Effects of high river discharge on decadal morphological evolution of the inner Yangtze Estuary

Hualong Luan*, Tonghuan Liu, Shiming Yao, Jinyou Lu
Changjiang River Scientific Research Institute, Wuhan, Hubei, 430010, China
*Corresponding author’s e-mail: luanhualong@126.com

Abstract. Morphological evolution of estuaries and deltas at the decadal timescale is becoming a global issue in recent decades due to their economic and environmental significances. Present study explores the decadal morphological evolution under high river discharge and decreasing river sediment. Quantitative analysis of bathymetric data indicates that frequent river floods in the 1990s enhanced erosion of the inner estuary superimposed with river sediment decline. A process-based modeling approach (Delft3D) is applied to investigate the physical mechanisms of river flooding on morphological change. Hydrodynamic simulations indicate that the water level gradient and residual transport in the inner estuary increase with river discharge. High water level gradient occurs simultaneously with peak ebb flow, and this status can last for about 5-6 hours. This hydrodynamic condition with sufficient long period facilitates channel erosion and sandbar incision. Morphological simulations indicate that erosion along the main channels is enhanced under higher river discharge, especially in the upstream part. The enhanced erosion can be offset by the increase in sediment load. River flooding superimposed with further decreased sediment supply in the future may induce more significant modifications of channel-shoal systems within the inner Yangtze Estuary than the present.

1. Introduction
Estuaries and deltas are the sinks of riverine water, sediment and nutrients, and the sources of river plume and continental sedimentation[1]. These productive regions with large expanses of wetlands hold high biodiversity, and they are habitats of many species of nekton and wildlife[2-3]. Large river deltas around the world are also densely populated, where many megacities locate[4]. Thus, estuarine and deltas are of significant social-economic and ecological values[5]. Due to the interaction of river and marine forcing, estuaries and deltas show dynamic and complex deposition patterns. Knowledge on estuarine morphodynamics enables integrated management and utilization of estuarine functions, particularly on the decadal timescale[6].

Controlling factors of medium/long term morphological evolution of estuaries have been extensively revealed, including river flow, tide, wave and their interactions and sediment properties[6-7]. Mean conditions of driving forcing often produce gradual and cumulative morphological changes at a long-term (decades to century), while extreme conditions can induce significant bed level change in a short period (days to months). As one of the most typical extreme conditions in river systems, river flood events plays an importance role in driving fluvial and estuarine morphodynamic evolution[8]. Large sediment flux accompanied with high river discharge often results in rapid shoal incision or accretion, which can be recorded by estuarine depositional facies[9]. A comprehensive study by Cooper (2002) revealed that tidal-dominant estuaries exhibit preferential erosion at sandy barriers and tidal deltas during river floods, while river-dominant estuaries experience consistent
erosion along channels during extreme floods[10]. Moreover, tidal-dominant systems can restore to pre-flood morphology in a shorter period than river-dominant systems. Guo et al. (2015) applied a 1D idealized numerical model and concluded that estuarine morphodynamic equilibrium can be reached under seasonal river discharge variations[11]. Boudet et al. (2016) simulated sediment transport in the mouth of the Rhone delta and model results indicated that a sufficiently high river flood discharge can break through wave-induced longshore transport and deliver sediment across the mouth towards the outer sea[12]. These studies have highlighted the significance of river flood on morphological change of estuarine systems under different physical conditions. However, their influencing mechanisms on decadal morphological evolution of estuaries under combined river and tidal forcing are still less understood, particularly overlapping with diminishing river sediment supply.

The large-scale Yangtze Estuary receives a huge amount of river inputs with strong seasonal variation and thereby provides a nice example to explore the morphological effects of high river discharge during river flooding (Fig. 1). Plenty of previous studies focused on the effects of river sediment decline[13-15], whereas systematic studies on river flooding are rare. Analysis on historical evolution indicated that high river discharge is regarded as an important driving forcing for the bifurcation pattern formation of the Yangtze Estuary[16]. Researchers have empirically estimated the dominant discharge (or channel-forming discharge) required for significant bed-level changes to be 60,000 m$^3$/s[16]. River sediment load in the recent decade had decreased to only ~30% of the value in the 1950-1960s[17]. Superimposed with decreasing sediment supply, it is necessary to explore the morphological response to high river discharge, which can provide scientific guidance for sustainable estuarine management. Bathymetric data analysis and process-based modeling approach are applied to address this issue. Morphological evolution processes of the inner Yangtze Estuary in 1986-2016 are quantified. A 2D morphological model based on Delft3D model system set up in our previous study is used and validated against observed morphological evolution. Variations of river discharge are considered in the morphological model, which enable the model to be a useful numerical tool. Model results of hydrodynamics and sediment transport in dry and wet seasons are compared and analyzed. Numerical experiments on the river discharge in the wet season are conducted. By analyzing the model results, the effects of high river discharge on decadal morphological evolution of the inner Yangtze Estuary are revealed.

