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Article in Global and Planetary Change · November 2010
DOI: 10.1016/j.gloplacha.2010.09.006

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50,000 dams later: Erosion of the Yangtze River and its delta

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A R T I C L E   I N F O

Article history:
Received 13 July 2010
Accepted 27 September 2010
Available online 27 October 2010

Keywords:
Yangtze Delta
Three Gorges Dam
sediment load
delta erosion

A B S T R A C T

Using 50 years of hydrologic and bathymetric data, we show that construction of ~50,000 dams throughout the Yangtze River watershed, particularly the 2003 closing of the Three Gorges Dam (TGD), has resulted in downstream channel erosion and coarsening of bottom sediment, and erosion of the Yangtze's subaqueous delta. The downstream channel from TGD reverted from an accretion rate of ~90 Mt (1 Mt = 1000 000 t)/yr between the mid-1950s and mid-1980s to an erosion rate of ~60 Mt/yr after closing of the TGD. The delta front has devolved from ~125 Mm3 (1 Mm3 = 1000 000 m3)/yr of sediment accumulation in the 1960s and 1970s, when river sediment load exceeded 450 Mt/yr, to perhaps 100 Mm3/yr of erosion in recent years. As of 2007 erosion seemed to have been primarily centered at 5–8 m water depths; shallower areas remained relatively stable, perhaps in part due to sediment input from eroding deltaic islands. In the coming decades the Yangtze's sediment load will probably continue to decrease, and its middle-lower river channel and delta will continue to erode as new dams are built, and the South-to-North Water Diversion is begun.

1. Introduction

Over the past several millennia, accelerating human land use led to increased terrestrial erosion and a corresponding increased sediment discharge to the coastal ocean (Milliman et al., 1987; Svendsen et al., 2005), but over the past century river damming and irrigation, as well as improved land use practices, have decreased sediment loads of many rivers, thereby triggering erosion of many deltas (Milliman, 1997; Svendsen et al., 2009), including those of the Nile (Fanos, 1995), Colorado (Carriquiry et al., 2001), Mississippi (Blum and Roberts, 2009), Ebro (Sanchez–Arcilla et al., 1998), Godavari and Krishna (Rao et al., 2010), and Yellow (Chu et al., 2006; Wang et al., 2007; Xu, 2008) rivers. Inadequate monitoring of these and other rivers, unfortunately, has often limited the extent to which changes in discharge and their impacts could be identified, let alone adequately quantified.

Unlike many other major rivers, the Yangtze River, the subject of this paper, has been intensively monitored for water and sediment discharges since the mid 1950s, and, since 1987, for suspended sediment particle size. In addition, a series of detailed bathymetric soundings between 1958 and 2007 allows us to delineate bathymetrically and volumetric changes to the Yangtze’s delta front, a topic that has been inadequately addressed previously. Collectively, this extensive database makes it possible to quantify changes in Yangtze and its subaqueous delta in greater detail than would be possible for most other impacted rivers.

As the largest (1,800,000 km2) and longest (6300 km) river in southern Asia (Fig. 1A), the Yangtze ranks 5th globally in terms of water discharge (900 km3/yr) and, until recently, 4th in terms of sediment load (470 Mt/yr) (e.g., Milliman and Farnsworth, 2010). Due to its large sediment supply, since the mid-Holocene the Yangtze delta has prograded more than 200 km into its incised river valley (Hori et al., 2001; Li et al., 2002). Vertical Holocene accretion in the river’s present-day subaqueous delta has locally exceeded 60 m (Hori et al., 2002; Li et al., 2002; Liu et al., 2007). With a watershed population approaching one half billion people, the Yangtze is also one of the most heavily impacted rivers in the world. To store water and to minimize flooding, furnish hydroelectric power, and facilitate irrigation, more than 50,000 dams, ranging in size from dams on farmers’ fields to dams more than 100 m high, have been built throughout the Yangtze’s watershed since 1950 (Yang et al., 2005). As of 2000, the Yangtze had 15 dams taller than 100 m in height, and another 20 or more scheduled to be constructed by 2015. Of particular interest has been the extent to which the world’s presently largest dam, the Three Gorges Dam (TGD), 185 m high, which was closed in 2003, would impact the river and its delta (e.g., Li et al., 2004; Yang et al., 2005, 2007a; Xu et al., 2007; Chen et al., 2008).

