1-1-2012

Channel adjustments in response to the operation of large dams: the upper reach of the lower Yellow River

Yuanxu Ma
Chinese Academy of Sciences

He Qing Huang
Chinese Academy of Sciences

Gerald C. Nanson
University of Wollongong, gnanson@uow.edu.au

Yongi Li
Yellow River Institute of Hydraulic Research China

Wenyi Yao
Yellow River Institute of Hydraulic Research, China

Channel adjustments in response to the operation of large dams: the upper reach of the lower Yellow River

Abstract

The Yellow River in China carries an extremely large sediment load. River channel-form and lateral shifting in a dynamic, partly meandering and partly braided reach of the lower Yellow River, have been significantly influenced by construction of Sanmenxia Dam in 1960, Liujiaxia Dam in 1968, Longyangxia Dam in 1985 and Xiaolangdi Dam in 1997. Using observations from Huayuankou Station, 128 km downstream of Xiaolangdi Dam, this study examines changes in the river before and after construction of the dams. The temporal changes in the mean annual flow discharge and mean annual suspended sediment concentration have been strongly influenced by operation of theses dams. Observations of sediment transport coefficient (ratio of sediment concentration to flow discharge), at-a-station hydraulic geometry and bankfull channel form observed from 1951 to 2006 have shown that, although variations in flow and sediment load correspond to different periods of dam operation, changes in channel form are not entirely synchronous with these. The channel has been subject to substantial deposition due to the flushing of sediment from Sanmenxia Dam, resulting in a marked reduction in bankfull cross-sectional area. Flows below bankfull had a greater impact on channel form than higher flows because of very high sediment load. At-a-station hydraulic geometry shows that the variation of channel cross-sectional area below bankfull in this wide and relatively shallow system largely depends on changes in width. Such at-a-station changes are significantly influenced by (1) events below bankfull and (2) overbank floods. Bankfull depth is the main component of channel adjustment in that depth adjusts synchronously with channel area. The channel adjusts its size by relatively uniform changes in depth and width since 1981. Channel morphology is not the product of single channelforming flow frequency. It is determined by the combination of relatively low flows that play an important role in fine sediment transport and bed configuration as with relatively high flows that are effective at modifying the channel's morphology. The sediment transport coefficient is a useful index for efficiently guiding the operation of the dams in a way that would minimize channel changes downstream. Sedimentation over the nearly 60 years of study period caused the lower Yellow River to aggrade progressively, the only significant exception being the two years following completion of Sanmenxia Dam.

Keywords

dams, large, operation, response, adjustments, channel, lower, river, reach, yellow, upper, GeoQUEST

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

Publication Details

Ma, Y., Huang, H., Nanson, G. C., Li, Y. , Yao, W. (2012). Channel adjustments in response to the operation of large dams: the upper reach of the lower Yellow River. Geomorphology, 147-148 35-48.

Channel adjustments in response to the operation of large dams: The upper reach of the lower Yellow River

Yuanxu Ma[a], He Qing Huang[a,*], Gerald C. Nanson[b], Yong Li[c], Wenyi Yao[c]

[a] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 11A Datun Road, Chaoyang District, Beijing, 100101, China

[b] School of Earth and Environmental Sciences, University of Wollongong, New South Wales, 2522, Australia

[c] Yellow River Institute of Hydraulic Research, Zhengzhou, 450003, China

*Correspondence to: Prof. He Qing Huang, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 11A Datun Road, Chaoyang District, Beijing, 100101, China (Email: huanghq@igsnrr.ac.cn)

Abstract: The Yellow River in China carries an extremely large sediment load. River channel-form and lateral shifting in a dynamic, partly meandering and partly braided reach of the lower Yellow River, have been significantly influenced by construction of Sanmenxia Dam in 1960, Liujiaxia Dam in 1968, Longyangxia Dam in 1985 and Xiaolangdi Dam in 1997. Using observations from Huayuankou Station, 115 km downstream of Xiaolangdi Dam, this study examines changes in the river before and after construction of the dams. The temporal changes in the mean annual flow discharge and mean annual suspended sediment concentration have been strongly influenced by operation of theses dams. Observations of sediment transport coefficient (ratio of sediment concentration to flow discharge), at-a-station hydraulic geometry and bankfull channel form observed from 1951 to 2006 have shown that, although variations in flow and sediment load correspond to different periods of dam operation, changes in channel form are not entirely synchronous with these. The channel has been subject to substantial deposition due to the flushing of sediment from Sanmenxia Dam, resulting in a marked reduction in bankfull cross-sectional area. Flows below bankfull had a greater impact on channel form than higher flows because of very high sediment load. At-a-station hydraulic geometry shows that the variation of channel cross-sectional area in this wide and relatively shallow system largely depends on changes in depth. Such at-a-station changes are significantly influenced by (1) events below bankfull and (2) overbank floods. Bankfull depth is the main component of channel adjustment in that depth adjusts synchronously with channel area. The channel adjusts its size by relatively uniform changes in depth and width. Channel morphology is not the product of single channel-forming flow frequency. It is determined by the combination of relatively low flows that play an important role in fine sediment transport and bed configuration as with relatively high flows that are effective at modifying the channel's morphology. The sediment transport coefficient is a useful index for efficiently guiding the operation of the dams in a way that would minimize channel changes downstream. Sedimentation over the nearly 60 years of study period caused the lower Yellow River to aggrade progressively, the only significant exception being the two years following completion of Sanmenxia Dam.

Keywords: Lower Yellow River; River channel adjustment; Dam impacts; At-a-station hydraulic geometry; Bankfull hydraulic geometry; Channel-forming discharge.

1. Introduction

Dams are designed to control floods, trap sediments, produce electric power, irrigate arable land, and satisfy the needs of municipal and industrial utilities. Large dams are effective for reducing peak discharges of flood events and increasing low discharges during dry periods. However, the downstream changes of flow and sediment regime caused by dams can vary significantly between river reaches and over time. The influence of dams on flow and sediment regime and subsequent channel morphology has long been a concern of fluvial geomorphologists and hydraulic engineers (Arroyo, 1925; Malhotra, 1951; Gregory and Park, 1974; Petts, 1979, 1980; Graf, 1980, 1999, 2006; Williams and Wolman, 1984; Chien, 1985; Andrews, 1986; Gregory, 1987; Carling, 1988; Xu, 1990; Phillips, 2003, Phillips *et al*., 2005; Petts and Gurnell, 2005; Magilligan and Nislow, 2005; Magilligan *et al*. 2008; Pan *et al*., 2006; Singer, 2007; Zahar *et al*., 2008; Fu *et al*., 2010; Chen *et al*., 2010).

Dams alter downstream flow and sediment regime over a range of timescales: hourly to yearly (Magilligan and Nislow, 2001; Assani *et al*., 2003; Petts and Gurnell, 2005; Lajoie *et al.*, 2007). The resulting channel adjustments can be classified into four groups: degradation, aggradation, planform change (Petts, 1979; Brandt, 2000a,b; Petts and Gurnell, 2005) and downstream variation of bed-material grain size (Singer, 2008, 2010). River channel scour occurs frequently immediately below dams after their construction, and has been well documented over the last 80 years (Lawson, 1925; Shulits, 1934; Andrews, 1986; Kondolf, 1997; Magilligan and Nislow, 2005; Graf, 2006; Chen *et al*., 2010). By contrast, channel aggradation downstream of dams has also been observed (Arroyo, 1925; Malhotra, 1951; Petts, 1979, 1980; Zahar *et al*., 2008), whereas Magilligan *et al.* (2008) found no significant difference between pre- and post-dam channel morphology in the forested upland watersheds in the Connecticut River basin, USA.

The earliest evaluation of downstream sediment transport change due to dam construction and the consequent geomorphic effects over a large regional scale was made by Williams and Wolman (1984), who showed that the stream bed degradation occurred in all cross sections they studied, but that channel width may increase, decrease or remain constant. The above range of studies has demonstrated that the stream channel downstream from a dam can exhibit an interactive combination of adjustments, referred to as complex responses (Petts, 1979; Xu, 1990; Sherrard and Erskine, 1991; Benn and Erskine, 1994; Phillips *et al*., 2005). Petts (1979) suggested that such adjustments vary spatially and change with time in response to the alteration of flow regime, and Xu (1990) presented further detailed discussion on the complexity of downstream temporal responses using evidence from laboratory experiments and field investigations. Phillips *et al.* (2005) found multiple combinations of increase, decrease or no change in width, depth, slope and roughness in response to dam regulation. Although there have been attempts to generalize the hydrogeomorphic effects of impoundment (Brandt, 2000a,b; Petts and Gurnell, 2005), it remains difficult to predict channel adjustment downstream of dams because of differences in dam operation modes since their construction. This is especially true for the lower Yellow River, a very large alluvial river with a periodical hyperconcentrated sediment load and where the operation of the dams has changed considerably since construction.

Alluvial river channels adjust to accommodate the imposed flow and sediment regime. In channel design and environmental management, a characteristic discharge is desired which will reflect the overall flow conditions (Shields *et al.*, 2003; Doyle *et al.*, 2005). This characteristic discharge is considered to play an important role in forming and maintaining a stream's morphology, hence is termed as the channel-forming discharge or dominant discharge (Wolman and Miller, 1960; Andrews, 1980; Simon *et al*., 2004; Crowder and Knapp, 2005; Lenzi *et al*., 2006). There have been many investigations in which bankfull and effective discharge (that is the most effective for the long-term transport of sediment) is used to represent channel-forming discharge.

Traditionally, it has been accepted that bankfull discharge approximates effective discharge and has a recurrence interval of 1-2 years (Wolman and Miller, 1960; Andrews, 1980; Simon *et al*., 2004). However, other studies show that bankfull or effective discharge may not be equivalent (Pickup and Warner, 1976; Ashmore and Day, 1988). Indeed, some studies indicate that because of variations in basin morphology, drainage area, hydrologic regime and sediment transport mode (bed-load and suspended sediment load), a single recurrence interval flow event cannot be considered to be representative of the effective or bankfull discharge (Ashmore and Day, 1988; Phillips, 2002; Lenzi *et al.*, 2006). Moreover, some field observations showed that there may be two types of flow event responsible for channel formation. One is a range of low flows effective for fine sediment transport that prevent channel aggradation. The other is a range of flood events active in forming the channel (Phillips, 2002; Lenzi *et al.*, 2006). This suggests that channel morphology results from a series of discharges and a single channel-forming discharge is a problematic concept (Petts, 1979; Pickup and Rieger, 1979). Osterkamp (2004) argued that all flow events are responsible for channel formation, because they all transport and sort sediment. Hence, it makes sense to analyze the role of different classes of flow discharge in sediment transport and channel adjustment in response to the alteration of flow and sediment regime resulting from dam operation. In this study, several different conceptual discharges are discussed in terms of the roles they play in suspended sediment transport in the lower Yellow River.

Several studies have examined the response of the river channel-form in the lower Yellow River (Fig. 1a) to floods (Xu, 2001; Zhang *et al*., 2002; Liang *et al.*, 2004), however, none have examined the mechanisms by which both at-a-station and bankfull hydraulic geometries have adjusted below Sanmenxia and Xiaolangdi Dams. This study offers itself as a large-scale experiment on the impact of varying discharge and sediment load on a single well-gauged alluvial section of a large river. The objectives are: (1) to analyze the temporal changes of annual flow and sediment regime in the lower Yellow River before and after the construction of Sanmenxia and Xiaolangdi Dams, and (2) to determine the changes over time in response to the changes in flow and sediment regime in river channel morphology at the Huayuankou gauging station (Figs. 1b and c)

2. Operation of the dams:

Construction of the Sanmenxia Dam, the first large dam in the Yellow River basin (Fig. 1a), started in 1957 and it was commissioned in 1960. In 1968, Liujiaxia Dam was built in the upper Yellow River

(Fig. 1a). Longyangxia, also on the upper Yellow River, started in 1985. Xiaolangdi Dam was built 130 km upstream of the Huayuankou gauging station and began to impound water in 1997. In addition to their construction, their varying modes of operation have had a big impact on the downstream river system. The post-dam period of 1960-2006 can be divided into five important operational periods (Table 1) (Pan *et al*., 2006; Wang *et al*., 2007a):

Period 1: September 1960 - March 1962. It was a period of water impoundment and sediment entrapment during which the reservoir of Sanmenxia was operated at high storage levels all year round. As a result, the downstream channel was intensively scoured until October 1964. During this period the reservoir was filled to more than 90% with sediment.

Period 2: March 1962 - October 1973. Flood mitigation and sediment release from the reservoir occurred during this period. Sanmenxia Dam was operated at low storage levels throughout the year, detaining floods only during flood seasons and draining sediments during the largest flow discharges (Wang *et al*., 2007a). The originally built but blocked diversion tunnels at the bottom of the dam were opened in 1962 to release sediment. Additional two diversion sediment-draining tunnels were excavated on the two sides of the dam and commenced operation in 1968. At the same time the construction of Liujiaxia Dam in the upper Yellow River (Fig. 1a) partly changed the flow and sediment regime in the lower Yellow River (Pan *et al*., 2006).

Period 3: November 1973 - October 1985. Water with normal sediment load was stored and highly turbid flow was released during operation of the sediment-draining tunnels in Sanmenxia Dam. The reservoir was operated to store water in the dry season (November-June) up to high levels (315-320 m above mean sea level) and to release high sediment concentrated flows through the bottom outlets in the flood season (July-October) down to lower levels (302-305 m) (Wang *et al*., 2007a). When the sediment concentration rose above 200 kgm-^{3}, density currents formed in the reservoir and these were commonly released directly from the reservoir through the bottom outlets, even when the water level remained high (Wang *et al*., 2007a).

Period 4: 1985 - 1997. Sanmenxia Dam on the lower Yellow River operated jointly with the newer Longyangxia Dam completed in 1985 as the largest dam in terms of water storage in the headwaters of the Yellow River upstream of Lanzhou (Fig. 1a). This was a period of an increasingly dry climate and water extraction for agricultural and domestic use (Xu, 2004, 2005; Pan *et al*., 2006). Its impact, however, is not recognizable from the record being studied here.

Period 5: After 1997. With the construction of Xiaolangdi Dam 100 km downstream of Sanmenxia Dam (Fig. 1a) in 1997, Sanmenxia and Xiaolangdi Dams have been combined to mitigate floods and control sediment transport in the lower Yellow River. When the peak flood at Huayuankou has a recurrence interval of less than 100 years, only Xiaolangdi Dam is used to mitigate flooding and to trap sediment. Otherwise, the two dams are jointly operated to control flood events (Lin and Tu, 1997). Xiaolangdi Dam was designed mainly for regulating flow and sediment regime downstream in order to alleviate deposition in the lower Yellow River. During the about 30 years from 2000 to 2030, the intention has been and will continue to be to form a narrow deep channel and high floodplain within the reservoir (Tu *et al*., 1997). Since 2000, with Xiaolangdi Dam fully operational, the channel of the lower Yellow River has experienced serious scour, the bed being locally incised.

3. Study area and the Yellow River

The 768 km long lower Yellow River is recognized to start from Mengjin on the southeastern slope of Loess Plateau before passing through the North China Plain and flowing into Bo Sea near Lijin (Fig. 1a). Most of its sediment load comes from the Loess Plateau. It is constrained by artificial levees on the plains. Rapid aggradation of some 20 to 80 mm per year has raised the bed of the main channel to a height of 4-6 m above the adjacent plain, in places even to a maximum of 12 m (Xu, 2003; Zhai, 2007). It is known in China as a “suspended river”, suspended above the plain. The Yiluo and Qin Rivers (Fig. 1a and b) are the two largest tributaries of the lower Yellow River and but only contribute <10% of the total runoff and < 2% of the total suspended sediment load of the whole Yellow River basin at the Huayuankou gauging station.