2. Study area

As the mouth of the largest and longest river in southern Asia, the Yangtze Estuary receives huge amount of freshwater and fine sediment from the upstream river basin, i.e., 893 km$^3$ for water discharge and 368 Mt of sediment load during 1950-2015[18], ranking the 5th and 4th around the world, respectively[19]. The large-scale estuary is influenced by meso-tides with the mean tidal range of 2.67 m at the mouth[16]. Waves, primarily induced by local winds, only shape shallow shoals at the delta front, and the effect is minor relative to riverine and tidal forcing. The Yangtze Estuary shows significant spatial variations in terms of hydrodynamic condition, sediment property and morphology due to its large scale and the river-tide interaction. Longitudinally, the prevailing process varies from river flow in the inner estuary to astronomic tides at the subaqueous delta, while these two governing factors conflict at the mouth bar area. The bed sediment also shows a clear coarse–fine-coarse trend from the inner estuary to the outer estuary[20]. The inner Yangtze Estuary is confined meandering channels with sandbars, whereas the mouth bar area consists of wide channels and parallel intertidal flats (Fig. 1b).

This study mainly concentrates on the ebb-dominant inner estuary defined from the bifurcation of North and South Branch to the Hengsha Island (Fig. 1b). Since the water diversion ratio of the North Branch decreased to <5% after the 1950s[16], the North Branch is more controlled by tidal currents than river flooding, and is thereby excluded from the study area. The length of the inner estuary is nearly 90 km, and the channel width increases from ~6.5 km at Xuliujing to ~25 km at Hengsha Island. Within the inner estuary, the South Branch is bifurcated into the North Channel and South Channel by the Changxing Island. Several sandbars formed along the channel, including Baimao Shoal and
Biandan Shoal. Similar channel-shoal systems had been widely found in tidal-influenced estuaries around the world[21]. In recent two decades, local human interventions are increasingly playing an important role on channel evolution. The Qingcaosha Reservoir, for instance, decreased the channel width and resulted in significant morphological change along the North Channel[22].

Figure 1. (a) Map of the Yangtze River Basin; (b) map of the Yangtze Estuary with bathymetry in 2010. Red dashed lines in (b) denote the domain of the inner estuary defined for erosion/accretion calculation (TGD: Three Gorge Dam; CX: Changxing Island; HS: Hengsha Island; XLJ: Xuliujing; JGJ: Jigujiao; QCSR: Qingcaosha Reservoir; EHLR: East Hengsha Land Reclamation; BS: Baimao Shoal; UBS: Upper Biandan Shoal; LBS: Lower Biandan Shoal; XS: Xinliuhe Shoal; RS: Ruifeng Shoal; ECM: East Chongming mudflat; EHS: East Hengsha Shoal; JS: Jiuduansha Shoal; ENM: East Nanhui mudflat).

3. Methods

3.1. Bathymetric data processing
To assess the morphological processes at a decadal timescale, we collected the marine charts in 1986 and observing depth samples in 1997, 2010 and 2016 to form a bathymetry dataset of the inner Yangtze Estuary. The inner Yangtze Estuary as concerned is defined from Xuliujing to Hengsha Island including the South Branch, the upstream part of North Channel and South Channel with the area of 1085 km² (Fig. 1b). An echo sounder and a global positioning system (Trimble Navigation Limited, California, USA) were used for depth measurements and position recordings, respectively, with vertical and horizontal errors of 0.1 m and 1 m. The scales of the maps range from 1:10,000 to 1:130,000, and the averaged data density ranges from 3.5 to 20.4 samples/km², which is sufficiently high for calculation of morphological evolution with acceptable accuracy[15, 23]. Depth points of each year, referenced to the theoretical lowest-tide datum at Wusong, are interpolated into a 50×50 m grid to generate a digital elevation model (DEM) for each year by the Kriging interpolation technique in the Surfer mapping software package. The erosion/accretion patterns are obtained by subtracting a later DEM from an earlier one. The area percentages (%) and sediment volume changes (Mm³/yr) of erosion and accretion are calculated based on the depth changes of each cell, cell size and amount. The
net volume changes and rates (mm/yr) are then obtained by summing the erosion/accretion volume and dividing the total area.

3.2. Model setup and numerical experiments

The process-based and fully integrated numerical model system Delft3D, which solves the shallow water equations under the hydrostatic pressure assumption, is applied to investigate the decadal morphological processes under high river discharge. The model computes flows (river and tide), sediment transport (cohesive and non-cohesive), wind waves and bed-level updating on a horizontal curvilinear grid[24]. Decadal morphological modeling is implemented through linearly accelerating bed-level change at each hydrodynamic time step with a carefully selected morphological factor (MF)[25]. Thus, medium- to long-term morphodynamic modeling is online coupled with hydrodynamic modeling. Many previous studies have demonstrate the high performance of the MF approach to reproduce estuarine and deltaic morphological processes[26-28].

