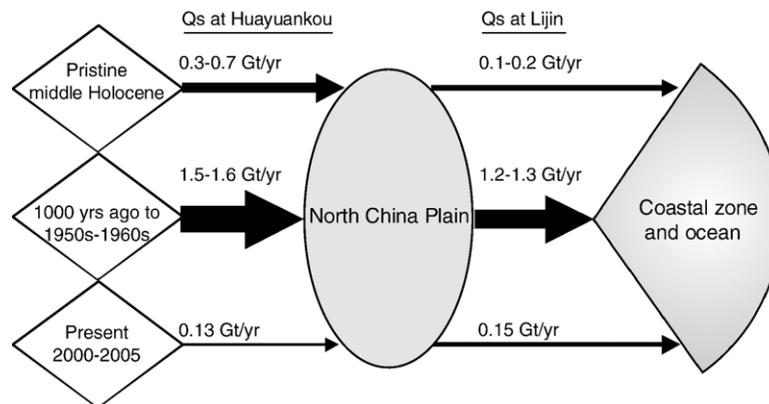


Fig. 12. Alluvial and marine deposition of the Huanghe sediment over different time periods since the middle Holocene. Estimates of the sediment yield from 6000 to 3000 yr BP vary considerably: 0.3–0.7 Gt/yr (Milliman et al., 1987; Ren and Zhu, 1994; Saito et al., 2001; Shi et al., 2002), 0.1–0.2 Gt/yr of which was assumed to be the pristine level of discharge to the sea before human intervention (see Milliman et al., 1987; Ren and Zhu, 1994; Saito et al., 2001; Liu et al., 2002), suggesting that most of the sediment load was then deposited on the North China Plain. Around 1000 yr BP, the sediment yield increased abruptly to 1.5–1.6 Gt/yr, with 1.2–1.3 Gt/yr discharging into the sea at that time, one order of magnitude higher than the pristine level. There are differences in the volumes of sediments deposited on the North China Plain during the early phase of the last 1000 yr and those of the 1950s to the 1960s because the man-made levee systems constructed in the 1950s and 1960s restricted flooding and thus limited the spread of flood deposits. At present (2000–2005) the sediment load discharging to the sea is reverting to its pristine level, and has become markedly higher than that passing Huayuankou since implementation of the Water–sediment Regulation Scheme in 2002.

discharging to the sea is reverting to the pristine levels of the middle Holocene (Fig. 11), and because of anthropogenic enhancement (e.g., the Water–sediment Regulation Scheme) it has become markedly higher than the sediment load passing Huayuankou (e.g., Wang et al., 2005). This suggests that channel scouring in the lower reaches in recent years has occurred instead of the severe flooding deposition that has been characteristic of the period before implementation of the Water–sediment Regulation Scheme (Fig. 12). Both human activities and climatic change are essential driving forces for the changes to river sediment loads during the period of human impact. The abrupt increase of 1000 yr ago, the drastic decreases from 1950 to 2005, and the changes to deposition in the lower reaches during the period from 2000 to 2005 are all examples of the effects of these driving forces (Fig. 11).

7.2. Anthropogenic impact and future sediment load

The combined impact from lower precipitation, soil conservation practices, and sediment retention within reservoirs has resulted in distinct stepwise decreases in the sediment load discharged to the sea by the Huanghe over the past 56 yr (Fig. 11). There has been much interest in these rapid changes of sediment load and they have been widely reported (Yang et al., 1998; Walling and Fang, 2003; Xu, 2003; Syvitski et al., 2005). However, the detailed assessment of the decreases in sediment load of the Huanghe presented in this study will help to clarify the relative contributions of natural and anthropogenic impacts to these dramatic changes.

Xu (2003) presented estimates of natural and anthropogenic impacts on the decrease in sediment load discharged to the sea by assuming a simple relationship between basin-wide precipitation and the sediment discharge to the sea recorded at Lijin. This approach is unlikely to produce meaningful results because the considerable sediment losses (Q_{SA} and Q_{SR} as illustrated in the present study) in the lower reaches were not taken into account.

Although sediment retention within reservoirs contributes only about 20% to the total decrease of sediment load, regulation of water flow by the reservoirs may also play an important role in the sediment decrease. The operation of reservoirs has changed the seasonal and interannual allocations of water discharge, and facilitated a rapid increase in water consumption, particularly in the lower reaches (Wang et al., 2006). Additionally, the reservoirs (e.g., Sanmenxia) can dampen water flow and thus retard sediment input from the tributaries (e.g., the Weihe and Jinghe tributaries), leading to the deposition

of considerable quantities of sediment in the tributaries (Li et al., 2004).