The river emerges from the foothills of the plateau in the vicinity of Huayuankou Station and is a partly meandering and partly anabranching channel with a tendency to braid at low flows (Fig. 1c). During the study period it has varied in width between 1 and 3.5 km and the channel and adjacent floodplain are partially confined by artificial levees, 10 km apart enclosing the channel and a portion of the adjacent floodplain used for flood routing. The bed of the channel is elevated by some 2-4 m above the floodplain that lies beyond the artificial levees, and it has a low bed slope of about 0.000172-0.000265. It is laterally unstable and tends to shift its location within the artificial levees (Fig. 1d).

During 1951-2006, the mean annual runoff and the mean annual suspended sediment load at Huayuankou Station were 38.44 billion m^3 and 0.95 billion t respectively, and the mean annual discharge was 1218 $m^3 s^{-1}$ (Table 2). The recorded maximum flood discharge of 22,300 $m^3 s^{-1}$ occurred on 17 July 1958, and the maximum suspended sediment concentration of 911 kg m^{-3} on 7 September 1977 partly as a result of sediment flushing from Sanmenxia Dam. The lower Yellow River is characterized by heavy sediment-laden flows with an average annual suspended sediment concentration of 24.8 kg m^{-3} from 1951 to 2006 at Huayuankou Station.

A huge amount of deposition occurs in the lower Yellow River. During 1950-1999, this consisted of 14.62 billion t of sediment, of which 60% was deposited in the partly meandering and partly anabranching reach in the vicinity of Huayuankou Station (Xia *et al*., 2010). This led to an annual accretion rate of about 10 cm, caused mainly by a poorly matched flow and sediment regime in the form of too little water carrying too much sediment. A sharp reduction in both flow discharge and high suspended sediment load resulted in a significant shrinking on the river channel, especially since 1986.

This study focuses on the morphological adjustments of this alluvial reach at Huayuankou Station. Adjustments in channels of alluvial rivers are complex because of complicated channel morphology and frequent channel shifting. At low stages, a number of wide and narrow braided channels form between unvegetated bars with different lengths and widths with frequent channel shifting. During the flood season the main channel changes position. At bankfull there is only one single channel and no exposed bars. The magnitude of bankfull discharge often changes significantly because of substantial alteration of the cross section during hyperconcentrated flood events.

4. Data and methods

4.1 Data

Since the 1950s, a number of hydrometric stations have been established by the Yellow River Water Conservancy Commission to conduct regular measurements of water stage, water surface width, flow depth, flow velocity, flow discharge, suspended sediment concentration and grain size. The methods for hydrological survey, sampling and sediment analysis are generally the same as those used internationally (Hydrological Bureau, 1962; Boiten, 2003). The quality and reliability of the data are checked and calibrated by the Yellow River Water Resources Commission before releasing it annually in a hydrology yearbook.

Huayuankou Station was chosen for study because it started prior to the construction of Sanmenxia and Xiaolangdi Dams. It is 130 km downstream from Xiaolangdi, the most downstream and recently built dam, and located in a self-adjusting alluvial reach, strongly impacted by these two dams. Because of the difficulty in data acquisition and compilation, different data sets from Huayuankou are available for different durations. The hydraulic geometry measurements were collected from 1951 to 1997 (except for 1990) and the annual flow discharge and suspended sediment concentrations from 1951 to 2006. Usually more than 100 measurements of hydraulic geometry data were obtained in each year. Mean annual discharges as well as mean annual suspended sediment concentrations were analyzed to show the temporal variations of flow and sediment. The datasets (width, mean depth, mean flow velocity and corresponding discharge in each calendar year at Huayuankou Station) were processed for the analyses of at-a-station hydraulic geometry. In addition, width, depth and discharged measured at bankfull stage were used to examine the changing temporal trend of channel adjustments. The bankfull stage was determined by identifying the elevation of the floodplain at the top of the bank as shown on the measured cross-sectional profiles (Wu *et al*., 2008; Xia *et al.*, 2010). Where the elevation of the surfaces of the active floodplain varied too much to determine a single bankfull stage, a series of measurements of cross-sectional profiles as well as upstream and downstream cross-sectional profiles were used. When several channels existed at stages below bankfull, at-a-station width and area were calculated by summing the widths and areas of the individual channels, and the average of the data sets were taken to represent the depth and velocity.

4.2 Methods

The temporal changes of annual runoff and annual suspended sediment load in the Yellow River have been of concern in recent years because of its importance in irrigation and domestic use (Xu and Sun, 2003; Xu, 2005; Wang *et al.*, 2007b). Temporal variations of mean annual flow discharge and mean annual sediment concentration have been examined in this reach at Huayuankou Station. Moreover, as an important parameter describing flow and sediment combination in a river, this study presents sediment transport coefficient (the ratio of sediment concentration to flow discharge) as used in previous studies of the lower Yellow River (Chien and Zhou, 1965; Xu, 2004; Hu *et al*., 2006; Wu *et al.*, 2008). The reason for adopting this ratio is to obtain an index of the changing sediment concentration that is more independent of changes in flow discharge than could be obtained otherwise.

Numerous indices have been used for quantifying the variation of flow and sediment regime and channel morphology (Williams and Wolman, 1984; Andrews, 1986; Hadley and Emmett, 1998; Chin *et al.*, 2002; Magilligan *et al.*, 2008; Schmidt and Wilcock, 2008). Due to the utility of at-a-station hydraulic geometry exponents for predicting alluvial channel behavior or discriminating different types of channel cross-section or pattern (Knighton, 1974, 1975; Richards, 1976; Ferguson, 1986; Ellis and Church, 2005; Beyer, 2006; Arp *et al*., 2007; Nanson *et al*., 2010), at-a-station hydraulic geometry relations are used here to differentiate channel morphological adjustment up to the bankfull stage.

Hydraulic geometry relations take the following forms of power function (Leopold and Maddock, 1953):

$$w = aQ^b \quad (1)$$

$$d = cQ^f \quad (2)$$

$$v = kQ^m \quad (3)$$

where Q is the flow discharge; w, d, and v are the channel width, depth, and velocity; a, c and k are coefficients; and b, f, and m are exponents. The values of b, f, and m indicate the rates of change of the hydraulic variables w, d, and v with a changing discharge respectively. In addition, the relation between channel cross-sectional area (A) and flow discharge can be written as:

$$A = \alpha Q^\beta \quad (4)$$

At-a-station hydraulic geometry measurements obtained each year for the alluvial channel cross-section at Huayuankou Station have been analyzed. Although river channel cross sections may be reworked significantly by individual large floods, and these influence the hydraulic geometry exponents to some extent, the results reflect longer term changes. The annual exponents have been plotted to show the temporal variation of at-a-station channel morphology. The moving average is used here to smooth out the short-term fluctuations and highlight the longer-term trends of flow and sediment regime and river channel adjustment.

5. Analyses and results

5.1 Temporal changes of flow and sediment regime

The mean annual flow discharge and suspended sediment load and the 4-year moving average curves illustrate the temporal changes of flow and sediment regime at Huayuankou Station from 1951 to 2006 (Fig. 2). These changes can be divided into six regime stages (Fig. 2a,b), according to their responses to dam operations as detailed in Table 1. The changing trend of mean annual suspended sediment concentration coincides with that of the mean annual sediment transport coefficient at Huayuankou Station (Fig. 2b,c).

The dams were initially designed to control floods and trap sediment, and with the use of the sediment-draining tunnels in Sanmenxia Dam, they still function effectively at regulating the intra-annual distribution of flows in association with sediment entrapment and release. The temporal changes of sediment transport coefficient during flood season (July-October) and dry season (January-June, November-December) are shown in Figure 2d. Both these seasonal trends in the sediment transport coefficient exhibit a similar pattern to mean annual values, but those in the flood season vary with a larger amplitude than those in the dry season. The changes in sediment transport coefficient during flood season do most to determine the overall changes in sediment regime.

The characteristics of the flow and sediment regime of the lower Yellow River exhibited at Huayuankou Station can be detailed for six different regime stages, which, after 1960, are related roughly but not exactly to the previously listed operational periods of the dams.

Stage I (1951 - 1960): The flow and sediment regime entering the lower Yellow River reflected the situation prior to dam construction. The mean annual runoff was 45.91 billion m^3, larger than the long-term average for the full period of 1951 to 2006 (Table 2). The mean annual suspended sediment load of 1.5 billion t was about 60% larger than the full-period average. The mean annual discharge showed a decreasing trend and the mean annual suspended sediment concentration an increasing one (Fig. 2a,b) because of the decrease in runoff resulting from precipitation reduction through this stage (Pan *et al*., 2006). The sediment transport coefficient showed an increasing trend (Fig. 2c).

Stage II (1961 - 1964): In later 1960, the mean annual flow discharge and sediment concentration dropped sharply due to water storage in Sanmenxia Dam. From 1961-1964, however, the mean annual flow discharge increased, and the mean annual suspended sediment concentration decreased, while the sediment transport coefficient stayed relatively constant (Fig. 2a,b,c). Because of the trap efficiency of Sanmenxia Dam, particularly in the early years, the suspended sediment concentration was less than 60% of the full-period average.

Stage III (1965 - 1973): The mean annual flow discharge decreased from 1965, while the trend in the mean annual suspended sediment concentration, although very variable, increased from 1965 to 1973. The resultant sediment transport coefficient, which also varied, increased markedly over this period to the operation of Sanmenxia Dam which controlled floods while simultaneously releasing a large amount of sediment trapped in the reservoir. The sediment transport coefficient during dry season when the sediment was released was comparable to sediment transport of the flood season (Fig. 2d)

Stage IV (1974- 1985): The trend of mean annual flow discharge was variable but generally increased over this period. The mean annual suspended sediment, also variable, decreased considerably as did the sediment transport coefficient (Fig. 2). This period can be divided into two sub-stages. From 1974-1980, the mean annual runoff was less than the average value for 1951-2006 while the mean annual suspended sediment load approximated the full-period average. However, the data for different years show considerable variation. For example, in 1977 the annual runoff and suspended sediment load were 35.1 billion m^3 and 2.01 billion t respectively. The annual runoff was less than the average for the entire period while the suspended sediment load was greater. A combination of this ratio gave a peak value for the sediment transport coefficient in 1977. During 1981-1985, high annual flows and low annual suspended sediment loads resulted in a decrease in the sediment transport coefficient. A reduction in the overall annual suspended sediment concentration in this stage was probably due to implementation of substantial soil conservation measures in the middle Yellow River basin (Pan *et al*., 2006).

Stage V (1986 - 1997): The annual runoff and suspended sediment load (Table 2) decreased while the suspended sediment concentration during floods increased, resulting in a rise in the sediment transport coefficient due to climate change, water extraction for human use (Xu, 2005), and the joint operation of Longyangxia and Sanmenxia Dams, both of which trapped sediment and stored water.

Stage VI (1998 - 2006): The mean annual flow discharge showed an increasing trend since 2000. The mean annual suspended sediment decreased sharply since 1997 (Fig. 2a,b) because of sediment impoundment by Xiaolangdi Dam built in that year. As a result, the sediment transport coefficient dropped to a level lower than in any of the previous stages.

5.2 Magnitude and frequency of flow discharges for suspended sediment transport

Discharges of the Yellow River can be divided into classes according to the method proposed by Ma *et al*. (2010) who demonstrated in the study of the sediment-transport process in a large tributary of the Yellow River passing through Loess Plateau that one quarter of the standard deviation of all flow discharges is the most appropriate class interval. The results of effective discharge during the six different time stages are shown in Figure 3 and Table 3. The magnitude of effective discharge significantly depends on the flow regime during different regime stages. Histograms of suspended sediment load per class of increasing water discharge can be grouped into two types: (1) essentially carrying a single peak in spite of considerable sediment transport during flows higher than the peak (Fig. 3a); and (2) with two or more peaks of comparable flow (Fig. 3b-f). The first type occurred during 1951-1960 and the second type after 1960. The multiple-peak form of histograms of suspended sediment load may reflect the complicated regulation of the dams and is discussed below when considering channel fill.

5.3 Temporal changes of river channel geometry

5.3.1 Bankfull channel-form adjustment

At-a-station hydraulic geometry relations reflect hydraulic and channel form characteristics up to bankfull stage. Bankfull discharge is considered to be at or close to the channel-forming discharge and as a particularly important hydrological and geomorphic parameter (Wolman and Leopold, 1957; Williams, 1978; Osterkamp, 2004; Wu *et al.*, 2008). Figure 4 and Table 5 show how the temporal change of bankfull discharge and the corresponding channel geometry in the study reach has been influenced by mean annual flow and sediment regime at each of the six stages over the period of 1951-2006.

It can be noted that after the construction of Sanmenxia Dam, bankfull discharges recovered to a maximum after four years and then exhibited a declining tendency with a gradually reduced range of fluctuations for several decades. Correspondingly, bankfull cross-sectional area and depth increased for four years, width for seven years, and then all measurements of these variables decline for several decades (Fig. 4b). Throughout the length of the whole record, bankfull width and velocity changed essentially in the opposite directions, and bankfull velocity showed a negative correlation with bankfull width, depth and area (Fig. 4c,d).

5.3.2 At-a-station hydraulic geometry

Figure 5 shows the temporal changes of at-a-station hydraulic geometry exponents. The exponents of three years (1951, 1956 and 1985) appear to have been influenced by morphological changes caused by individual flood events and were not considered because of their high deviation from the relationship $b + f + m = 1$. The responses of at-a-station hydraulic geometry exponents to dam operation are clearly shown in the channel velocity and cross-sectional area data (Fig. 5c,d).

The construction of Sanmenxia Dam in 1960 and later dams significantly influenced the fluvial processes in the lower Yellow River below the dam. Since 1986, the river channel has also been modestly affected by a dry climate trend and more markedly by water extraction (Xu, 2004; Pan *et al*., 2006). Nevertheless, at-a-station hydraulic geometry was influenced not only by flow and sediment regime resulting from normal dam operation, but also by hyperconcentrated flood events caused by the flushing of sediment through the sediment-draining tunnels. Data on flow discharges and corresponding suspended sediment concentrations in relation to flood events in 1959, 1971, 1973, 1977 and 1992 are related to changes in channel form (w, d and w/d) in Table 4. These years were chosen because they represent different pattern of flood events. For example, changes in the width and depth relationships (b and f) in 1977, evident in Figures 5a and b, were caused by three hyperconcentrated flow events that occurred in that year during which the river channel was incised and large quantities of sediment were deposited on the floodplain, causing the channel to become deeper and narrower (Table 4). Interestingly, the exponents of channel cross-sectional area and velocity changed less in adjacent years because the reduction in width was compensated by a nearly equivalent reduction in mean flow depth, leaving area and velocity relatively unchanged. The variations of at-a-station hydraulic geometry at the six different stages are presented in Table 6.

In Figure 6, all 44 at-a-station hydraulic geometry points have been plotted in the *b*-*f*-*m* diagram proposed by Rhodes (1977). Figure 6 shows that all the exponents are constrained by the following characteristics: $m<0.5$ and $m/f >2/3$. This indicates that there is not much difference between at-a-station hydraulic geometry between pre-dam and post-dam periods. Thirty nine of the 44 points fall into the region: $b>f$, m$>f$ and $m<0.5$ indicating that with increasing discharge, width increases faster than depth. Because $m<0.5$, velocity increases more slowly than channel cross-sectional area, indicating that the stream channel has unstable dimensions and is prone to erosion. This reach of the lower Yellow River is wide and shallow, sensitive to erosion and deposition, and the channel cross-sectional area varies with discharge faster than any other parameters.

Rhodes (1977) argued that if channel width changes with flow discharge, the rate of increase of suspended sediment with discharge is inversely related to the rate of increase of width. In this reach of the lower Yellow River, the rate of increase in width with discharge is generally high, probably indicating that the rate of increase of suspended sediment with discharge is relatively low. The flows are not competent to move all suspended sediment load imposed from upstream, which has led to ongoing siltation.