The model grid spans from Datong (the tidal limit) to the East China Sea (Fig. 2), and the cell size varies from ~300 m within the estuary to ~3000 m near the offshore boundary, which is sufficient for morphological modeling with acceptable accuracy. The model is in a 2DH mode in this study, which means that only depth-averaged processes are simulated. Secondary flow is included making the model quasi-3D. Forced by river flow, astronomic tides and wind wave, the model considers multiple sediment fractions and the variations in river water discharge and sediment discharge.

![Figure 2. Numerical model grids](image)

The model has been calibrated and validated against water level, tidal currents and historical decadal morphological in our previous study[29]. The root mean square errors of water level and velocity at 14 tidal station within the estuarine area are 0.19 m and 0.21 m/s, respectively, which are acceptable for hydrodynamic modeling. Validations against morphological changes also showed relatively high agreement with data in terms of erosion/deposition pattern, volume changes and hypsometry curves[29]. Therefore, it can be a useful numerical tool to explore the physical mechanisms of high river discharge on decadal evolution processes. Since the period 2002-2010 among three hindcast periods shows the best model performance, it provides a nice reference case for numerical experiments. River discharge in the dry and wet season is 13,290 m³/s and 45,754 m³/s, respectively. Three numerical experiments on the river discharge in July during the flood season are conducted: (S1) increase by 15%; (S2) increase by 30% and (S3) increase by 45% (Table 1). The river flood discharge in S3 is over 66,000 m³/s, which is higher than the dominant discharge (60,000 m³/s) of the Yangtze Estuary[16]. Sediment load in above experiments remained constant by accordingly decreasing the suspended sediment concentration (SSC) at the river boundary (Table 1). One additional experiment (S4) is conducted to increase the river discharge in July by 45% with constant
SSC at the river boundary (Table 1). Erosion/accretion patterns and volumes in the reference case and numerical experiments are compared and analyzed.

Table 1. River input conditions in the reference case and numerical experiments (2002-2010).

| Month       | Dec., Jan., Feb. | Mar. | Apr., May, Jun. | Jul. | Aug., Sep. | Oct., Nov. |
|-------------|------------------|------|-----------------|------|------------|------------|
| Reference case | Q<sub>w</sub> (m<sup>3</sup>/s) | 13290 | 18975 | 31630 | 45754 | 40886 | 22568 |
|             | SCC (kg/m<sup>3</sup>) | 0.107 | 0.137 | 0.176 | 0.247 | 0.274 | 0.151 |
| S1          | Q<sub>w</sub> (m<sup>3</sup>/s) | 13290 | 18975 | 31630 | 52617 | 40886 | 22568 |
|             | SCC (kg/m<sup>3</sup>) | 0.107 | 0.137 | 0.176 | 0.215 | 0.274 | 0.151 |
| S2          | Q<sub>w</sub> (m<sup>3</sup>/s) | 13290 | 18975 | 31630 | 59480 | 40886 | 22568 |
|             | SCC (kg/m<sup>3</sup>) | 0.107 | 0.137 | 0.176 | 0.190 | 0.274 | 0.151 |
| S3          | Q<sub>w</sub> (m<sup>3</sup>/s) | 13290 | 18975 | 31630 | 66343 | 40886 | 22568 |
|             | SCC (kg/m<sup>3</sup>) | 0.107 | 0.137 | 0.176 | 0.247 | 0.274 | 0.151 |
| S4          | Q<sub>w</sub> (m<sup>3</sup>/s) | 13290 | 18975 | 31630 | 66343 | 40886 | 22568 |
|             | SCC (kg/m<sup>3</sup>) | 0.107 | 0.137 | 0.176 | 0.247 | 0.274 | 0.151 |

4. Results

4.1. Observed morphological changes

According to the observed bathymetry maps, the channel-shoal pattern within the inner estuary was retained during 1986-2016 although several local modifications were remarkable (Fig. 3). The geometry of the Baimao Shoal and Biandan Shoal evolved smoother and moved downstream, and the two small shoals at the upstream of the Xinliuhe Shoal were eroded and merged into the Xinliuhe Shoal. The main channels of the South Branch was deepened and widened. Scouring of the Ruifeng Shoal resulted in the disappearance of the shoal spit. Construction of the Qingcaosha Reservoir decreased the width of the North Channel and induced the deepening of the main channel.