Thirty-five years after the accelerated dam construction and more than five years after the commissioning of the TGD, it is perhaps now time to reflect on some of the impacts that these activities have had on the Yangtze and its delta. Any number of previous studies have focused on various water and sediment aspects of the Yangtze impact (e.g. Chen et al., 2005, 2008; Dai et al., 2008; Hu et al., 2009; Xu and Milliman, 2009; Xu et al., 2010a; Yang et al., 2001, 2002, 2005, 2006; Zhang and Wen, 2004; Zhang et al., 2006), but to the best of our
knowledge, no previous work has shown the collective impact both on the middle and lower courses of the river as well as the impact on the Yangtze’s subaqueous delta, the objective of the present study.

2. Materials and methods

For this study we gathered monthly and annual water and suspended sediment discharges between the years 1953 and 2008 at the Yichang, Hankou and Datong gauging stations (Fig. 1) maintained by the Yangtze Water Conservancy Committee, Ministry of Water Conservancy of China. We also utilized the mean grain size data of suspended sediments at the Yichang and Hankou stations as well as the bottom sediment texture between Yichang and Hankou.

To calculate temporal and spatial changes in the Yangtze subaqueous delta, we used bathymetric maps at a scale of 1:75,000 obtained by the Maritime Survey Bureau of Shanghai, Ministry of Communications of China. 2000, 2004 and 2007 data were collected using a DESO-17 echo-sounder, precision 0.1 m; navigation was obtained using a GPS (Trimble Co., USA) with a horizontal error of ±1 m 1958 and 1977 echo-sounder data had vertical precisions of ~0.1 m; navigation error was ~30 m in 1958 (using a sextant) and ~20 m in 1977 (using Loran S). Bathymetric soundings for the five surveys totaled 1350 (1958), 1580 (1977), 2220 (2000), 1570 (2004) and 2590 (2007) km in length. All surveys were carried out between early May and early June, prior to peak discharge. Tidal corrections used recorded tidal levels in and near the study area. Maps were processed using ArcGIS software developed by ESRI (Environmental Systems Research Institute, USA).

Each set of depth soundings was interpolated to a grid with 30 x 30-m cells using Kriging interpolation technique. Digitized maps were used to calculate the vertical accretion/erosion rates and for delineating accretion/erosion areas. At each grid, deduction of the later depth from the earlier depth gave the thickness of accretion (positive) or erosion (negative). The total volumes of accretion and erosion and the difference between them were then calculated. The rate of annual accretion or erosion rate could then be calculated with the net volume divided by area and time length (years).

The Kriging interpolation technique is widely used in GIS analysis. The error associated with the value of sediment volume based on bathymetry and the Kriging interpolation technique rests with the difference in depth between the neighboring bathymetric data points and the complexity of the seabed morphology. The greater the difference in depth between the data points and the more complicated

Fig. 1. A) Yangtze River watershed, showing locations of the Three Gorges Dam (TGD) and the Yichang, Hankou and Datong gauging stations. B) Subaqueous delta, showing Study Areas 1 and 2, the Twin-Jetties Groyne Complex (TJ-GC) and its associated dredged channel.
the seabed morphology, the greater the error associated with the calculated sediment volume. If there are numerous data points in a study area, however, the overall error is reduced because of the counter-balancing between positive and negative errors. As a result, error estimation associated with sediment volume using the Kriging interpolation technique is customarily omitted. In the present study, there are numerous data points on each bathymetric map (as addressed above), and the seabed of the subaqueous delta is smooth, with gradients typically <1‰ (see Fig. 1b). So, errors associated with sediment volume estimation using Kriging interpolation is assumed to be very low (<1%, as we estimated).