6. Discussion

6.1 River channel adjustment to the operation of dams

A number of studies deal with the complex response of alluvial river channels due to dam construction (Xu, 1990; Sherrard and Erskine, 1991; Phillips *et al*., 2005). There are, however, few investigations on alluvial sand-bed rivers with very variable flow regimes and suspended sediment loads which are comparable to the Yellow River (Chien, 1985; Xu, 2001; Hu *et al*., 2006) (Table 1 and 2). Different combinations of variable flow discharges, suspended sediment concentrations, and unstable channels have resulted in a variety of complex channel responses in channel form parameters in the meandering-braided reach of the shifting lower Yellow River below Sanmenxia Dam (Fig. 4-6).

The annual changes of sediment transport coefficient and channel expressed as a change in the volume of sediment deposited (positive values) and/or scoured (negative values) from 1951-2004 are shown in Figure 7a. Generally, when the sediment transport coefficient is high, sediment load exceeds the flow capacity and deposition occurs. The significant difference of channel change between the flood season (Fig. 7b) and dry season (Fig.7c) suggests that channel deposition and/or scour to a large extent depend on the sediment transport coefficient during the flood season, because sediment deposition and/or scour account for a large portion of the total. During the dry season, a higher sediment transport coefficient tends to result in limited deposition, such as the periods of 1951-1960 and 1965-1970. Since 1971, the river channel has experienced scour in the dry season. Despite periods of scour, the problem of channel deposition in the lower Yellow River has not been solved with the dams. Figure 8 shows water levels recorded for a discharge datum of 3000 m^3 s^{-1} indicating that the channel has continued to aggrade for most of the period since 1950. The two years following completion of Sanmenxia Dam in 1960 were the only significant exceptions.

Figure 9 shows how channel change responded to changes in the sediment transport coefficient. The channel change is expressed in volumes of channel fill or scour in the 300 km long reach upstream of Gaocun for 1951-2004. When the annual sediment transport coefficient is less than 0.012 kg s m^{-6}, river channel deposition does not occur (Fig. 9a). Thus, this value can be seen as a threshold for net accretion. During the flood season (Fig. 9b), scatter in the data makes it difficult to determine the threshold for channel equilibrium. However, we can define 0.006 kg s m^{-6} as a threshold (Fig. 9b) for the sediment transport coefficient at which channel deposition varies from 0 to 0.25 $\times 10^9$ t. During the dry season, when the sediment transport coefficient is less than 0.00135 kg s m^{-6} (Fig.

9c), the volume of channel scour is generally in the range of zero to 0.25 $\times 10^9$ t.

The statistics presented in Table 7 exhibit the difference in sediment transport coefficients between flood and dry seasons. The dams should operate to regulate the flow and sediment regime and achieve a reasonable allocation of sediment load between flood and dry seasons. Because the annual threshold for sediment transport coefficient is about 0.012 kg s m^{-6}, and the definitive threshold during flood season is 0.006 kg s m^{-6}, the sediment transport coefficient during dry season should be adjusted to less than 0.0135 kg s m^{-6}, which will prevent channel to be deposited.

The annual at-a-station hydraulic geometry relations show considerable variability. Figure 5 indicates that, for most periods, the variation of channel cross-sectional area (β) in this wide and relatively shallow system as it fills and empties with water largely depends on changes in width (b) Adjustments in velocity depend on changes in depth. However, as Figure 10 shows, bankfull channel form adjustments differ considerably from those of at-a-station below bankfull hydraulic geometry on this meandering-braided reach of the lower Yellow River. Bankfull discharge exerts a large influence on bankfull depth and cross-sectional area (Fig. 10a). Bankfull area depends predominantly on adjustments in bankfull channel depth (Fig. 10b) while bankfull velocity is indirectly related to bankfull width and depth (Fig. 10c,d). Bankfull channel depth is the main component of channel adjustment and bankfull cross-sectional area adjust accordingly following scour or deposition. To verify this, net channel changes and bankfull water level changes during different periods were plotted (Fig. 11). The deposition and scour in river channel leads to a rising or falling water level respectively (Fig. 11). During periods of net erosion, bankfull water levels fell and bankfull depths and cross sectional areas increased. During periods of net deposition, bankfull water levels rose and bankfull depths and areas decreased. Channel deposition and scour impose substantial changes on bankfull channel capacity. It is apparent from Figure 11 that there were two periods of significant channel erosion; 1961 to 1964 associated with completion of Sanmenxia Dam, and 1998 to2004 associated with completion of Xiaolangdi Dam.

Figure 12 shows the effect of sediment transport coefficient on bankfull channel geometry. Bankfull depth and cross sectional area show generally decreasing trends with the increase of sediment transport coefficient (Fig. 12a). Low sediment transport coefficient prevents sediment deposition and channel shrinkage. As sediment transport coefficient rises, channel area exponent β decreases and velocity exponent m increases (Fig. 12b,c). A changing β manifests that to keep river channel from narrowing the sediment transport coefficient should not be high. However, sediment transport coefficient should also not be too low because low values mean that velocity does not increase rapidly with increasing discharge and this limits sediment transport.

Compared with the pre-dam period of 1951-1959, the temporal changes of bankfull channel dimensions and at-a-station hydraulic geometry during post-dam periods are not linear but are clearly related to the regime stages (Figs. 4 and 5). Intensified deposition during 1951-1960 arose not only from high sediment transport coefficients but also from large width to depth ratios, which resulted from serious channel bed deposition (Fig. 13). After 1960, bankfull width to depth ratio varied significantly. There was not much difference in the mean width-depth ratio between the deposition periods and scour episodes for 1981-2003 (Table 8). The channel adjusted its size by changing in depth and width, keeping the ratios of width to depth relatively uniform.

6.2 The response of river channel change to flow and sediment regime

Flows as the hydraulic efficiency and geomorphic effectiveness of hyperconcentrated low flows are much greater than flows with the low suspended sediment concentrations that occur during larger flows (Wang *et al.*, 2009). For example, 1959, 1971 and 1977 were years when hyperconcentrated flow events occurred which resulted in abnormally dramatic changes in at-a-station hydraulic geometry (Fig. 5). These resulted in considerable changes in channel cross sections (Table 4). During f 1961-1964 and 1998-2006, when substantial scour occurred, both low flow and high flows were effective at transporting suspended sediment (Fig. 3).

Figure 14 shows temporal changes of four conceptually different expressions of flow discharge.

Effective discharge is generally larger than the mean annual discharge but lower than bankfull discharge and annual maximum daily discharge. Flows below bankfull stage play an important role in suspended sediment transport as shown in Figure 3. They are identified as effective discharge in Table 3, while flows near to or higher than bankfull discharge play an important role in determining channel dimensions as shown in Figure 4. The variations of relationships between four conceptually different flow discharges during different periods may identify different adjusting processes. During 1960-1964, bankfull discharge was generally larger than maximum mean daily discharges. Most of the flow events during this period barely reached bankfull stage (Fig. 14) probably suggesting that river channel adjustments during this period were dominated by inner-channel processes at flows lower than bankfull. The increase in bankfull width resulted from bank erosion caused by flow events below bankfull stage. In contrast, during 1981-1985, bankfull discharge was substantially lower than maximum mean daily discharges. During this period, the above bankfull non-hyperconcentrated flood events would have played an important role in river channel widening and deepening (Pan *et al*., 2006). It would appear that river channel adjustments during the two different periods (1960-64 and 1981-85) were dependent on two correspondingly different flow regimes.

7. Conclusion

Sanmenxia Dam was constructed in 1960 and initially designed to control floods and trap sediment. Over time the operating modes have changed resulting in considerable variation in the flow and sediment regime in the lower Yellow River. With the sequential construction and operation of Liujiaxia (1968), Longyangxia (1985) and Xiaolangdi (1997) Dams on the upper and lower Yellow River, five major changes in the channel-form parameters can be identified at Huayuankou Station. Those initiated in 1960, 1964 and 1973 can be attributed to changes in the operational modes of Sanmenxia Dam, whereas those during 1986-1996 appear to have been induced by a combination of climate change (Xu, 2005), water extraction (Xu, 2005; Wang *et al*., 2007b) and the joint operational procedures of the newer Longyangxia Dam with the older Sanmenxia Dam. The operation of Xiaolangdi Dam has been the main factor affecting channel adjustment since 1997.

Although the variation of flow and sediment regime corresponds to different periods of dam operation, the adjustment of channel form differs significantly between states at-a-station and bankfull.

At-a-station hydraulic geometry relations are influenced, not only by regular dam operations, but also by hyperconcentrated flood events associated with the periodic flushing of sediment from the Sanmenxia reservoir. The changing trend of bankfull discharge, which is synchronous with annual flow and sediment regime, appears to indicate that bankfull discharge adjusts in response to variations in the annual flow and sediment regime (Figs. 2 and 4). Comparable trends in the change of sediment transport coefficient show that adjustments of bankfull cross-sectional area and depth are regulated by channel scour and fill (Figs. 4b and 11). The channel forming discharges in this reach are a combination of relatively low flows, which play an important role in fine sediment transport and channel bed configuration, and relatively high flows, which are effective at modifying channel morphology. The sediment transport coefficient provides a useful guide on how to operate the dams in a way that minimizes channel change downstream. In order to better understand how the river channels adjust, further work needs to focus on the physical causes and the role of different flow frequencies on channel morphology, especially in the lower Yellow River, where sediment concentrations and discharges are strongly asynchronous.

Acknowledgements:

This study is supported by the National Natural Science Foundation of China (40788001), National Basic Research Program of China (2011CB40330A), and a visiting professorship to Gerald Nanson from the Chinese Academy of Sciences. This work is also partly supported by China Postdoctoral Science Foundation (20110490568). The manuscript has benefited greatly from comments by Professor Zhongyuan Chen, Avijit Gupta, Adrian Harvey and the anonymous reviewers.

References:

Andrews, E. D., 1980. Effective and bankfull discharges of streams in the Yampa River Basin, Colorado and

Wyoming. Journal of Hydrology 46, 311-330.

Andrews, E. D., 1986. Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah. Geological Society of America Bulletin 97, 1012-1023.

Arp, C. D., Schmidt, J. C., Baker, M. A., and Myers, A. K., 2007, Stream geomorphology in a mountain lake district: hydraulic geometry, sediment sources and sinks, and downstream lake effects. Earth Surface Processes and Landforms 32, 525-543.

Arroyo, S., 1925. Channel improvements of Rio Grande and El Paso. Eng. News-Rec. 95, 374-376.

Ashmore, P. E., Day, T. J., 1988. Effective discharge for suspended sediment transport in streams of the Saskatchewan River Basin. Water Resource Research 24, 864-870.

Assani, A. A., Stichelbout, E., Roy, A. G., Petit, F., 2006. Comparison of impacts of dams on the annual maximum flow characteristics in the three regulated hydrological regimes in Québec. Hydrological Processes 20, 3485-3501.

Brandt, S. A., 2000a. Classification of geomorphological effects downstream of dams. Catena 40, 375-401.

Brandt, S. A., 2000b. Prediction of downstream geomorphological changes after dam construction: a stream power approach. International Journal of Water Resources Development 16, 343-367.

Benn, P. C., Erskine, W. D., 1994. Complex channel response to flow regulation: Cudgegong River below Windermere Dam, Australia. Applied Geography 14, 153-168.

Beyer, P. J., 2006. Variability in channel form in free-flowing dryland river. River Research and Applications 22, 203-217.

Boiten, W., 2003. Hydrometry. Swets & Zeitlinger B.V., Lisse, the Netherlands. Second Edition. 248pp.

Carling, P. A., 1988. Channel change and sediment transport in regulated U. K. rivers. Regulated Rivers 2, 369-388.

Chen, Z. Y., Wang, Z. H., Finlayson, B., Chen, J., Yin, D. W., 2010. Implications of flow control by the Three Gorges Dam on sediment and channel dynamics of the middle Yangtze (Changjiang) River, China, Geology 38, 1043-1046.

Chien, N., 1985. Changes in river regime after the construction of upstream reservoirs. Earth Surface Processes and Landforms 10, 143-159.

Chien, N., Zhou, W. H., 1965. Channel Processes of the Lower Yellow River. Beijing, Science Press (in Chinese).

Chin, A. Harris, D. L., Trice, T. H., Given, J. L., 2002. Adjustment of stream channel capacity following dam closure, Yegua Creek, Texas. Journal of the. American Water Resources Association 38, 1521-1531.

Crowder, D.W., Knapp, H.V., 2005. Effective discharge recurrence intervals of Illinois streams. Geomorphology 64, 167-184.

Doyle, M. W., Stanley, E. H., Strayer, D. L., Jacobson, R. B., Schmidt, J. C., 2005. Effective discharge analysis of ecological processes in streams. Water Resources Research 41, W11411. doi:10.1029/2005WR004222.

Ellis, E. R., Church, M., 2005. Hydraulic geometry of secondary channels of lower Fraser River, British Columbia, from acoustic Doppler profiling. Water Resources Research 41, W08421, doi:10.1029/2004WR003777.

Ferguson, R. I., 1986. Hydraulics and hydraulic geometry. Progresses in Physical Geography 10, 1-31.

Fu, B., Wu, B. F., Lu, Y. H., Xu, Z. H., Cao, J. H., Niu, D., Yang, G. S., Zhou, Y. M., 2010, Three Gorges Project: Efforts and challenges for the environment, Progress in Physical Geography 34, 741-754.

Graf, W. L., 1980. The effect of dam closure on downstream rapids. Water Resources Research 16, 129-136.

Graf, W. L., 1999. Dam nation: a geographic census of large American dams and their hydrologic impacts. Water Resources Research 35, 1305-1311.

Graf, W. L., 2006. Downstream Hydrologic and Geomorphic Effects of Large Dams on American Rivers. Geomorphology 72, 336-360.

Gregory, K. J., 1987. Environmental effects of river channel change. Regulated Rivers 1, 358-363.

Gregory, K. J., Park, C. C., 1974. Adjustment of river channel capacity downstream from a reservoir. Water Resources Research 10, 870-873.

Hadley, R. F., Emmett, W. W., 1998. Channel changes downstream from a dam. Journal of the American Water Resources Association 34, 629-637.

Hu, C. H., Chen, J. G., Liu, D. B., 2006. Studies on the features of cross section's profile in lower Yellow River under the conditions of variable incoming water and sediment. Journal of Hydraulic Engineering 11, 1283-1289 (in Chinese).

Hydrological Bureau, Ministry of Water Conservancy and Electric Power, PRC, 1962. National Standards for Hydrological Survey. Beijing, China Industry Press, Vols. 1-7 (in Chinese).

Knighton, A. D., 1974. Variation in width-discharge relation and some implications for hydraulic geometry. Geological Society of American Bulletin 85, 1069-1076.

Knighton, A. D., 1975. Variations in at-a-station hydraulic geometry. American Journal of Science 275, 186-218.

Kondolf, G. M., 1997. Hungry water: effects of dams and gravel mining on rivers channels. Environmental Management 21 , 533-551.

Lajoie, F., Assani, A. A., Roy, A. G., Mesfioui, M., 2007. Impacts of dams on monthly flow characteristics. The influence of watershed size and seasons. Journal of Hydrology 334, 423-439.

Lawson, J. M., 1925. Effect of Rio Grande storage on river erosion and deposition. Engineering News Record 327-334 (Sept. 3, 1925).

Lenzi, M. A., Mao, L., Comiti, F., 2006. Effective discharge for sediment transport in a mountain river: computational approaches and geomorphological effectiveness. Journal of Hydrology 326, 257-276.

Leopold, L. B., Maddock, Jr., T., 1953. The hydraulic geometry of stream channels and some physiographic implications. US Geological Survey Professional Paper 252. Washington, DC.

Liang, Z. Y., Liu, J. X., Zhang, H. J., 2004. Study on critical conditions of scour and siltation in flood seasons in the lower Yellow River. Journal of China Institute of Water Resources and Hydropower Research 2, 146-150 (in Chinese).