![Figure 3. Observed bathymetry of the inner Yangtze estuary in different periods](image-url)

Erosion and accretion patterns of the inner estuary showed distinct features in the three periods during 1986-2016 (Fig. 4). In 1986-1997, the main channels was dominated by erosion, which was stronger in the upstream than the downstream. Accretion mostly occurred at shallow shoals, including the Baimao Shoal, the southern side of Lower Biandan Shoal and the head of Ruifeng Shoal. Area of erosion accounted to 57% of the total domain, and the net volume change and rate were −66.3 Mm<sup>3</sup>/yr and −61 mm/yr, respectively (Table 2). In 1997-2010, the overall pattern was still dominated by erosion, though the percentage of area involving erosion decreased to 53%. The downstream part of the Baimao Shoal was largely eroded, leading to the disappearance of the shoal tail. The Biandan Shoal extended downstream as the sand body evolved to be more aligned with the ebb flow direction (Fig. 3). The bifurcation area of the North and South Channel experienced strong erosion, and the location of Xinliuhe Shoal was fixed by submerged engineering structures. The main channel of the North Channel was deepened due to the construction of Qingcaosha Reservoir. Notably, erosion at the northern main channel of the Baimao Shoal in 1986-1997 was replaced by accretion in 1997-2010. This conversion was also observed at the main channel near Qiyakou. Overall, the net volume change in 1997-2010 was −45.8 Mm<sup>3</sup>/yr, which was less than the value in 1986-1997 (Table 2). In the latest period 2010-2016, accretion was found at downstream of erosion area. Remarkable changes occurred...
at the Biandan Shoal and adjacent main channel. Incision of the Biandan Shoal led to two small connecting channels, and the -5 m isobath between the Upper and Lower Biandan Shoal was cut through. The percentage of erosion area in this period increased back to 57% with both erosion and accretion volumes larger than those in 1986-1997. The net volume change in 2010-2016 was −59.1 Mm$^3$/yr, which was larger than that in 1997-2010 and smaller than that in 1986-1997 (Table 2). Overall, the inner estuary show the strongest net erosion in 1986-1997, though the river sediment load decreased continuously among three periods.

![Figure 4. Observed erosion/ accretion patterns of the inner Yangtze estuary in different periods](image)

Table 2. Observed erosion/accretion area percentage, volume and rate of the defined domain as shown in Fig. 1.

|                | 1986-1997 | 1997-2010 | 2010-2016 |
|----------------|-----------|-----------|-----------|
| Sediment load  |           |           |           |
| Erosion Area (%) | 57        | 53        | 57        |
| Volume (10$^6$ m$^3$/yr$^{-1}$) | −177.7 | −156.7 | −195.6 |
| Accretion Area (%) | 43        | 47        | 43        |
| Volume (10$^6$ m$^3$/yr$^{-1}$) | 111.4 | 110.9 | 136.5 |
| Net Volume (10$^6$ m$^3$/yr$^{-1}$) | −66.3 | −45.8 | −59.1 |
| Rate (mm yr$^{-1}$) | −61     | −48      | −63      |

4.2. Hydrodynamic and sediment transport modeling

The modeled water level isolines at ebb maximum in the reference case show that both the water level and its gradient are lifted by high river discharge in wet season (Fig. 5a). The increase in water level is gradually damped downstream, for example, +0.6 m at Baimao Shoal and +0.3 m at the head of the Hengsha Island. The tide falling near the southern bank is faster than that near the northern bank due to the effect of Coriolis force. Modeled residual currents in both dry and wet season are towards ebb direction because of the considerable river discharge (Fig. 5b). Under the longitudinal variation of river/tide interaction, residual currents are larger in the South Branch than the North and South Channel, and are enhanced in wet season, particularly in the main channel. The Xinqiao Channel in the north of Biandan Shoal shows flood residual currents in dry season, forming a circulation system around the Biandan Shoal. However, the residual currents along the Xinqiao Channel convert to ebb direction in wet season. This features are also found in the modeled residual sediment transport fields in dry and wet season (Fig. 5c). Sediment circulation around the Biandan Shoal in dry season can lead to shoal accretion, while large gradient of residual sediment transport along the main channel in wet season indicates channel erosion.

To explore the hydrodynamic processes controlling the bathymetric changes of channel-shoal system, modeled velocity and water level at Qiyakou and the water level differences from Qiyakou to
Liuhekou (longitudinal) and from Qiyakou to Nanmen (transverse) during a spring tidal cycle are presented (Fig. 6). Longer ebb period and larger ebb velocity at Qiyakou suggest ebb asymmetry. During the ebb tide, the long-channel and cross-channel ebb velocity increase to the maximum and last for about 6 hours until the lowest water level. Simultaneously, the longitudinal and transverse positive water level differences increase to the maximum. Thus, the maximum ebb velocity in the main channel and water level difference at two sides of the Biandan Shoal are at the same phase. However, the lasting time of maximum flood velocity and water level differences is about 1-2 hours. Simulations with varying river discharge from 10,000 to 70,000 m$^3$/s indicate that the water level gradient increases linearly with the river discharge, and the increasing rate of the transverse gradient is slightly faster than the longitudinal direction (Fig. 7).