3. Sedimentary changes along the middle and lower reaches of the Yangtze

Except for several extremely wet or dry years, particularly in 1954, Yangtze water discharge has remained relatively constant since the 1950s (Fig. 2), averaging about 900 km³/yr as measured at Datong, 600 km from the river mouth, just upstream of the tidal influence (Fig. 1A). The sediment discharge past Datong, by contrast, fell from ~490 Mt/yr in the 1950s and 1960s to ~150 Mt/yr after the closure of the TGD (Fig. 2). The decline in sediment discharge in the upper reaches of river, as measured at Yichang, 37 km downstream from the TGD and 1800 km from the river mouth (Fig. 1A), has been even greater, falling from ~530 Mt/yr in the 1950s and 1960s to ~60 Mt/yr after 2003 (Fig. 3A).

Of particular interest has been the evolving sedimentary regime in the middle reaches of the river, as measured at Hankou, ~700 km downstream from Yichang and 500 km upstream from Datong (Fig. 1A). Sediment reaching Hankou should reflect the sediment passing Yichang plus sediment introduced from the Han River and ungauged tributaries (Yang et al., 2007a) as well as sediment exchange with Dongting Lake. Between the mid-1950s and mid-1980s, the total amount of sediment reaching Hankou from these various sources should have totaled ~530 Mt/yr, whereas only ~440 Mt/yr were measured at Hankou. This ~90 Mt/yr sediment “loss” (Fig. 3) suggests deposition along the middle reaches of the river. The slightly higher sediment load at Datong during the same period, 470 Mt/yr, may reflect the sediment import from downstream tributaries (Xu and Milliman, 2009). Between the mid-1980s and late 1990s, sediment deposition in the middle reaches of the river declined to ~60 Mt/yr, in large part the response to upstream damming (Xu et al., 2007), and from 2000 to 2002, total sediment import between Yichang and Hankou and the amount reaching Hankou were essentially equal, suggesting little or no net sediment gain or loss in the middle reaches of the river (Fig. 3A).

For the first six years (2003–2008) following the TGD closure, the sediment discharge past Hankou averaged 125 Mt/yr, 29 Mt/yr more than the one measured at Hankou, suggesting further erosion in the lower reaches of the river. Using the approach by Yang et al. (2007a), the tributaries between Hankou and Datong supplied 18 Mt/yr in 2003–2008. That is, the combined erosion rate between Yichang and Datong was 61 Mt/yr, ~40% of the amount of sediment trapped behind the TGD (Yang et al., 2007a,b); the erosion along the 700 km reach from Yichang to Hankou (0.071 Mt/yr/km) was three times higher than along the 500 km reach from Hankou to Datong (0.024 Mt/yr/km). It is necessary to indicate that here the erosion, based on the sediment budget, reflects only the responses to decline in the sediment supply. Sand extractions in the Yangtze (Chen et al., 2005) and other rivers in China (e.g. the Pearl River, Lu et al., 2007) presumably also have resulted in significant additional erosion.

Erosion along the middle reaches of the river is also suggested by the coarsening of the Yangtze channel sediment, the mean grain size of...
river-bottom samples taken at fixed locations between Yichang and Hankou increasing from 210 μm in 2002 to 300 μm in 2008. The closer the sampling sites to the TGD, the greater the difference in grain size between 2002 and 2004. At Yichang, the grain size increased from 0.36 mm in 2002 to 25 mm in 2008; at Chenglinji, 400 km downstream from Yichang, grain size increased from 0.18 mm in 2002 to 0.19 mm in 2008 (Xu et al., 2010b). Another measure of channel erosion along the middle reaches of the river is seen in the change of the grain size of the suspended sediment. Between 1987 and 2002, the mean grain size of the suspended sediment at Yichang and Hankou averaged 8–10 μm, whereas after 2003 the suspended sediment particle size at Yichang declined to 3 μm in response to the settling of coarser sediments behind the TGD, but increased to 17–19 μm at Hankou (Fig. 4), we assume because of the aforementioned channel erosion.