Lin, X. S., Tu, Q. H., 1997. The capacity and integrated operating modes of Xiaolangdi Dam. In: Lin, X. S. (Ed.), Symposium on Xiaolangdi Reservoir in the Yellow River. Yellow River Water Resources Publication, Zhengzhou, pp.5-10 (in Chinese).

Ma, Y. X., Huang, H. Q., Xu, J. X., Brierley, G. J., Yao, Z. J., 2010. Variability of effective discharge for suspended sediment transport in a large semi-arid river basin. Journal of Hydrology 388, 357-369.

Magilligan, F. J., Nislow, K. H., 2001. Long-term changes in regional hydrologic regime following impoundment in a humid-climate watershed. Journal of the American Water Resources Association 37, 1551-1569.

Magilligan, F. J., Nislow, K. H., 2005. Changes in hydrologic regime by dams. Geomorphology 71, 61-78.

Magilligan, F. J., Haynie, H. J., Nislow, K. H., 2008. Channel adjustments to dams in the Connecticut River basin: implications for forested mesic watersheds, Annals Association American Geographers 98: 267-284.

Malhotra, S. L., 1951. Effects of barrages and weirs on the regime of rivers. Proceedings of International Association of Hydraulic Research, 4th Meeting, pp. 335-347.

Nanson, R., Nanson, G. C., Huang, H. Q., 2010. Bio-geomorphology and hydraulic geometry of narrow and deep channels in peatland floodplains: evidence for optimisation. Geomorphology 117, 143-154.

Osterkamp, W. R., 2004. Bankfull discharge. In Goudie, A. S. (Ed.), Encyclopedia of Geomorphology: Routledge, London, pp. 52-54.

Pan, X. D., Li, Y., Zhang, X. H., Shen, G. Q., Yue, D. J., 2006. The fluvial process in the lower Yellow River after completion of Sanmenxia Reservoir. Yellow River Water Resources Press, Zhengzhou, 458 pp. (in Chinese).

Petts, G. E., 1979. Complex response of river channel morphology subsequent to reservoir construction. Progress in Physical Geography 3, 329-362.

Petts, G. E., 1980. Morphological changes of river channels consequent upon headwater impoundment. Journal of Institute of Water Engineering and Science 34, 374-382.

Petts, G. E, Gurnell, A. M., 2005. Dams and geomorphology: research progress and future directions. Geomorphology 71, 27-47.

Phillips, J. D., 2002. Geomorphological impacts of flash flooding in a forested headwater basin. Journal of Hydrology 269, 236-250.

Phillips, J. D., 2003. Toledo Bend reservoir and geomorphic response in the Lower Sabine River. River Research and Application 19, 137-159.

Phillips, J. D., Slattery, M. C., Musselman, Z. A., 2005. Channel Adjustments of the Lower Trinity River, Texas, Downstream of Livingston Dam. Earth Surface Processes and Landforms 30, 1419-1439.

Pickup, G., Rieger, W. A., 1979. A conceptual model of the relationship between channel characteristics and discharge. Earth Surface Processes 4, 37-42.

Pickup, G., Warner, R.F., 1976. Effects of hydrologic regime on magnitude and frequency of dominant discharge. Journal of Hydrology 29, 51-75.

Rhodes, D. D., 1977. The b-f-m diagram: graphical representation and interpretation of at-a-station hydraulic geometry. American Journal of Science 277, 73-96.

Richards, K. S., 1976, Complex width-discharge relations in natural river sections. Geological Society of America Bulletin 87, 199-206.

Schmidt, J. C., Wilcock, P. R., 2008. Metrics for assessing the downstream effects of dams. Water Resources Research 44, W04404, doi:10.1029/2006WR005092.

Sherrard, J. J., Erskine, W. D., 1991. Complex response of a sand-bed stream to upstream impoundment. Regulated Rivers 6, 53-70.

Shulits, S., 1934. Experience with bed degradation below dams on European rivers. Engineering News Record. June 1934, 838-839.

Shields Jr., F. D., Copeland, R. C., Klingeman, P. C., Doyle, M. V., Simon, A., 2003. Design for stream restoration. Journal of Hydraulic Engineering 129, 575-584.

Singer, M. B., 2007. The influence of major dams on hydrology through the drainage network of the Sacramento Valley, California. River Research and Applications 23, 55-72.

Singer, M. B., 2008. Downstream patterns of bed-material grain size in a large, lowland alluvial river subject to low sediment supply. Water Resources Research 44, W12202, doi: 10.1029/2008WR007183.

Singer, M.B., 2010. Transient response in longitudinal grain size to reduced gravel supply in a large river. Geophysical Research Letters 37, L18403, doi:10.1029/2010GL044381.

Simon, A., Dickerson, W., Heins, A., 2004. Suspended-sediment transport rates at the 1.5-year recurrence interval for ecoregions of the United States: transport conditions at the bankfull and effective discharge? Geomorphology 58, 243-262.

Tu, Q. H., Zhang, J. H., Zeng, Q., 1997. The operating modes of Xiaolangdi Reservior for alleviating deposition in the lower Yellow River. In: Lin, X. S. (Ed.), Symposium on Xiaolangdi Reservoir in the Yellow River. Yellow River Water Resources Publication, Zhengzhou, pp. 37-47 (in Chinese).

Wang, Z. Y., Wu, B. S., Wang, G. Q., 2007a. Fluvial processes and morphological response in the Yellow and Weihe Rivers to closure and operation of Sanmenxia Dam. Geomorphology 91, 65-79.

Wang, H. J., Yang, Z. S., Yoshiki Saito, Liu, J. P., Sun, X. X., Wang, Y., 2007b. Stepwise decreases of the Huanghe (Yellow River) sediment load (1950–2005): Impacts of climate change and human activities. Global and Planetary Change 57, 331-354.

Wang, Z. Y., Qi, P., Melching, C. S., 2009. Fluvial hydraulics of hyperconcentrated floods in Chinese rivers. Earth Surface Processes and Landforms 34, 981-993.

Williams, G. P., 1978. Bankfull discharge of rivers. Water Resources Research 23, 1471-1480.

Williams, G. P., Wolman, M. G., 1984. Downstream Effects of Dams on Alluvial Rivers. U. S. Geological Survey Professional Paper 1286. U.S. Government Printing Office, Washington, DC. 83 pp..

Wolman, M.G., Leopold, L. B., 1957, River Flood Plains: Some Observations on their Formation, U.S. Geological Survey Professional Paper 282-C. 30pp..

Wolman, M. G., Miller, J. P., 1960. Magnitude and frequency of forces in geomorphological processes. Journal of Geology 68, 54-74.

Wu, B. S., Wang, G. Q., Xia, J. Q., Fu, X. D., Zhang, Y. F., 2008. Response of bankfull discharge to discharge and sediment load in the Lower Yellow River. Geomorphology 100, 366-376.

Xia, J. Q., Wu, B. S., Wang, G. Q., Wang, Y. P., 2010. Estimation of bankfull discharge in the Lower Yellow River using different approaches. Geomorphology 117, 66-77.

Xu, J. X., 1990. An experimental study of complex response in river channel adjustment downstream from a reservoir. Earth Surface Processes and Landforms 15, 43-53.

Xu, J. X., 2001. Complex response in channel adjustment in the lower Yellow River during the period of clear-water scour. Advances in Water Science 12, 291-299 (in Chinese).

Xu, J. X., 2003. Sedimentation rates in the lower Yellow River over the past 2300 years as influenced by human activities and climate change. Hydrological Processes 19, 3359-3371.

Xu, J. X., 2004. A study of anthropogenic seasonal rivers in China. Catena 55, 17-32.

Xu, J. X., 2005. The water fluxes of the Yellow River to the sea in the past 50 years, in response to climate change and human activities. Environmental Management 35, 620-631.

Xu, J. X., Sun, J., 2003. Influence of precipitation and human activities on water fluxes of the Yellow River to the sea in the past 50 years. Advances in Water Sciences 14, 690-695 (in Chinese).

Yao, W. Y., Li, Y., Zhang, Y. F., Hu, C. H., Zhang, J. L., 2007. Key techniques for maintaining the basic functions of flood drainage and sediment transport in the lower Yellow River. Science Press, Beijing, China (in Chinese).

Zahar, Y., GhoRbel, A., Albergel, G., 2008. Impacts of large dams on downstream flow conditions of rivers:

Aggradation and reduction of the Medjerda channel capacity downstream of the Sidi Salem dam (Tunisia). Journal of Hydrology 351, 318-330.

Zhai, J. R., 2007. Contemplation for floodplain problems in the lower Yellow River. In: Shang, H. Q., Luo, X. X. (Eds.), Proceedings of the Seconed International Yellow River Forum, Vol. III. Yellow River Conservancy Press, Zhengzhou, China, pp. 3-10 (in Chinese).

Zhang, O. Y., Xu, J. X., Zhang, H. W., 2002. The Response of the Channel Form Adjustment at the Meandering-braided reaches of the lower Yellow River to Flood Events. Acta Geographica Sinica 57 648-654 (in Chinese).

Figure Captions:

Figure 1. Maps of the Yellow River basin and the lower Yellow River: (a) map of the Yellow River basin (thick black line denotes the location of the lower Yellow River); (b) the reach between Sanmenxia Dam and Xiaolangdi Dam and the meandering-braided reach in the lower Yellow River; (c) planform of the reach at Huayuankou Station； and (d) Cross-sectional profiles for 1985 and 2006 between the levees at Huayuankou Station.

Figure 2. Temporal changes of annual flow and sediment regime during the period of 1951-2006 at Huayuankou Station: (a) Temporal change of mean annual flow discharge; (b) Temporal change of mean annual suspended sediment concentration; (c) Temporal change of annual sediment transport coefficient; and (d) Temporal changes of sediment transport coefficient during flood season (July-October) and dry season (January-June, November-December) (dots denote annual change, dashes denote 4-year moving average change, and numbers of I -VI denote six different stages; timeline of major dame operation: Sanmenxia Dam completed in 1960, sediment released from Sanmenxia reservoir during 1962-1964, Liujiaxia Dam completed in 1968, change in the mode of sediment release from Sanmenxia in 1973, Longyangxia Dam completed in 1985, and Xiaolangdi Dam completed in 1997).

Figure 3. Magnitude and frequency analyses of flow discharge for suspended sediment transport at Huayuankou Station during different regime stages plotted in a to f. The histograms represent suspended sediment load for each class of flow discharge, where *SSL* denotes suspended sediment load, Q_{eff} effective discharge, and Q_{b} bankfull discharge.

Figure 4. Temporal changes of: (a) bankfull discharge; (b) bankfull cross-sectional area and bankfull depth; (c) bankfull width and bankfull velocity; and (d) the relationships between bankfull width, depth, area and velocity (since 1960, bankfull discharge has similar changing trends to mean annual flow discharge; during 1950-1960, mean annual discharge decreased, while bankfull discharge increased; bankfull dimensions (width, depth and area) exhibit different changing patterns with bankfull discharge; diagram d shows that bankfull velocity is inversely proportional to bankfull dimensions.).

Figure 5. Temporal changes of at-a-station hydraulic geometry exponents at Huayuankou Station: (a) the width exponent *b*; (b) the mean depth exponent *f*; (c) the mean velocity exponent *m*; and (d) the cross-sectional area exponent *β*.

Figure 6. Ternary plot of at-a-station hydraulic geometry exponents at Huayuankou Station from 1951 to 2006 but not including1951, 1956, 1985, 1998-2005.

Figure 7. Temporal channel changes in relation to volumes of channel deposition or scour (10^9 t) in the reach upstream of Gaocun (the lower end of the meandering-braided reach in the lower Yellow River) with positive values for channel deposition and negative values for channel scour: (a) annual, (b) flood season and (c) dry season. Values of sediment transport coefficient (kg s m^{-6}) are shown as open circles.

Figure 8. Temporal change of water level (elevation above mean sea level) water levels recorded for a discharge datum of 3000 m^3 s^{-1} at Huayuankou from 1951 to 1999.

Figure 9. The relationship between sediment transport coefficient at Huayuankou Station and channel change expressed as volumes of channel fill or scour (10^9 t) in the reach upstream of Gaocun (the lower end of the meandering-braided reach in the lower Yellow River) during 1951-2004: (a) annual; (b) flood season; and (c) dry season.

Figure 10. Bivariate relationships between bankfull parameters：(a) bankfull depth and bankfull area with bankfull discharge; (b) bankfull depth with bankfull area; (c) bankfull velocity with bankfull width; and (d) bankfull depth and bankfull velocity.

Figure 11. Channel change in volume (shaded columns) in the reach upstream of Gaocun (the lower end of the meandering-braided reach in the lower Yellow River) with positive values for channel deposition and negative values for channel scour and water level (open columns) change at 3000 m^3 s^{-1} in the meandering-braided reach during different periods (channel change data are derived from Yao *et al.* (2007) and water level data from Pan *et al*. (2006)).

Figure 12. Bivariate relationships between sediment transport coefficient and (a) bankfull depth and area, (b) exponent *β* for channel cross-sectional area, and (c) exponent *m* for flow velocity.

Figure 13. Temporal change of bankfull width/depth ratio from 1954 to 2002. Dashed line is a 4-year moving average.

Figure 14. Temporal changes of mean annual discharge, maximum mean daily discharge, bankfull discharge, and effective discharge during 1951-2006.

Table Captions:

Table 1 Description of five important operational periods occurring in the five change-point years

Table 2 Summary of annual flow and sediment regime statistics at Huayuankou Station during six different regime stages from 1951 to 2006 and averages for the 56 year period. Data for some years are not available.

Table 3 Effective discharges for six different periods

Table 4 Changes in channel form (*w*, *d* and *w*/*d*) at Huayuankou Station before and after specified flood events in 1959, 1971, 1973, 1977 and 1992 are related to the maximum flood discharges and corresponding suspended sediment concentrations for these events, revised from Pan *et al*. (2006).

Table 5 Bankfull channel-form adjustments during different stages at Huayuankou Station.

Table 6 At-a-station hydraulic geometry variations during different stages at Huayuankou Station.

Table 7 Sediment transport coefficient ranges and mean values for flood and dry seasons at Huayuankou Station for seven different episodes.

Table 8 Bankfull width/depth ratio ranges and mean values at Huayuankou Station for seven different episodes.