Figure 5. Modeled flow and sediment processes in dry and wet season: (a) water level isolines at ebb maximum; (b) residual currents; (c) residual sediment transport.

Figure 6. The along/across channel velocity and water level at Qiyakou and the water level difference from Qiyakou to Nanmen (WLD1) and from Qiyakou to Liuhekou (WLD2) during a spring tidal cycle under medium river discharge (22,800 m$^3$/s). The water level differences are enhanced by a factor of 3 for clarity, positive velocity denotes ebb tidal flow and northward flow, positive WLD denotes higher water level at Qiyakou (see Fig. 1 for the locations of Qiyakou, Nanmen and Liuhekou).

4.3. Morphological modeling
The modeled erosion/accretion pattern in the reference case showed relatively good agreement with the observation (Fig. 8). The observed erosion along main channels and accretion at shallow shoals are
reproduced by the model. The inner estuary showed net erosion in 2002-2010, which was also captured in the reference case (Table 3). Details of the morphological model validation are referred to Luan et al. (2017)[29]. In the numerical experiments S1–S3, erosion along the main channels is enhanced relative to the reference case, especially in the upper region from Xuliujing to Qiyakou (Fig. 9a-c). The area of the enhanced erosion increased along with the river discharge in flood season. In the S3, the effect of increased river flood discharge covers the entire inner estuary and extends to the upper part of the mouth bar area. Several enhanced accretion scatters are also found at the downstream side of erosion areas due to deposition of eroded sediment. Moreover, the modeled sediment volume changes indicate that the net erosion volumes in the inner estuary increase as the flood river discharge increases in numerical experiments. In the reference case, net erosion volume of the entire inner estuary as defined in Fig. 1 is -84.06 Mm³/yr (Table 3). The net erosion volumes in S1–S3 increase 0.53 Mm³/yr, 1.91 Mm³/yr, 3.93 Mm³/yr, respectively. The upstream part of the inner estuary showed stronger erosion than the downstream. For instance, the increased erosion volume of Area 1 in S3 account for 12.0% of the reference case, and this value decreases to 3.9% for Area 2 and 2.6% for Area 3.

Figure 7. Relationships between river discharge and modeled maximum water level gradient (WLG). WLG1: from Qiyakou to Nanmen; WLG2: from Qiyakou to Liuhekou (see Fig. 1 for the locations of Qiyakou, Nanmen and Liuhekou).

Figure 8. (a) Modeled erosion and accretion patterns of the reference case in 2002-2010; (b) observed erosion and accretion patterns in 2002-2010. The red dash lines divide the inner estuary into three areas, i.e., Area 1 from Xuliujing to Liuhekou, Area 2 from Liuhekou to Wusong and Area 3 from Wusong to Hengsha.

In the additional experiment S4, the SSC at the river boundary remains constant as the flood discharge increases by 45%, which means that sediment input in July increase by 45% accordingly. Model result indicates that the main channels near Xuliujing, along the South Branch and North
Channel showed enhanced erosion, while more accretion or less erosion was produced within the inner estuary and even the mouth bar area (Fig. 9d). The net erosion volume of the entire inner estuary decreases for 4.02 Mm$^3$/yr, and the largest decrease is found in Area 2. Sediment tends to accumulated at the lower Biandan Shoal and the Xinliuhe Shoal relative to the reference case. This result suggests that increased flood discharge do not necessarily enhanced erosion, but the combined effects of flood discharge and sediment load determine the bed-level change in the inner estuary.

![Figure 9. Differences of modeled erosion/accretion patterns between numerical experiments (S1~S4) and the reference case](image)

Table 3. Modeled erosion/accretion volumes and the volume differences between numerical experiments and the reference case (Unit: Mm$^3$/yr). The domains of Area 1~3 are defined in Fig. 8.

| Model runs | Reference case | Differences between numerical experiments and the reference case |
|------------|----------------|---------------------------------------------------------------|
|            |                | S1               | S2               | S3               | S4               |
| Area 1     | Erosion volume | -55.12           | -0.86            | -1.90            | -3.08            | -1.86            |
|            | Accretion      |                  |                  |                  |                  |                  |
|            | volume         | 39.80            | 0.50             | 0.90             | 1.24             | 2.48             |
|            | Net volume     | -15.32           | -0.35            | -1.00            | -1.84            | 0.61             |
| Area 2     | Erosion volume | -48.98           | -0.26            | -0.68            | -1.22            | 0.17             |
|            | Accretion      |                  |                  |                  |                  |                  |
|            | volume         | 27.63            | 0.24             | 0.35             | 0.38             | 1.92             |
|            | Net volume     | -21.36           | -0.02            | -0.33            | -0.84            | 2.09             |
| Area 3     | Erosion volume | -61.56           | -0.23            | -0.65            | -1.24            | 0.54             |
|            | Accretion      |                  |                  |                  |                  |                  |
|            | volume         | 14.18            | 0.07             | 0.07             | -0.01            | 0.78             |
|            | Net volume     | -47.38           | -0.16            | -0.59            | -1.25            | 1.31             |
| Entire area| Net volume     | -84.06           | -0.53            | -1.91            | -3.93            | 4.02             |

