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Letter

Morphodynamics of the Qiantang Estuary, China: Controls of river flood events and tidal bores

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ABSTRACT

The importance of seasonal variations in river discharge on the morphological development of estuaries has been recognized in recent years, yet in situ observations about such variations are rare. Here we report a long-term dataset of bathymetry in the middle reach of the Qiantang Estuary, China, characterized by the presence of a large inner bar. Moreover, a hydrographic survey was carried out in the Yanguan reach where one of the largest tidal bores in the world occurs, covering a spring-neap tidal cycle in 2015. Meanwhile, detailed seasonal bathymetric data together with daily river discharges of 2015 were collected. The bed morphology shows strong seasonal and inter-annual variations. During the high flow season, the river flow erodes the bed and transports a large amount of sediments seaward. A good power-law relationship exists between the high river discharge and the channel volume at the upper estuary. Flood tides dominate under usual river flow condition. In particular, the tidal bore during spring and intermediate tides is characterized by large current velocity and high suspended sediment concentration, and transports a large amount of sediment landward. Over a year, a dynamic morphological equilibrium can be maintained. Moreover, the estuary has also been significantly influenced by the large-scale embankment in recent decades, constraining the lateral thalweg migration, bank erosion and point bar deposition, which usually occur in natural sinuous estuaries.

1. Introduction

Estuaries are defined as semi-enclosed coastal bodies of water which have free connection with the open sea (Fairbridge, 1980). They are among the most important interfaces on earth. They provide navigation channels, ports, land resources, conditions for recreational activities, and so on. They also play an important role in global carbon/biogeochemical cycling, and provide habitats for flora and fauna. Estuaries are fairly ephemeral features at the geological time scale and frequently influenced by natural changes and human interventions (e.g. Dyer, 1995; Savenije, 2005; Townend et al., 2007; Wang et al., 2015). From the management point of view, it is of major significance to understand and predict the sediment transport and morphological evolution in estuaries.

Morphological evolution in an estuary is controlled by the nonlinear interactions among hydrodynamics, sediment transport and bed level changes (e.g. Dyer, 1995; Hibma et al., 2004; Dalrymple and Choi, 2007). In recent years, many morphodynamic models have revealed that an equilibrium state of morphology can be reached asymptotically when erosion and deposition balance over a long enough time span, assuming that the river discharge is much smaller than the prevailing tidal discharge and can be ignored (e.g. Lanzoni and Seminara, 2002; van der Wegen and Roelvink, 2008; Leonardi et al., 2013). On the other hand, it has been recognized that seasonal variations of river discharge play an important role on the morphological development in estuaries, especially at the landward end where smaller channel cross sections and tidal prisms prevails (e.g. Perillo, 1995; Savenije, 2005; Shaw and Mohrig, 2014; Guo et al., 2014; Zhang et al., 2016). In the case of a near-equilibrium of an estuary, sediment import during low flows can approximately balance sediment export during high flow over a seasonal cycle (Uncles et al., 1998; Hoitink et al., 2017). It would be valuable to offer a better illustration of such concept, using a time series of morphological and hydrological data from a real estuary.

Sand bars, one of the most important sedimentary systems within an

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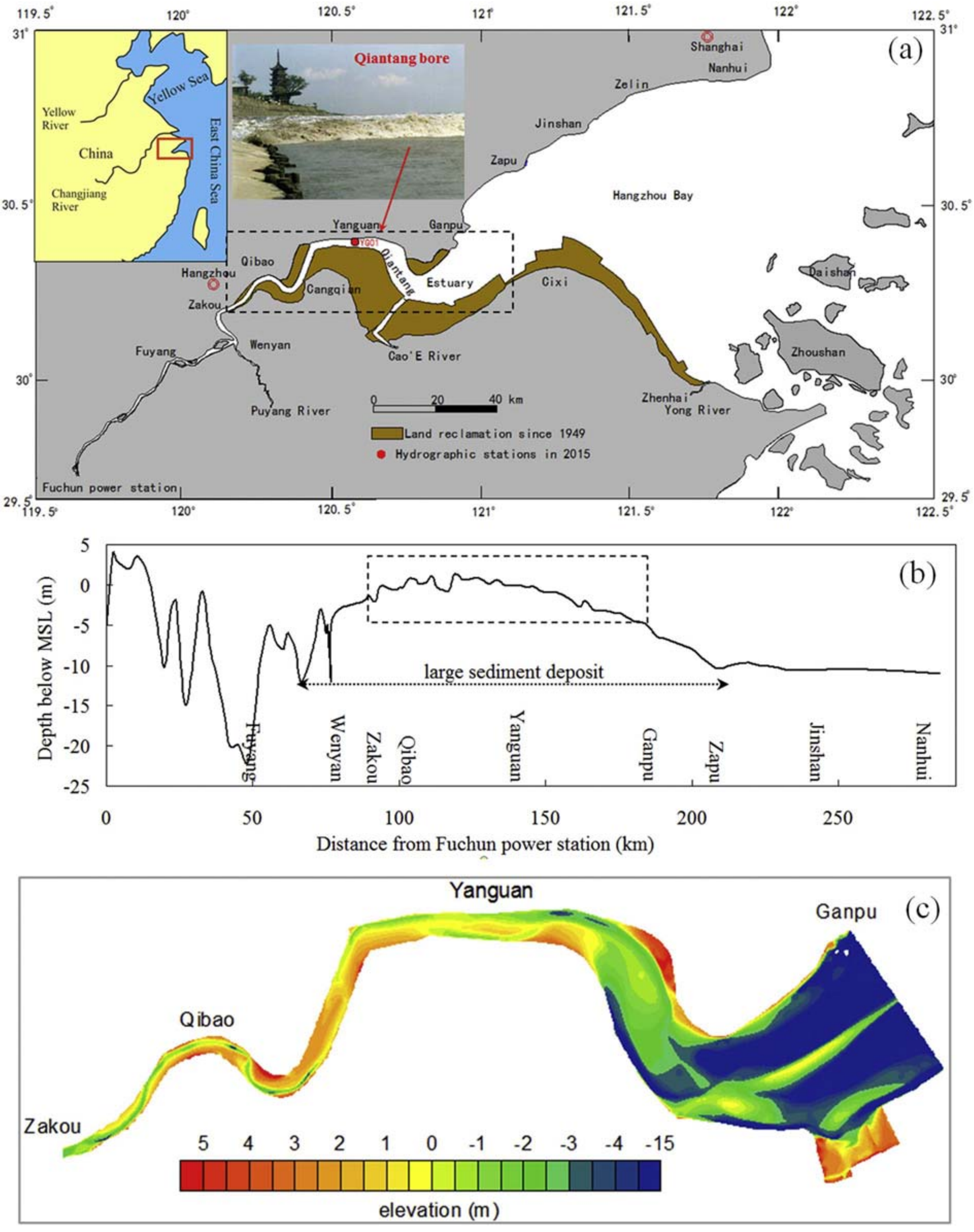