Yang et al. (2006) reported on the decrease of sediment load during the past 55 yr in the Changjiang, the largest river in China, and attributed the decrease to the operation of dams and reservoirs in the major tributaries and main stream; they also discussed the future impact of the Three Gorges Dam. Compared with the changes in the Changjiang, the decreases in both sediment load and water discharge to the sea from the Huanghe are more complicated (Wang et al., 2006), and reflect the combined impacts of climate change and human activities. In a scenario of global climate change and extensive human activities, the changes in these two major Chinese rivers provide good illustrations of the transformation of global river systems in the Anthropocene.

The sediment load discharged to the sea by the Huanghe is expected to decrease continuously in the future for the following reasons: (1) regional precipitation is strongly affected by frequent and strengthening ENSO events (Wang and Li, 1990; Wang et al., 2006) and will continue to decrease in the arid and semi-arid Huanghe River basin; (2) soil conservation practices will continue to be effective in reducing sediment yield in the middle reaches; and (3) the recently completed Xiaolangdi reservoir will trap a considerable amount of sediment supplied from the upper and middle reaches.

Increasing sediment loss due to water abstraction in the lower reaches will be only partly offset by a decrease in channel deposition. Therefore, the mega-delta of the Huanghe, which has prograded into the epicontinental Bohai Sea over the past 150 yr, will be starved and will decline, because the river will be incapable of supplying more sediment and water than the present level. With the dramatic decrease in discharge of water and sediment to the sea, as well as a decrease of riverine nutrients and total dissolved solids (Chen et al., 2005), many aquatic ecosystems in the lower reaches and in the coastal Bohai Sea are expected to experience significant changes. The decrease of sediment discharge will change the Si:N ratio in the coastal ocean and thus affect the composition of ecological communities in the Bohai Sea, as has happened in the East China Sea since the commissioning of the Three Gorges Dam (e.g., Gong et al., 2006).

8. Conclusions

Up-to-date datasets (1950–2005) indicate that sediment load of the Huanghe has undergone distinct stepwise decreases during a time of significant global climate change and extensive human activities.

In response to the operation of the Liujiaxia and Longyangxia reservoirs in the upper reaches of the river, the sediment load at Toudaoguai gauging station, at the downstream end of the upper reaches, has decreased in two steps over the past 56 yr. These steps occurred between the 3 comparatively stable periods of 1950–1968, 1969–1985 and 1986–2005. There were successive decreases of approximately 40% from the reference level (1950–1968) at each step.

Sediment loads at Huayuankou gauging station, at the downstream end of the middle reaches, were affected by soil conservation practices and the operation of the Sanmenxia and Xiaolangdi reservoirs, and show a more complicated pattern of stepwise decreases than at Toudaoguai. At Huayuankou, the stable periods separating the downward steps were 1950–1978, 1979–1999, and 2000–2005. The average sediment load from 1950 to 1978 was 1.31 Gt/yr and was used here as the reference level. From 1979 to 1999 the sediment load at Huayuankou decreased by 0.5 Gt/yr, or nearly 40% of the reference level, and the sediment load during 2000–2005 amounted to only 10% of the reference level. Based on annual precipitation and annual sediment load, we estimated that the decrease in precipitation accounted for 30% of the sediment load decrease at Huayuankou. We ascribe the remaining 70% of the decrease to human activities in the river basin. Effective soil conservation practices in the middle reaches since the late 1970s contributed 40% to the total decrease at Huayuankou. Sediment retention within reservoirs appears not to have been as important as might be expected, accounting for only 20% of the sediment load decrease, although there was notably high sediment retention in the Xiaolangdi reservoir from 2000 to 2005. The remaining 10% of the sediment load decrease at Huayuankou that we attributed to human activities resulted from the operation of reservoirs in the upper reaches.

In the lower reaches, channel deposition and water abstraction have caused considerable loss of sediment; finally, 80% of the sediment load recorded at Huayuankou reaches Lijin. Soil conservation practices and the operation of reservoirs have reduced the coarser fraction ($D > 0.05$ mm) of the sediment load recorded at Huayuankou, which has resulted in less channel deposition in the lower reaches. In contrast, the sediment loss due to water abstraction in the lower reaches has increased considerably, as water consumption to satisfy agriculture needs has rapidly increased. Therefore, the combined impacts of climate change and human activities over the past 56 yr in the upper, middle, and lower reaches have resulted in stepwise decreases in the

discharge of sediment and water to the sea by the Huanghe.

The Huanghe provides an excellent example of how climate changes and extensive human activities alter a river system. Considering the causes of the sediment load decreases that have occurred over the past 56 yr, we expect the sediment load discharged from the Huanghe to the sea to decrease further in the future; it seems to be reverting to the pristine levels of the middle Holocene, when human intervention was negligible. The dramatic decrease in the volume of sediment delivered to the sea by this famous river, and the decrease in water discharged, will trigger profound geological, morphological, ecological, and biogeochemical responses in the estuary, delta, and the coastal sea that will demand attention.

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