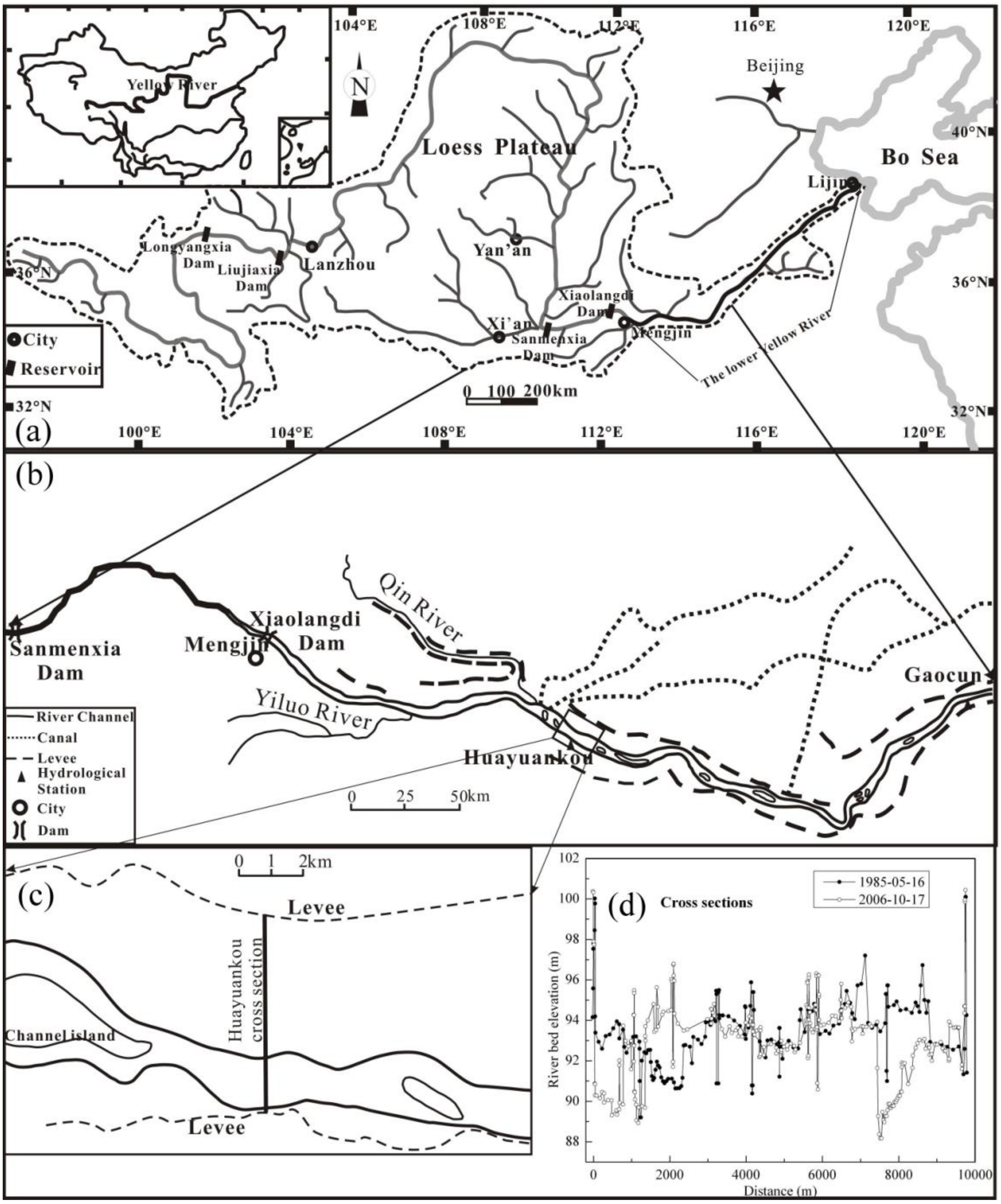
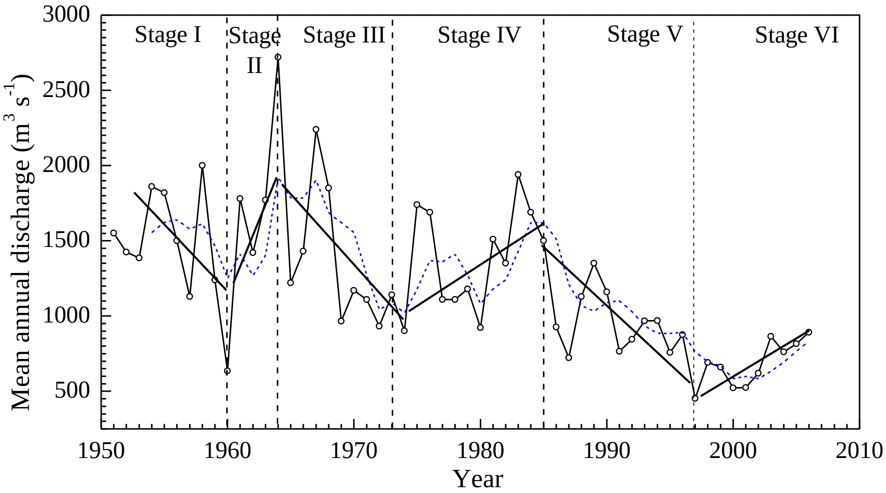
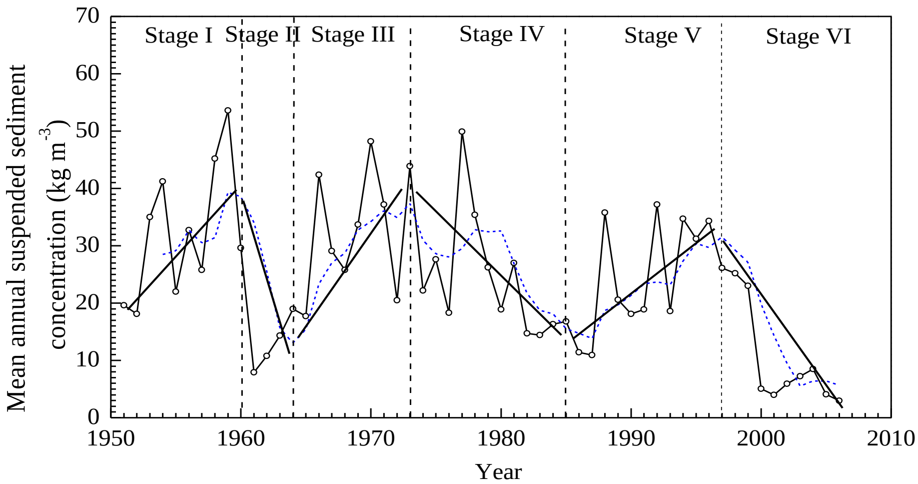

Yellow River
104°E
108°E
112°E
116°E
120°E
Beijing
Loess Plateau
Bo Sea
40°N
Lijin
36°N
Longyangxia Dam
Liujiaxia Dam
Lanzhou
Yan'an
Xiaolangdi Dam
Xi'an
Sanmenxia Dam
Mengjin
The lower Yellow River
City
Reservoir
32°N
0 100 200km
(a)
100°E
(b)
Qin River
Xiaolangdi Dam
Sanmenxia Dam
Mengjin
Yiluo River
Gaocun
Huayuankou
River Channel
Canal
Levee
Hydrological Station
City
Dam
0 25 50km
(c)
0 1 2km
Levee
Huayuankou cross section
Channel island
Levee
(d)
Cross sections
1985-05-16
2006-10-17
River bed elevation (m)
Distance (m)

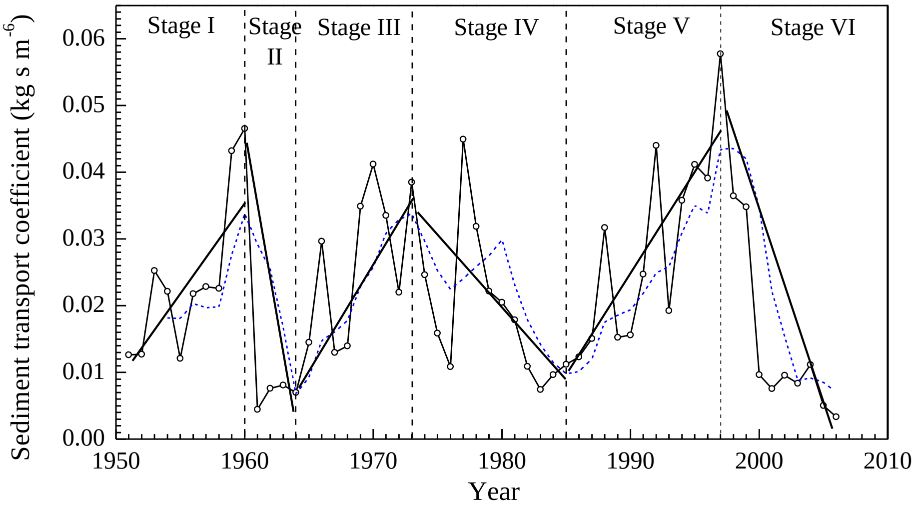
Figure 1


Stage I
Stage II
Stage III
Stage IV
Stage V
Stage VI
Mean annual discharge (m3 s-1)
Year
3000
2500
2000
1500
1000
500
1950
1960
1970
1980
1990
2000
2010

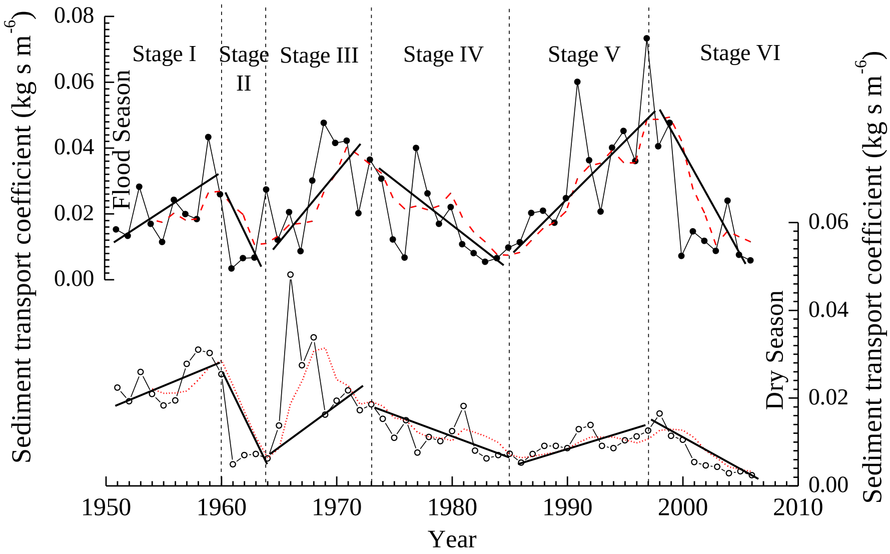
(a)


Stage I
Stage II
Stage III
Stage IV
Stage V
Stage VI
Mean annual suspended sediment concentration (kg m-3)
Year
70
60
50
40
30
20
10
0
1950
1960
1970
1980
1990
2000
2010

(b)


Stage I
Stage II
Stage III
Stage IV
Stage V
Stage VI
Sediment transport coefficient (kg s m-6)
Year
0.06
0.05
0.04
0.03
0.02
0.01
0.00
1950
1960
1970
1980
1990
2000
2010

(c)


Sediment transport coefficient (kg s m-6)
0.08
0.06
0.04
0.02
0.00
Flood Season
Stage I
Stage II
Stage III
Stage IV
Stage V
Stage VI
Dry Season
Sediment transport coefficient (kg s m-6)
1950
1960
1970
1980
1990
2000
2010
Year

(d)

Figure 2

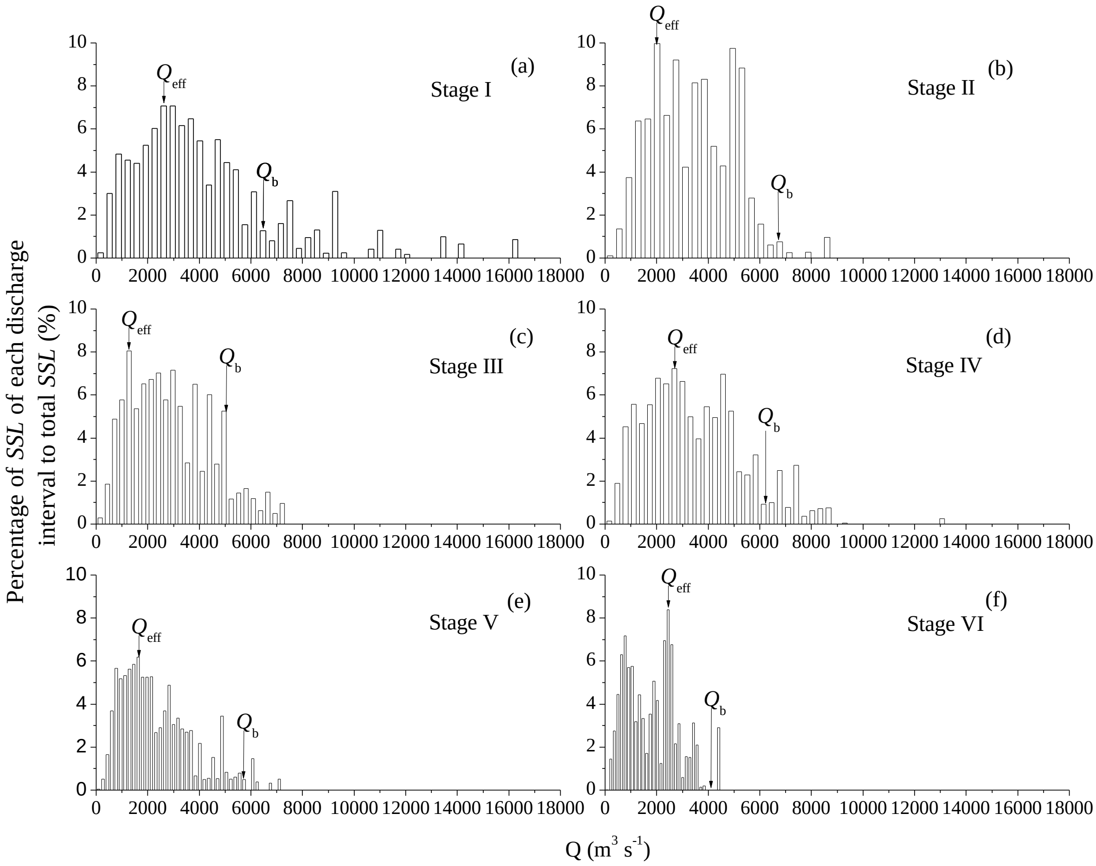
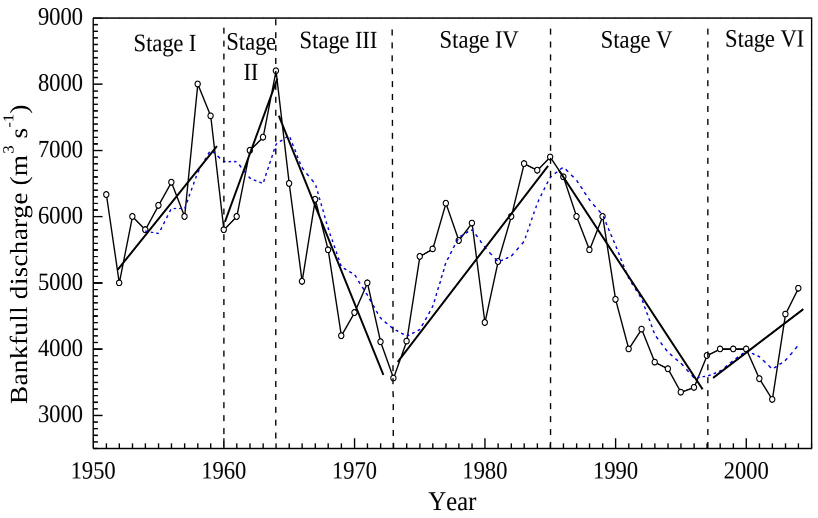
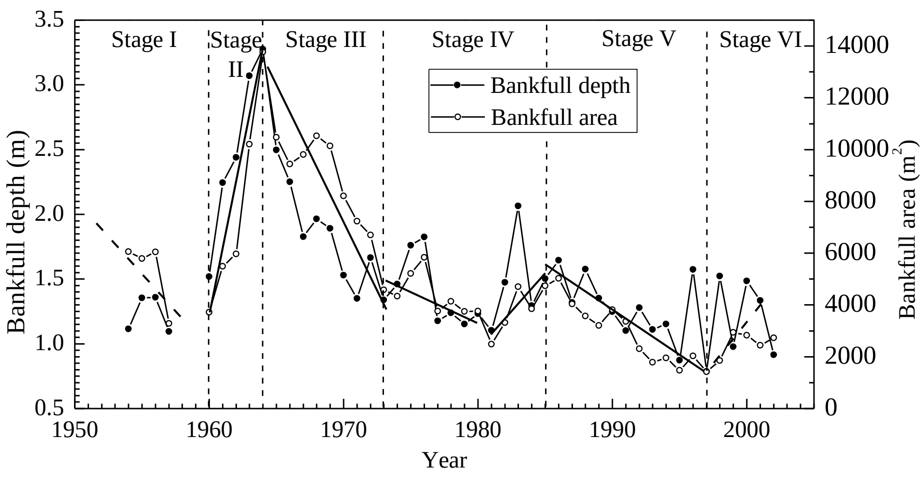