5. Discussion

5.1. Hydrodynamic condition under high river discharge

In tidal-influenced estuaries, river/tide interactions and sediment properties are regarded as controlling factors on medium to long term morphological evolution[30]. For a large-scale estuary with huge
amount of river discharge, like the Yangtze Estuary, seasonal variation of river discharge also plays an important role in the morphological evolution. In specific, river flood discharge enhanced hydrodynamics and induce strong modification of channel-shoal morphology. One profound effect of high river discharge is lifting the water levels, which is longitudinally damped by tides along the estuary. The mean water level referred to mean sea level at Xuliujing in July 2010 is 1.43 m, while the value at Jigujiao is 0.42 m (Fig. 10). In the hydrologic dry year 2009, the river discharge in July is only about 40,000 m$^3$/s, and the mean water level at Xuliujing is 1.14 m. Even in the dry season (01/2010), the mean water level at Xuliujing is still 0.35 m. Higher water level in the wet season than that in the dry season results in submergence of shallow shoals, accompanied with larger flow velocity. This hydrodynamic condition facilitates morphological changes of estuarine channel-shoal systems.

![Figure 10. Longitudinal variations of mean water level from Xuliujing to Jigujiao](see their locations in Fig. 1)

High river discharge also alters the water level gradient and residual transport pattern around channel-shoal systems. Both the longitudinal and transverse water level gradients are higher in the wet season than the dry season. The former can induce erosion along main channels, while the latter is regarded as an important trigger of shoal incision[16]. Moreover, maximum ebb flow and seaward water level gradient occur simultaneously and last for a sufficiently long time. This is a driving force for erosion, downstream movement and incision of shallow shoals. The residual transport pattern around the Biandan Shoal in the dry season showed ebb dominant along the main channel and flood dominant in the Xinqiao Channel (flood channel) which favors shoal accretion. However, the residual current and sediment transport along the Xinqiao Channel converted to ebb direction under high river discharge, while implies net erosion of the Biandan Shoal. Overall, the model results in this study can provide physical explanation for seasonal morphological evolution of channel-shoal systems in the inner Yangtze Estuary.

5.2. Decadal morphological evolution due to high river discharge

Previous studies have identified the river sediment decline as the governing factor of the conversion from accretion to erosion of the Yangtze Estuary[14, 23, 31]. Luan et al. (2016) demonstrated that the inner estuary showed net accretion under high river sediment supply before the 1980s, while it converted to net erosion after 1980s under decreasing sediment supply[23]. However, the decadal evolution processes of the inner estuary during 1986-2016 show distinct pattern, which cannot be merely explained by river sediment decline. Specifically, the net erosion volume in 1986-1997 is higher than those in 1997-2010 and 2010-2016, though the sediment discharge showed continuous decrease. This suggests other controlling factors on decadal morphological evolution on the inner estuary.

With the continuous decreasing of sediment discharge since 1985, the water discharge showed no significant trend except for the frequent river flood events in the 1990s. Peak flood discharge of every
year in the 1990s exceeded 60,000 m$^3$/s (Fig. 11), which is the channel-forming discharge of the Yangtze Estuary[16]. Frequent river flooding induced significant erosion at a decadal timescale, and the effect even exceeded the decreased sediment supply. Larger net erosion volume in 1986-1997 than that in 1997-2010 is mainly contributed by the strong bed erosion due to river floods. The mean SSC in the wet season of the recent decade decreased to a low level (Fig. 11), while only episode river floods occurred. The net erosion volume in 2010-2016 is thereby higher than the value in 1997-2010. Besides, the recovery from the erosion in 1990s also contributed to lower erosion amount in 1997-2010, which is reflected by the accretion of the north Baimao channel and the main channel near Qiyakou (Fig. 3).