Decline in sediment load along the Yangtze also affected sedimentation in the linked lakes. A great deal of water and sediment flows from the Yangtze into Lake Dongting via several inlets, although the water and some of the sediment return to the Yangtze via an outlet (Dai et al., 2005). The deposition rate within Lake Dongting decreased from 146 Mt/yr between 1956 and 1980 to 84 Mt/yr between 1981 and 2002 (Yang et al., 2007b). Since the closure of the TGD, the sediment transported from the Yangtze into Lake Dongting has been drastically reduced, and the deposition rate within Lake Dongting has decreased to <10 Mt/yr, in some years (2006 and 2008) showing a net erosion of 2 and 1 Mt/yr, based on our calculated sediment budget. Although there is only one channel linking the Yangtze with Lake Poyang, the decline in the Yangtze’s sediment load might have eroded at a rate of 7 Mt/yr in 2003 (Yang et al., 2007) and transported southward to form an extensive nearshore mud wedge extending into Taiwan Strait (Liu et al., 2007). Isotopic data from several cores suggest that sediment accumulation in the subaqueous delta in the 1950s–1980s averaged in the range of 3–5 cm/yr (DeMaster et al., 1985; Zhang et al., 2008).

Between 1958 and 1977, when the Yangtze river (as measured at Datong) discharged an average of 470 Mt/yr of suspended sediment, bathymetric data indicate that the 5-m contour east of Hengsha Island prograded as much as 5 km (Fig. 6). The 10-m isobath prograded overall more than 12 km although retreating ~2 km in the north. The 20-m contour, by contrast, showed little overall change (Fig. 6). During this 19-year period, 55% of the area shoaled by >5 cm/yr, whereas 8% deepened by more than 5 cm/yr, mostly off the North Channel and the North Passage of the South Channel (Fig. 7A). Average shoaling within the study area was 6.8 cm/yr.

Between 1977 and 2000, most of the Yangtze subaqueous delta continued to prograde, but, presumably because of declining sediment discharge (Fig. 2), shoaling was generally ~5 cm/yr. Although some of the north-central delta and areas off Jiuduansha shoaled by as much as 15 cm/yr, there was little net change to the south (Fig. 7A). Calculated net shoaling for the entire study area was 3.2 cm/yr.

Between the 2000 and 2004 bathymetric surveys, Yangtze sediment discharge at Datong fell from 340 (2000) to 205 Mt/yr (2003) (Fig. 2). The ~5-m contour east of Hengsha Island continued to prograde — locally as much as 2 km — but showed little change in position east of Hengsha or Jiuduansha islands. The 10-m contour, by contrast, retreated 0.5–1.5 km throughout much of the study area, particularly east of Hengsha (Fig. 6). Overall, between 2000 and 2004, 70% of the study area experienced erosion; the average vertical erosion rate for the study area was ~3.8 cm/yr. The difference in vertical erosion between Areas 1 and 2 is noteworthy: ~0.7 vs. ~11 cm/yr, much of Area 2 deepening by as much as 25 cm/yr (Fig. 7A).

Between 2004 and 2007, after the closing of the TGD, the 5-m contour off both Hengsha and Chongming islands continued to prograde, locally by as much as 1–2 km (Fig. 6), perhaps in response to erosion from the eastern ends of the islands (see above). The 10-m isobath, in contrast, retreated on average ~1 km, and locally by nearly 2 km. Erosion seems to have been concentrated between 5 and 8 m depths, this depth range decreasing in Area 1 by 30% (~150 km²) (Fig. 6); the 8–11 m depth interval, by contrast, increased by 120 km². Depths greater than 11 m showed no significant change in total area (Fig. 8), which in part may reflect dumping of the dredge spoil removed from the TJ-GC channel. Calculated net erosion rate for Area 1 was ~4.5 cm/yr.

Interestingly, since 1958 bathymetric changes within the study area have shown a strikingly linear correlation with the Yangtze’s

4. Morphologic changes in Yangtze Delta

It is still not clear how islands at the seaward edge of the Yangtze estuary have responded to change in river flow, in part because the islands’ shorelines are reinforced by jetties and revetments. A comparison of transects taken in 1982 and 1990 show a 2-km progradation of eastern Chongming Island. By contrast, between 2006 and 2010, salt marsh progradation was only ca.100 m and the mudflats vertically eroded as much as 30 cm (Fig. 5).