Percentage of SSL of each discharge interval to total SSL (%)
Q (m3 s-1)
(a)
Stage I
(b)
Stage II
(c)
Stage III
(d)
Stage IV
(e)
Stage V
(f)
Stage VI
Qeff
Qb

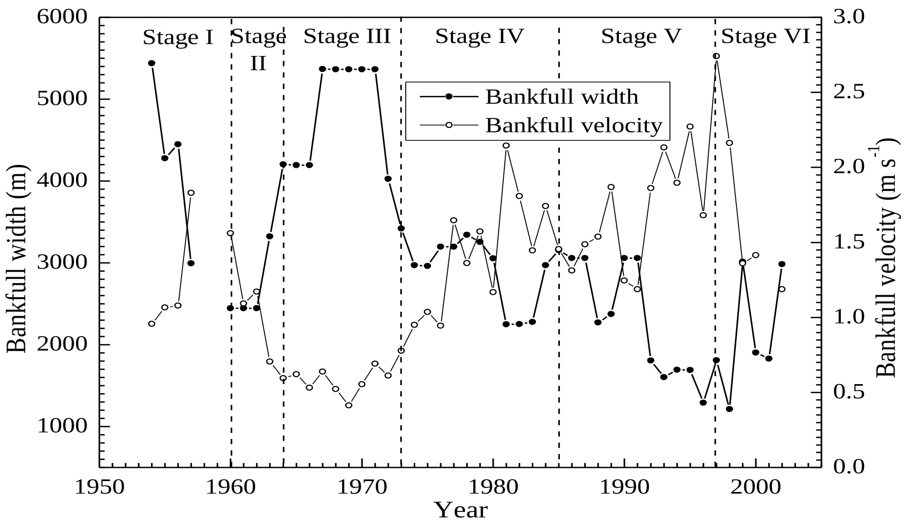
Figure 3


Stage I
Stage II
Stage III
Stage IV
Stage V
Stage VI
Bankfull discharge (m3 s-1)
Year

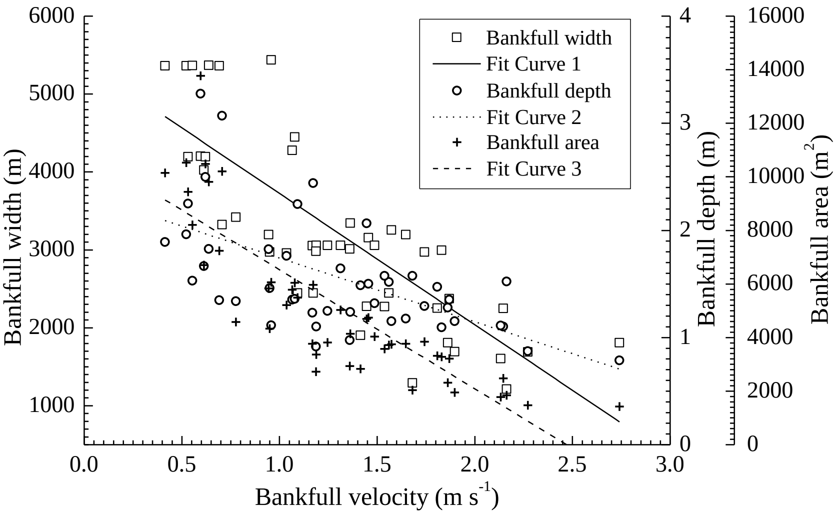
(a)


Stage I
Stage II
Stage III
Stage IV
Stage V
Stage VI
Bankfull depth
Bankfull area
Bankfull depth (m)
Bankfull area (m2)
Year

(b)


Stage I
Stage II
Stage III
Stage IV
Stage V
Stage VI
Bankfull width
Bankfull velocity
Bankfull width (m)
Bankfull velocity (m s-1)
Year

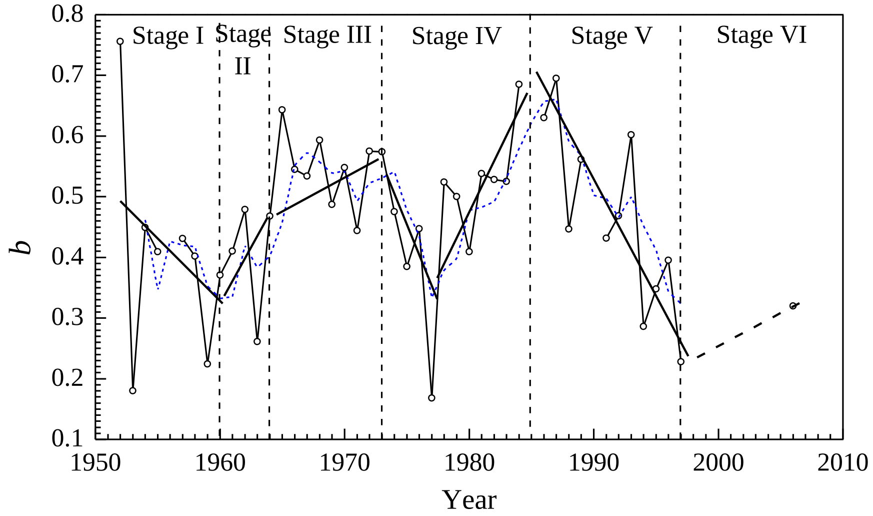
(c)



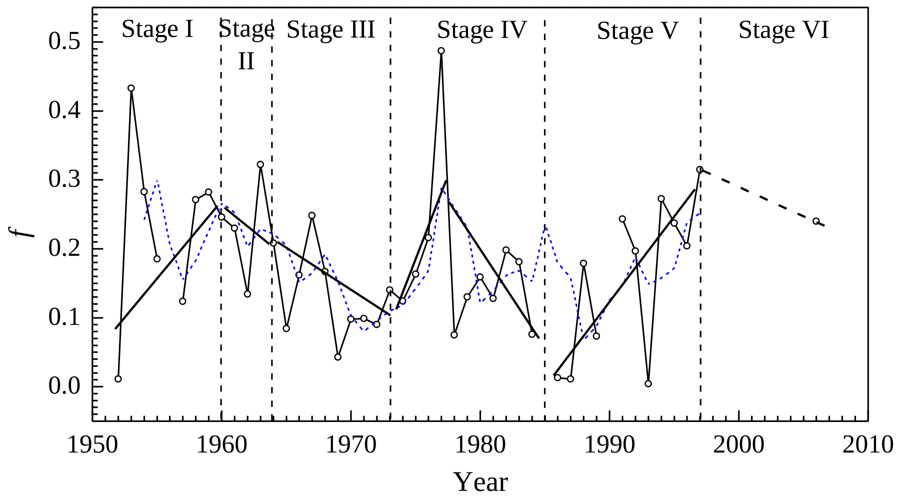
6000
5000
4000
3000
2000
1000
Bankfull width (m)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Bankfull velocity (m s-1)
4
3
2
1
0
Bankfull depth (m)
16000
14000
12000
10000
8000
6000
4000
2000
0
Bankfull area (m2)
Bankfull width
Fit Curve 1
Bankfull depth
Fit Curve 2
Bankfull area
Fit Curve 3

(d)

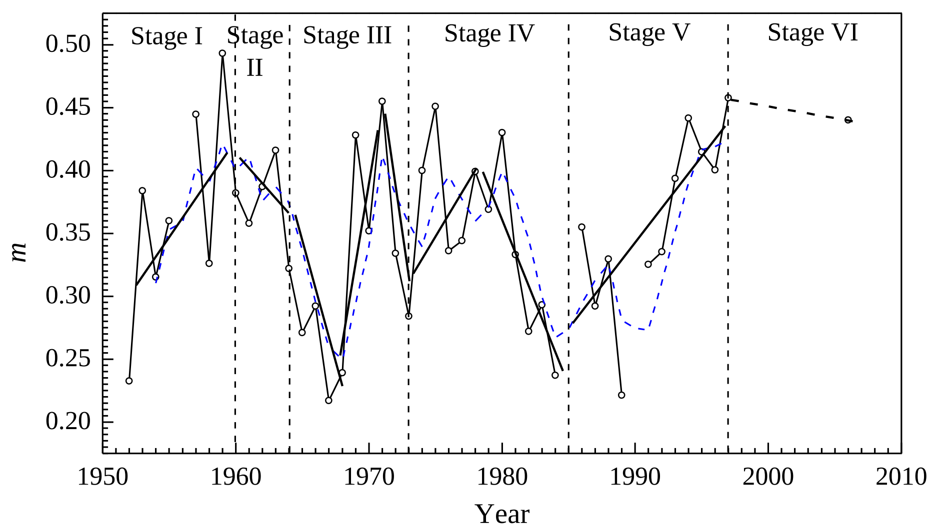
Figure 4


Stage I
Stage II
Stage III
Stage IV
Stage V
Stage VI
b
Year

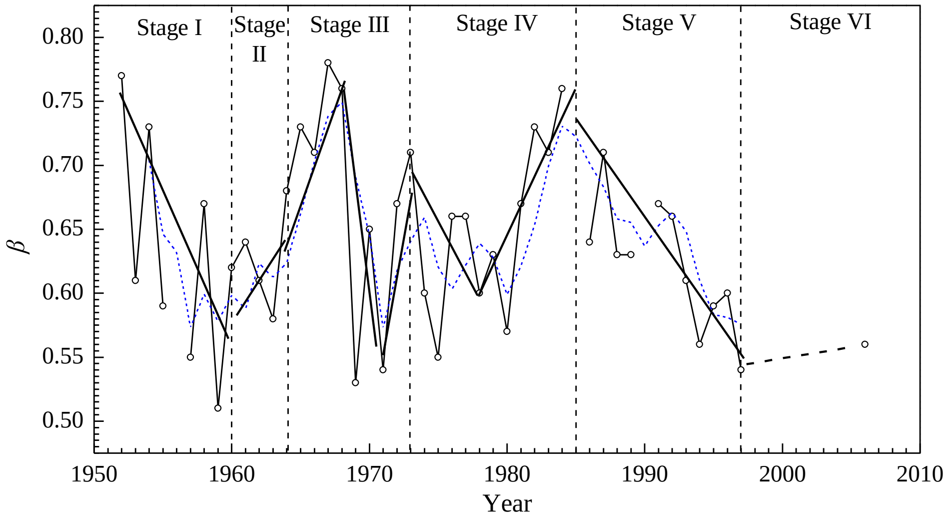
(a)


Stage I
Stage II
Stage III
Stage IV
Stage V
Stage VI
f
Year

(b)


Stage I
Stage II
Stage III
Stage IV
Stage V
Stage VI
m
Year

(c)



Stage I
Stage II
Stage III
Stage IV
Stage V
Stage VI
0.80
0.75
0.70
0.65
0.60
0.55
0.50
β
1950
1960
1970
1980
1990
2000
2010
Year

(d)

Figure 5

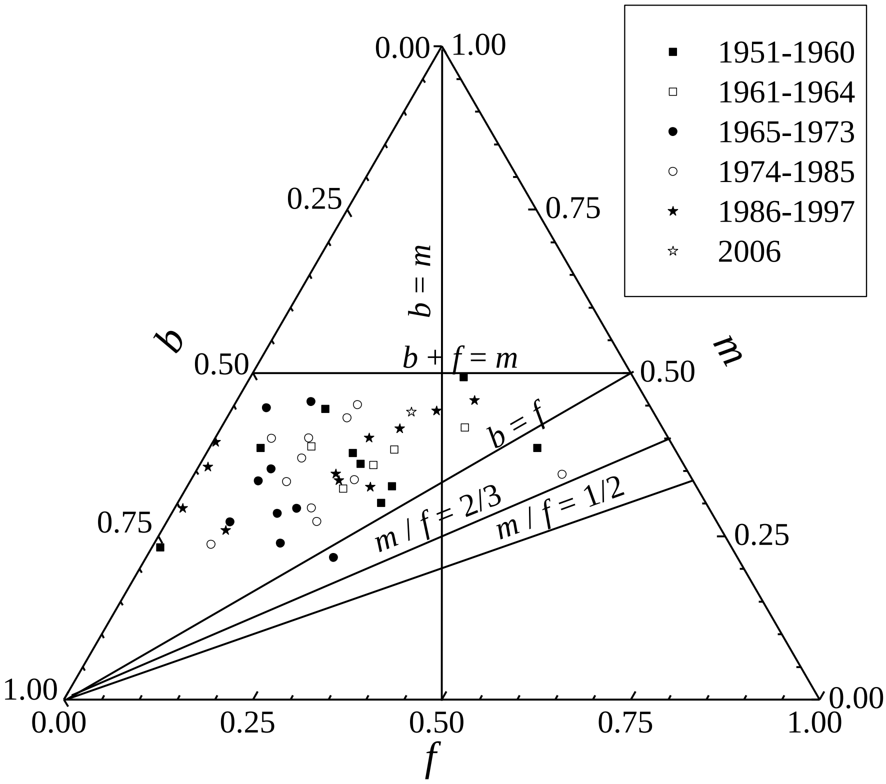

1951-1960
1961-1964
1965-1973
1974-1985
1986-1997
2006
b = m
b + f = m
b = f
m / f = 2/3
m / f = 1/2
b
m
f
0.00
0.25
0.50
0.75
1.00

Figure 6

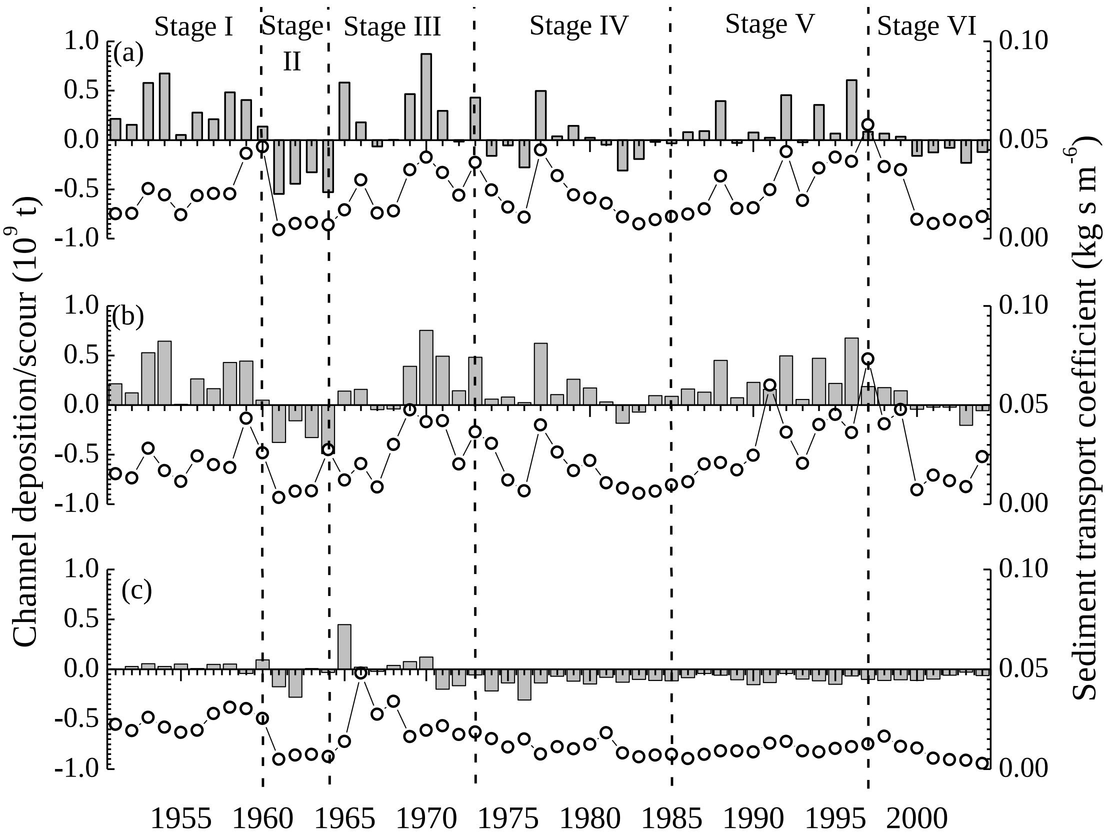

Stage I
Stage II
Stage III
Stage IV
Stage V
Stage VI
(a)
(b)
(c)
1.0
0.5
0.0
-0.5
-1.0
0.10
0.05
0.00
Channel deposition/scour (10^9 t)
Sediment transport coefficient (kg s m^-6)
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000