5.3. Implications for future evolution trend

In the initial operation period (2003-2016) of the Three Gorge Dam (TGD), annual water and sediment discharge at Datong station decreased by 5.22% and 67.4%, respectively, relative to the pre-TGD period. The mean sediment load at Datong station in 2010-2016 dropped to as low as 132 Mt/yr (Table 2). The seasonal distribution of water discharge is altered with decreased discharge in the wet season (July to October) and increased discharge in the dry season (January to March) due to the operation of upstream reservoirs (Fig. 12a). For the seasonal variation of SSC, decrease in the wet season is the primary contributor of the river sediment decline. The peak of the SSC in the wet season was vanished after the closure of the TGD (Fig. 12b). At present, the inner Yangtze Estuary is dominated by overall erosion under low river sediment supply. Considering the completion of the upstream Cascade Reservoirs in the future, river sediment discharge will continue to decrease[32]. Though the reservoir impounding reduce the peak flood discharge, it is still possible for large river floods reaching the Yangtze Estuary when extreme river flood occurs in the middle and lower reaches of Yangtze River. It is reported that the peak flood discharge in 2016 and 2017 was 70,700 and 70,100 m$^3$/s, respectively, and days with river discharge over 60000 m$^3$/s were 29 and 16. Overlaying the high river discharge and low SSC, remarkable erosion and channel deepening are likely to occur, which may disturb the stability of channel-shoal systems and deteriorate their ecosystem functions within the Yangtze Estuary.
6. Conclusions

Decadal morphological processes of the large-scale Yangtze Estuary in 1986-2016 are quantified based on observed bathymetric data, with an emphasis on the inner part. The inner estuary defined from Xuliujing to Hengsha showed overall net erosion since 1986, which was subject to continuous river sediment decline. Moreover, frequent river flood events in the 1990s contributed to higher yearly net erosion amount in 1986-1997 than that in 1997-2010. Thus, high river discharge in wet season plays an important role in decadal morphological evolution. The process-based modeling approach is applied to investigate the mechanisms on the morphological effects of high river discharge. Hydrodynamic modeling indicates that the water level and its gradient are enhanced under high river discharge. Higher longitudinal and transverse gradient facilitate erosion along the main channels and the central sandbars, respectively. The maximum ebb flow and maximum water level gradient at the same phase are the main driven forces. High river discharge also enhance the residual current and sediment transport. Numerical experiments on river discharge in the wet season (July) show that channel deepening is enhanced by higher river flood discharge, especially in the upstream part. Though the operation of reservoirs in the upstream river basin vanishes the flood peak, extreme river flood events is still possible in the future. Overlaying with the further decrease in river sediment supply due to the completion of Cascade Reservoirs, the morphological effects of high river discharge on the Yangtze Estuary will be more significant, particularly for the stability of channel-shoal systems and their ecosystem functions.

Acknowledgments

This study was financially supported by the Ministry of Science and Technology of China (2016YFC0402307), the National Natural Science Foundation of China (51679010) and the Fundamental Research Funds for Central Public Welfare Research Institutes (CKSF2019411/HL).

References

[1] Milliman, J. D., Meade, R. H. (1983) World-Wide Delivery of River Sediment to the Oceans. The Journal of Geology 91:1-21.
[2] Day, J., Hall, C. S., Kemp, W. M., Yanez-Aranciba, A. (1989) Estuarine Ecology. John-Wiley, New York.
[3] Pont, D., Day, J. W., Hensel, P., Franquet, E., Torre, F., Rioual, P., Ibàñez, C. et al. (2002) Response scenarios for the deltaic plain of the Rhone in the face of an acceleration in the rate of sea-level rise with special attention to Salicornia-type environments. Estuaries 25:337-358.
[4] Syvitski, J. P. M., Saito, Y. (2007) Morphodynamics of deltas under the influence of humans. Global and Planetary Change 57:261-282.

Figure 12. (a) Monthly averaged river discharge and (b) SSC at Datong station in different periods
[5] Woodroffe, C. D., Nicholls, R., Saito, Y., Chen, Z., Goodbred, S. (2006) Landscape Variability and the Response of Asian Megadeltas to Environmental Change. In Harvey, N. (EdS.), Coastal Systems and Continental Margins. Springer Netherlands. pp. 277-314.

[6] Day, J. W., Agboola, J., Chen, Z., D Elia, C., Forbes, D. L., Giosan, L., et al. (2016). Approaches to defining deltaic sustainability in the 21st century. Estuarine, Coastal and Shelf Science, 183, Part B:275-291.

[7] Galloway, W. E. (1975) Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. In Broussard, M. L. (Eds). Deltas: Models for Exploration, Houston Geological Society. pp. 87-98.

[8] Wolman, M. G., Miller, J. P. (1960) Magnitude and Frequency of Forces in Geomorphic Processes, The Journal of Geology 68:54-74.

[9] Gray, A. B., Pasternack, G. B., Watson, E. B. (2018). Estuarine abandoned channel sedimentation rates record peak fluvial discharge magnitudes. Estuarine, Coastal and Shelf Science, 203:90-99.

[10] Cooper, J. A. G. (2002). The role of extreme floods in estuary-coastal behaviour: contrasts between river- and tide-dominated microtidal estuaries. Sedimentary Geography, 150(1-2):123-137.

[11] Guo, L., van der Wegen, M., Roelvink, D., He, Q. (2015). Exploration of the impact of seasonal river discharge variations on long-term estuarine morphodynamic behavior. Coastal Engineering, 95(0):105-116.