To delineate temporal trends in the Yangtze subaqueous delta bathymetry and morphology, we compared bathymetric data from 1958, 1977, 2000, 2004 and 2007 within an 1825-km² area in the river’s South Branch through which more than 98% of the Yangtze water and sediment are discharged (Chen et al., 1985). Bathymetric extensions of Chongming, Hengsha and Jiuduansha define the western limits of the study area; 15 to 20-m depth contours define the eastern limits. Most of the study area, which we term Area 1 (1280 km², Fig. 1B), was surveyed all five years; Area 2 (545 km²), directly off the North Channel of the Yangtze’s South Branch, was not surveyed in 2007. Calculating bathymetric changes based on the less accurate 1958 and 1977 navigation was partly compensated for by the longer time intervals between subsequent surveys (19 and 23 years, respectively). Delineating bathymetric change was somewhat complicated in 1997 by construction of the Twin Jetty-Groyne Complex (TJ-GC; 103 km² within Area 1) in the North Passage of the South Channel, to facilitate navigation (Du and Yang, 2007). By 2004 the TJ-GC extended into the southwestern portion of the study area (Fig. 1B). In conjunction with the TJ-GC, a 350-m-wide channel (8.5 km² in area) has been dredged regularly to 10 m below lowest tide level, most of the spoil being dumped beyond the 10-m depth contour. Historically most of the Yangtze’s annual sediment load was deposited on the subaqueous delta during flood season, much of it eroded during winter storms (DeMaster et al., 1985; Milliman et al., 1985) and transported southward to form an extensive nearshore mud wedge extending into Taiwan Strait (Liu et al., 2007). Isotopic data from several cores suggest that sediment accumulation in the subaqueous delta in the 1950s–1980s averaged in the range of 3–5 cm/yr (DeMaster et al., 1985; Zhang et al., 2008).

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Interestingly, since 1958 bathymetric changes within the study area have shown a strikingly linear correlation with the Yangtze’s
sediment load as measured at Datong (Figs. 7B, 9). Between 1958 and 1977, when the average annual suspended sediment discharge was 470 Mt, the subaqueous delta shoaled by ~125 Mm³/yr. In contrast, between 2000 and 2004 an average discharge of 245 Mt/yr resulted in 70 Mm³/yr of delta front erosion (Fig. 7B). These data and trends suggest that the Yangtze delta will continue to erode as long as the river annually discharges less than ~270 Mt/yr of sediment (See Fig. 9). In 2007 and 2008, sediment discharge past Datong averaged only 130–140 Mt/yr; extrapolating the linear trends shown in Fig. 9 suggests that erosion in the subaqueous delta may have already surpassed 100 Mm³/yr. Whether the erosion continues to be confined primarily to 5–8 m depths remains to be seen.

5. Conclusions

The sediment discharge of the Yangtze River, as measured at Datong, fell from 490 Mt/yr in the 1950s and 1960s to ~150 Mt/yr after the closure of the TGD. In contrast, water discharge remained relatively stable, indicating that the decline in sediment load stemmed primarily from trapping behind the watershed’s 50,000 dams, in particular the TGD. In response to this drastic decrease in sediment supply, the river channel downstream from the TGD has changed from one of net accretion to one of net erosion. Since 2003, the middle stretches of the river have experienced on average ~50 Mt/yr of erosion, compared with a deposition rate of ~90 Mt/yr between the...
mid-1950s and mid-1980s. River channel erosion, which also is
reflected by the coarsening of bottom sediments, has only com-
pen-sated for about 20% of the river’s decreased sediment discharge. As a
result, the estuary has experience sediment starvation, and a
responding decrease in coastal salt marsh accretion and net
erosion in subaqueous delta front. The erosion seems to have occurred
primarily between 5 and 8 m below the lowest tide. The conversion
from delta front accretion to erosion seems to have occurred when
river’s sediment load fell below 270 Mt/yr. Because of the TGD
operation and the construction of new large dams and the South-to-
North Water Diversion in the watershed, the sediment load of the
Yangtze River most likely will continue to decline and thus the erosion
along the main river channel of the middle and lower reaches and in
the delta front will continue in the coming decades.

Acknowledgements

We are grateful to the Editor and reviewers who provided valuable
comments and suggestions. The study was supported by the Ministry
of Science and Technology of China (2010CB951202, 2008DBF090240), the Natural Science Foundation of China (40721004), and the State Key Laboratory of Estuarine and Coastal Research of China (SKLEC-2008KYYW01, SKLEC-2009KYYW02). JDM was funded partly by the U.S. National Science Foundation.

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