Figure 7

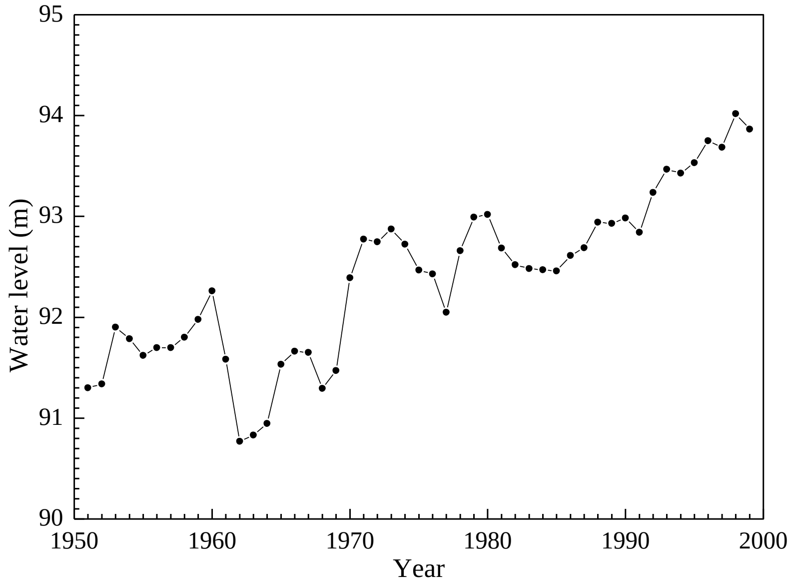
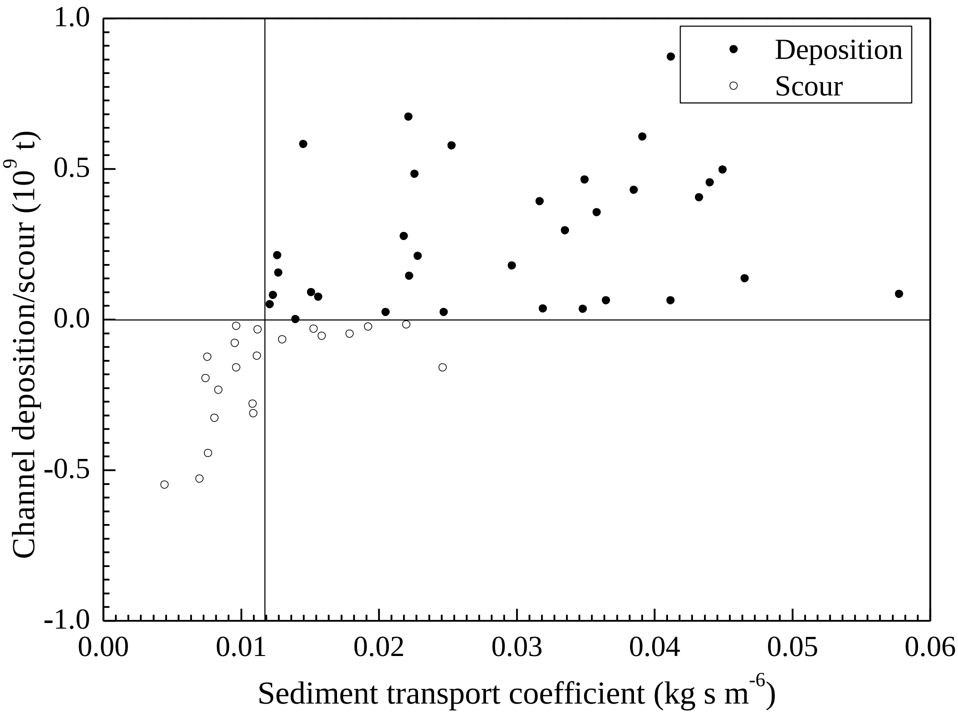
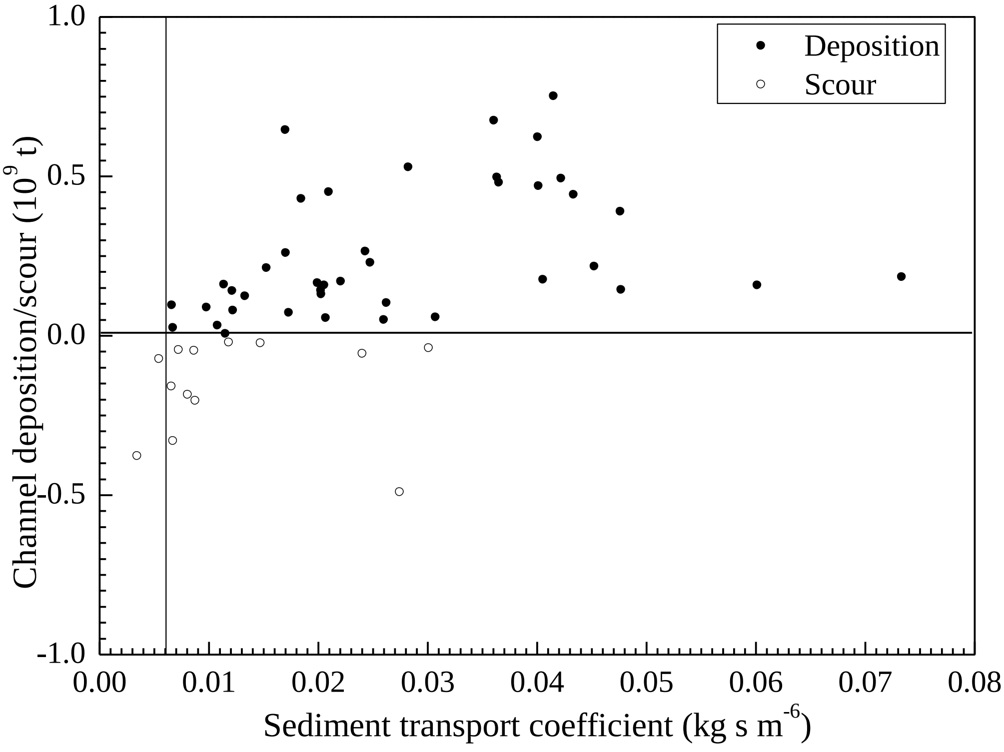

95
94
93
92
91
90
Water level (m)
1950
1960
1970
1980
1990
2000
Year

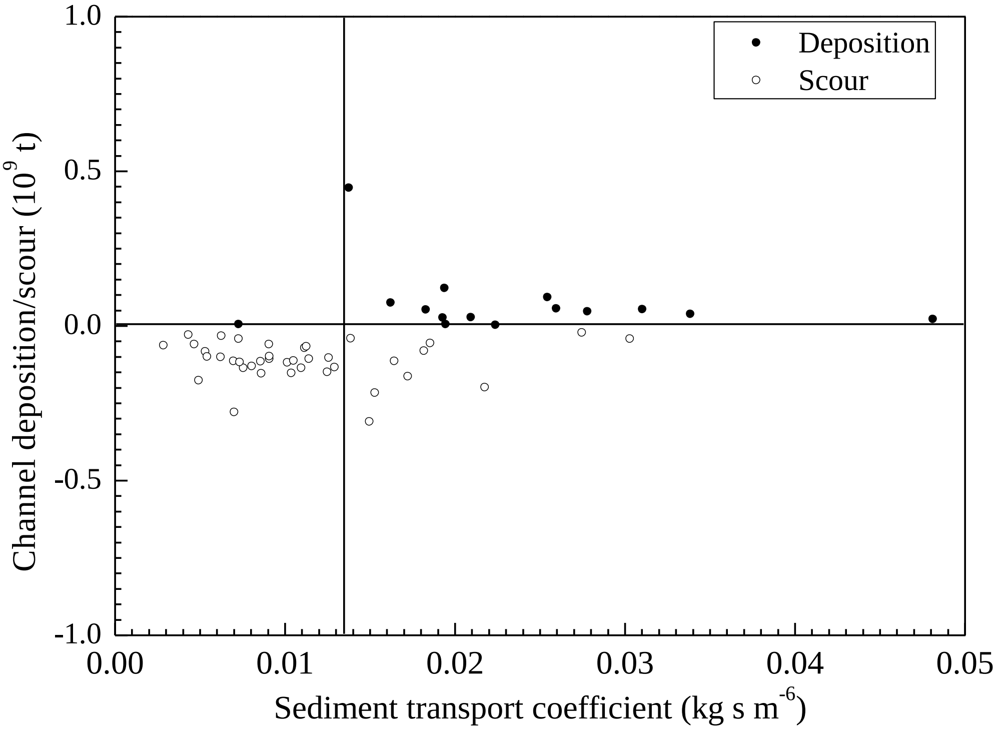
Figure 8


Deposition
Scour
Channel deposition/scour (10^9 t)
Sediment transport coefficient (kg s m^-6)
1.0
0.5
0.0
-0.5
-1.0
0.00
0.01
0.02
0.03
0.04
0.05
0.06

(a)

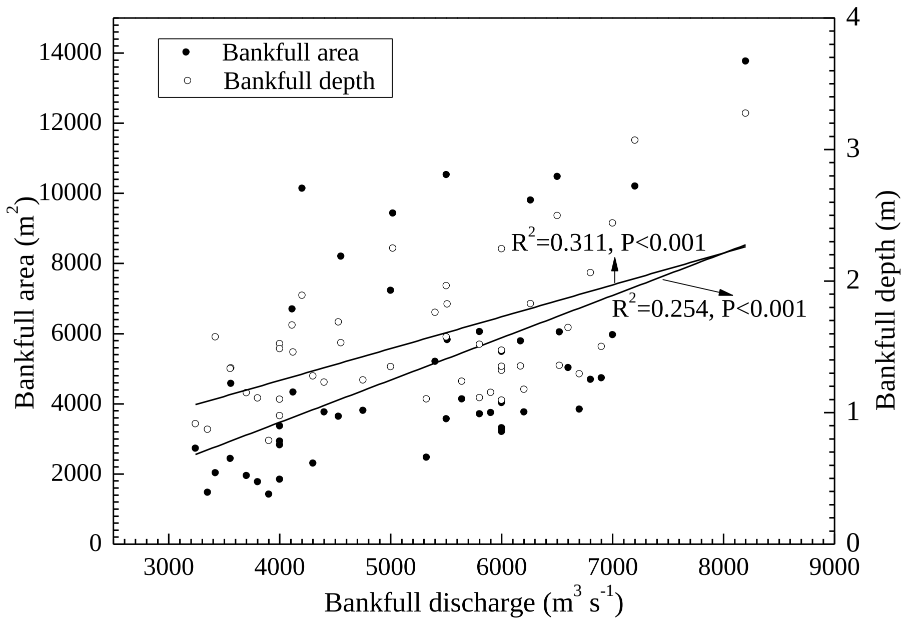

Deposition
Scour
Channel deposition/scour (10^9 t)
Sediment transport coefficient (kg s m^-6)
1.0
0.5
0.0
-0.5
-1.0
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08

(b)


Deposition
Scour
1.0
0.5
0.0
-0.5
-1.0
Channel deposition/scour (10^9 t)
0.00
0.01
0.02
0.03
0.04
0.05
Sediment transport coefficient (kg s m^{-6})

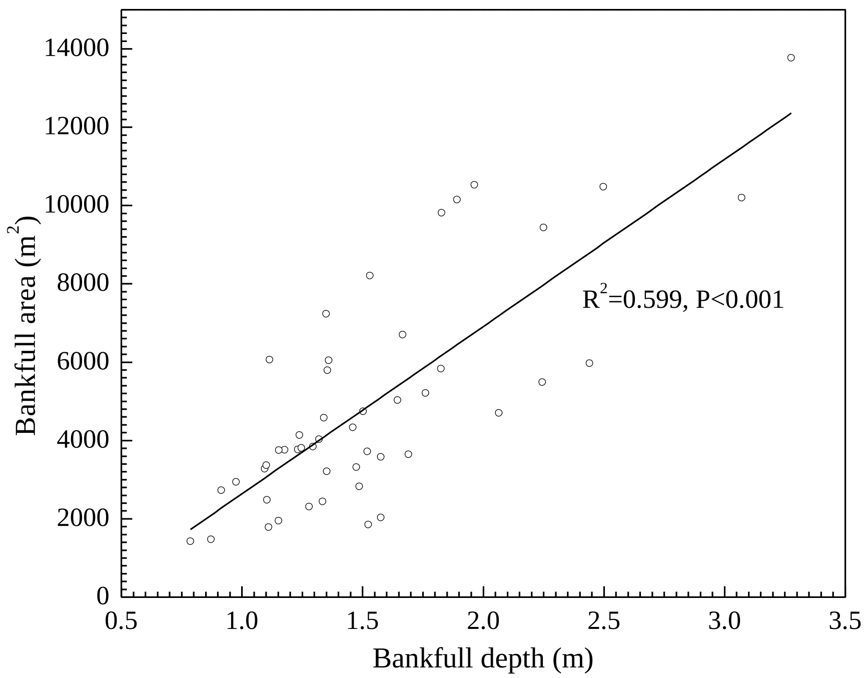
(c)

Figure 9



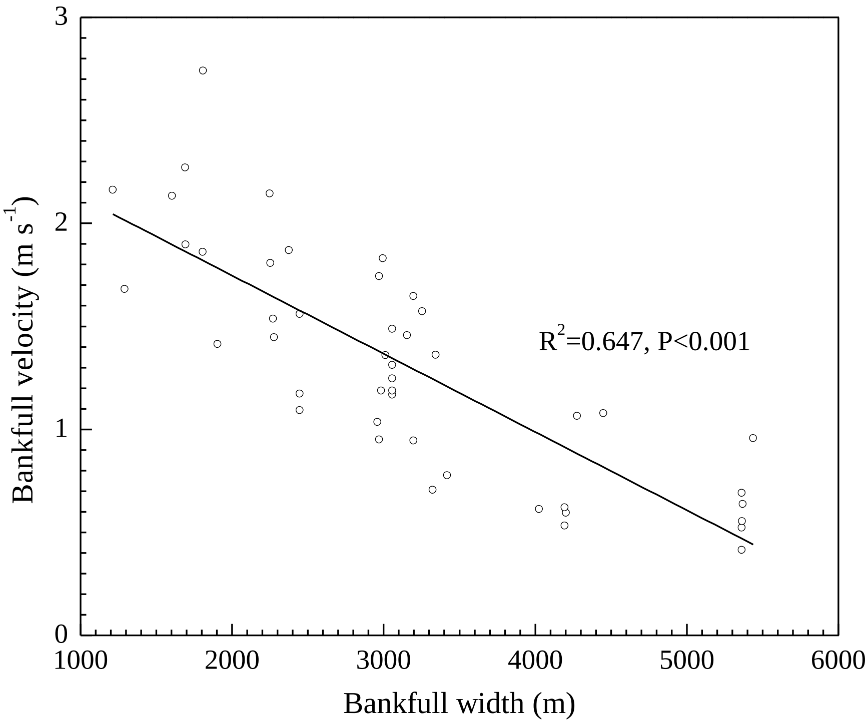
Bankfull area
Bankfull depth
R^2=0.311, P<0.001
R^2=0.254, P<0.001
Bankfull area (m^2)
Bankfull depth (m)
Bankfull discharge (m^3 s^{-1})