[12] Boudet, L., Sabatier, F., Radakovitch, O. (2016). Modelling of sediment transport pattern in the mouth of the Rhone delta: Role of storm and flood events. Estuarine, Coastal and Shelf Science, 198, Part B:568-582.

[13] Yang, S. L., Zhang, J., Zhu, J., Smith, J. P., Dai, S. B., Gao, A., et al. (2005). Impact of dams on Yangtze River sediment supply to the sea and delta intertidal wetland response. Journal of Geophysical Research: Earth Surface, 110(F3):F3006.

[14] Yang, S. L., Milliman, J. D., Li, P., Xu, K. (2011). 50,000 dams later: Erosion of the Yangtze River and its delta. Global and Planetary Change, 75(1-2):14-20.

[15] Dai, Z., Liu, J. T., Wei, W., Chen, J. (2014). Detection of the Three Gorges Dam influence on the Changjiang (Yangtze River) submerged delta. Scientific Reports, 4:6600.

[16] Yun, C. (2004). Recent evolution of Yangtze Estuary and its mechanisms. China Ocean Press, Beijing (in Chinese).

[17] Yang, S. L., Xu, K. H., Milliman, J. D., Yang, H. F., Wu, C. S. (2015). Decline of Yangtze River water and sediment discharge: Impact from natural and anthropogenic changes. Scientific Reports, 5:12581.

[18] CWRC (Changjiang Water Resources Commission). (2016) Changjiang Sediment Bulletin. Changjiang Press, Wuhan.

[19] Milliman, J. D., Farnsworth, K. L. (2011). River discharge to the coastal ocean: a global synthesis. Cambridge University Press, Cambridge.

[20] Liu, H., He, Q., Wang, Z., Weltje, G. J., Zhang, J. (2010). Dynamics and spatial variability of near-bottom sediment exchange in the Yangtze Estuary, China. Estuarine, Coastal and Shelf Science, 86(3):322-330.

[21] van Veen, J., van der Spek, A. J. F., Stive, M. J. F., Zitman, T. (2005). Ebb and Flood Channel Systems in the Netherlands Tidal Waters (No. 0749-0208).

[22] Wu, S., Cheng, H., Xu, Y. J., Li, J., Zheng, S. (2016). Decadal changes in bathymetry of the Yangtze River Estuary: Human impacts and potential saltwater intrusion. Estuarine, Coastal and Shelf Science, 182:158-169.

[23] Luan, H. L., Ding, P. X., Wang, Z. B., Ge, J. Z., Yang, S. L. (2016). Decadal morphological evolution of the Yangtze Estuary in response to river input changes and estuarine engineering projects. Geomorphology, 265:12-23.
[24] Lesser, G. R., Roelvink, J. A., van Kester, J. A. T. M., Stelling, G. S. (2004). Development and validation of a three-dimensional morphological model. Coastal Engineering, 51(8–9):883-915.

[25] Roelvink, J. A. (2006). Coastal morphodynamic evolution techniques. Coastal Engineering, 53(2–3):277-287.

[26] Hu, K., Ding, P., Wang, Z., Yang, S. (2009). A 2D/3D hydrodynamic and sediment transport model for the Yangtze Estuary, China. Journal of Marine Systems, 77(1–2):114-136.

[27] Ganju, N. K., Schoellhamer, D. H., Jaffe, B. E. (2009). Hindcasting of decadal-timescale estuarine bathymetric change with a tidal-timescale model. Journal of Geophysical Research: Earth Surface, 114(F4):F4019.

[28] van der Wegen, M., Jaffe, B. E., Roelvink, J. A. (2011). Process-based, morphodynamic hindcast of decadal deposition patterns in San Pablo Bay, California, 1856–1887. Journal of Geophysical Research: Earth Surface, 116(F2):F2008.

[29] Luan, H. L., Ding, P. X., Wang, Z. B., Ge, J. Z. (2017). Process-based morphodynamic modeling of the Yangtze Estuary at a decadal timescale: Controls on estuarine evolution and future trends. Geomorphology, 290:347-364.

[30] Orton, G. J., Reading, H. G. (1993). Variability of deltaic processes in terms of sediment supply, with particular emphasis on grain size. Sedimentology, 40(3):475-512.

[31] Luo, X. X., Yang, S. L., Wang, R. S., Zhang, C. Y., Li, P. (2017). New evidence of Yangtze delta recession after closing of the Three Gorges Dam. Scientific Reports, 7.

[32] Yang, S. L., Milliman, J. D., Xu, K. H., Deng, B., Zhang, X. Y., Luo, X. X. (2014). Downstream sedimentary and geomorphic impacts of the Three Gorges Dam on the Yangtze River. Earth-Science Reviews, 138:469-486.