(a)

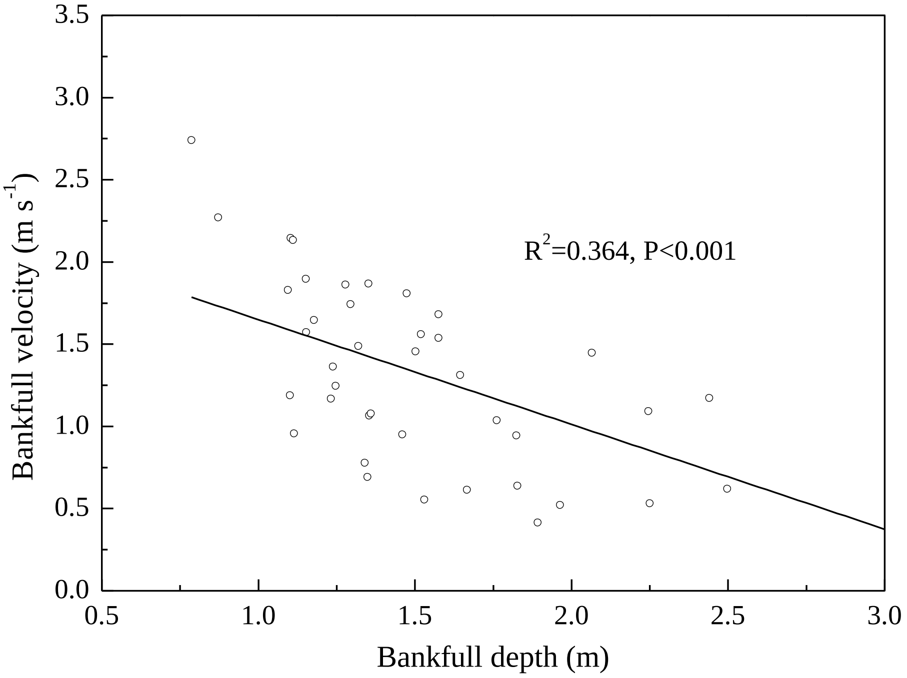


R^2=0.599, P<0.001
Bankfull area (m^2)
Bankfull depth (m)

(b)

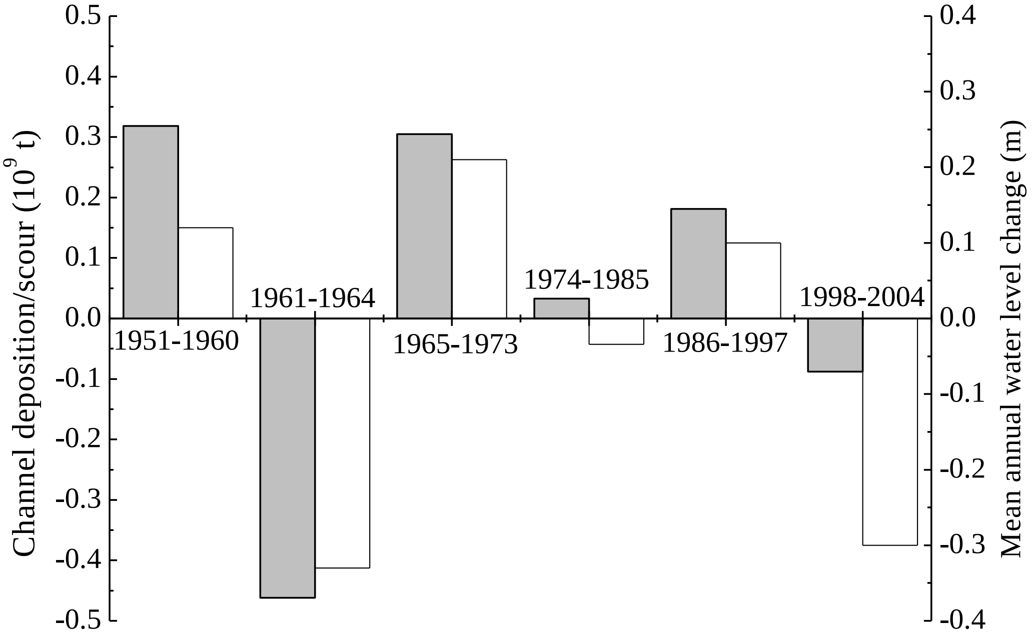

Bankfull velocity (m s-1)
Bankfull width (m)
R2=0.647, P<0.001
0
1
2
3
1000
2000
3000
4000
5000
6000

(c)


Bankfull velocity (m s-1)
Bankfull depth (m)
R2=0.364, P<0.001
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0.5
1.0
1.5
2.0
2.5
3.0

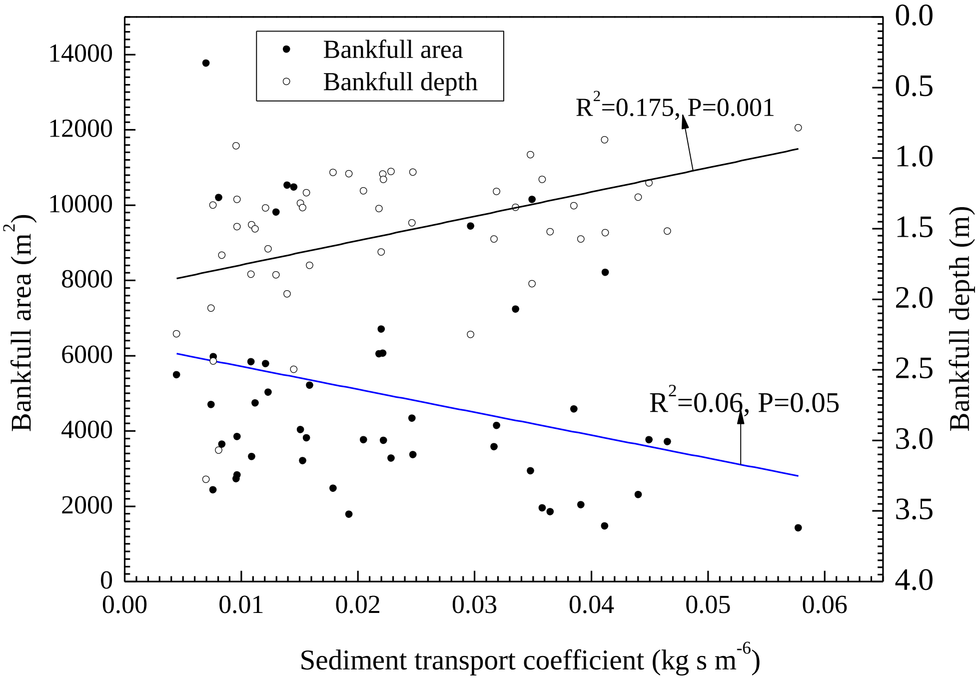
(d)

Figure 10

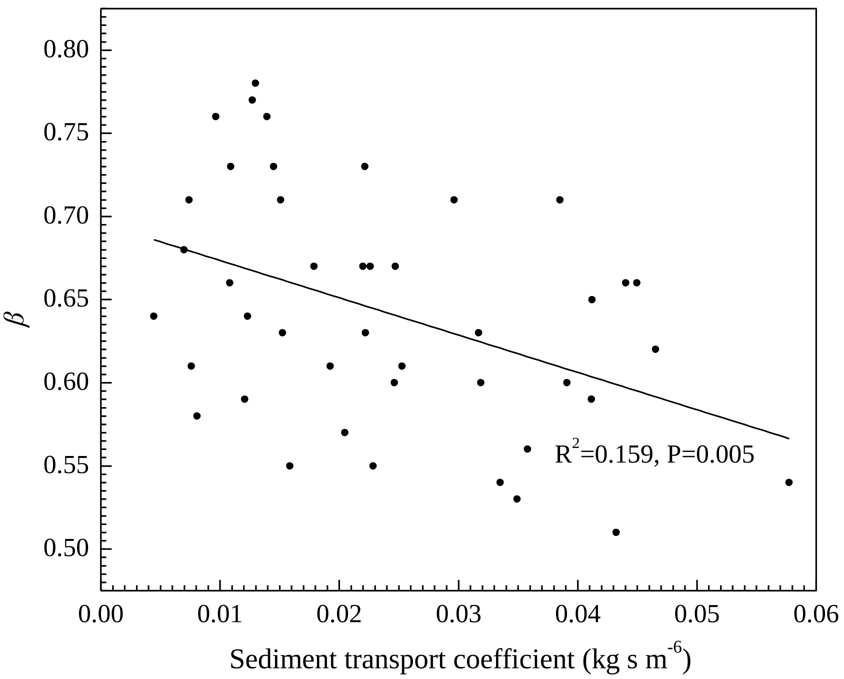


0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
Channel deposition/scour (10^9 t)
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
Mean annual water level change (m)
1951-1960
1961-1964
1965-1973
1974-1985
1986-1997
1998-2004

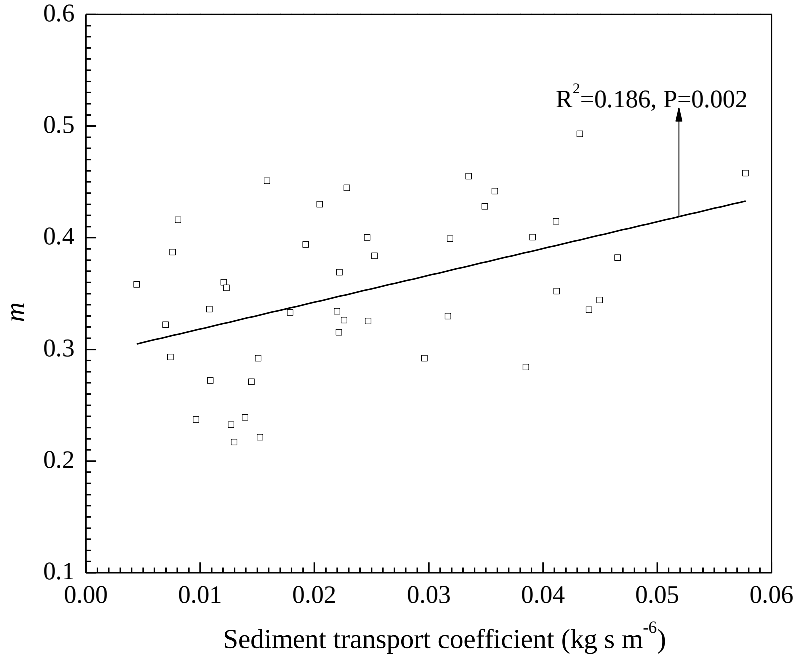
Figure 11


Bankfull area
Bankfull depth
R^2=0.175, P=0.001
R^2=0.06, P=0.05
Bankfull area (m^2)
Bankfull depth (m)
Sediment transport coefficient (kg s m^{-6})

(a)


R^2=0.159, P=0.005
β
Sediment transport coefficient (kg s m^{-6})

(b)


R2=0.186, P=0.002
0.6
0.5
0.4
0.3
0.2
0.1
m
0.00
0.01
0.02
0.03
0.04
0.05
0.06
Sediment transport coefficient (kg s m-6)

(c)

Figure 12

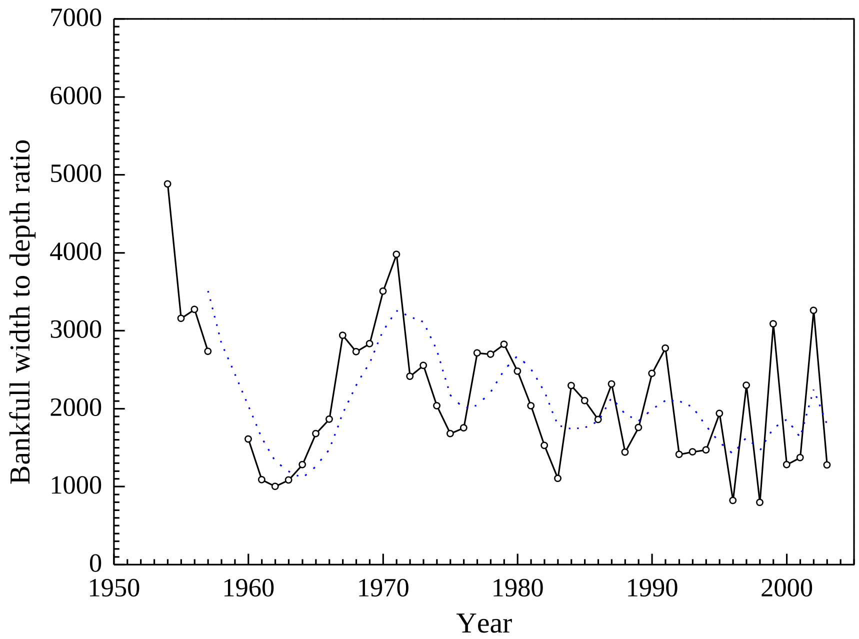
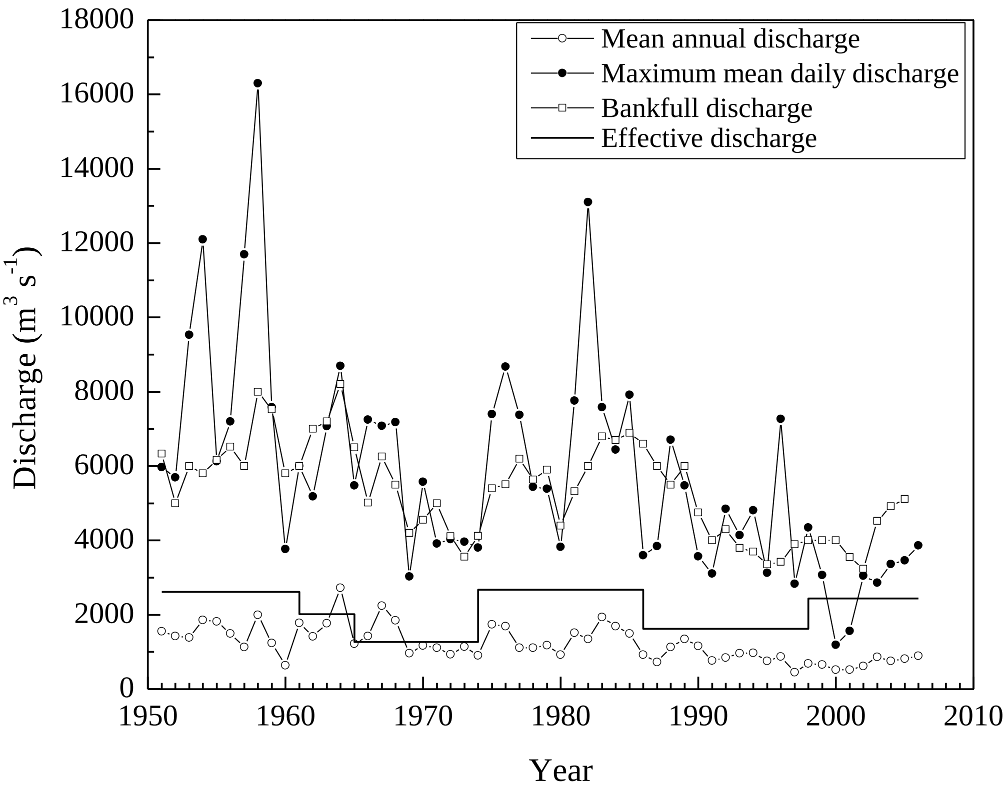

7000
6000
5000
4000
3000
2000
1000
0
1950
1960
1970
1980
1990
2000
Bankfull width to depth ratio
Year

Figure 13



Mean annual discharge
Maximum mean daily discharge
Bankfull discharge
Effective discharge
Discharge (m^3 s^{-1})
Year
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
1950
1960
1970
1980
1990
2000
2010

Figure 14