Fig. 1. (a) Location of the Qiantang Estuary, in which YG01 denotes the hydrographic observation station in October 2015. (b) The lateral-averaged longitudinal bathymetry along the estuary measured in 2014. (c) Bathymetry of the middle estuary measured in April 2015. Panels a and b were modified from Xie et al. (2017a). The bed elevations in panels b and c are with respect to the Chinese National Vertical Datum of 1985. The dashed box in panels a and b denotes the middle reach of the estuary, as shown in panel c.

estuary, can form when the estuary received sufficient sediment supply (Dyer, 1995; Gao and Collins, 2014). One typical example is the large subaqueous bar in the upper and middle reaches of the Qiantang Estuary, China. It starts at about 80 km from the mouth, extends by about 130 km longitudinally, and has a height of 10 m above the baseline at the top part (Fig. 1). Based on sedimentological surveys, it has been revealed that the sediment of this large deposit is from the adjacent Changjiang River (Chien et al., 1964; Chen et al., 1990). Yu et al. (2012) reproduced the formation of the large bar in Qiantang Estuary using a long-term morphodynamic model by assuming that the river discharge is a constant, and analyzed the physical mechanisms for the bar evolutions. More recent morphodynamic modeling by Xie et al. (2017a) indicates that under normal discharge condition, the bar would grow unlimitedly and a central shoal can be formed gradually around the bar top, due to the continuous sediment import by flood dominance, and the growth can be constrained by seasonal high discharge. Based on historical charts, Xie et al. (2017b) also analyzed the decadal morphological response of the Qiantang Estuary to the reduction of sediment load from the adjacent Changjiang Estuary and the large-scale embankment within the estuary, but they did not pay attention to the seasonal morphological changes. Thus far, few field data have been reported on the morphological equilibrium, leaving a gap between the sediment transport and morphological evolution, especially because of the lack of observed hydrological data.

The Qiantang Estuary is strongly influenced by the river flood events and one of the largest tidal bores in the world (Bartsch-Winkler and Lynch, 1988; Pan and Huang, 2010). As a result, the estuary is characterized by active morphological changes on seasonal and inter-annual time scales. In this study, we analyze the seasonal and long-term morphodynamic evolutions of the inner bar in the Qiantang Estuary, quantify the roles of the flood events and the tidal bore and deepen our understanding of the underlying physical mechanisms for the dynamic equilibrium.

2. Study area

Located on the coast of the East China Sea, the Qiantang Estuary is a 282-km long convergent estuary, with the width decreasing from 98.5 km at the mouth to less than 1 km at the landward end (Fig. 1a). The upper reach from Fuchun power station (FPS) to Zakou is dominated by river flow, where the sediment is predominantly composed of gravely coarse sand and the morphology is basically stable; the middle reach from Zakou to Ganpu is controlled by both the river flow and tides, while the lower reach downstream of Ganpu, also well known as Hangzhou Bay, is dominated by tidal currents (Chen et al., 1990; Han et al., 2003; Fan et al., 2014). The Qiantang Estuary has thick Holocene sedimentary sequences, with a maximum thickness of more 100 m (Lin et al., 2005; Zhang et al., 2014). The top layer of the sedimentary materials in the middle and lower estuary is mainly composed of fine and well-sorted silt and clay, mainly derived from the adjacent Changjiang Estuary (Milliman et al., 1985; Chen et al., 1990; Gao, 2013). The middle and upper reaches of the estuary are overwhelmed by a large longitudinal bar that elongated from Zapu in the middle of Hangzhou Bay to about 130 km upstream; the bed level rises gradually from 10 m below mean sea level (MSL) to 1 m above MSL and then lowers to more than 10 m below MSL (Fig. 1b; Chien et al., 1964; Chen et al., 1990; Xie et al., 2017a). The present study focuses on the middle reach between Zakou and Ganpu, where active morphological changes occur.

The annual mean discharge of the Qiantang River is 952 m^3/s. Due to the monsoon climate, the river discharge shows a clear seasonal variation: the low discharge occurs from August to the following March and the high discharge occurs from April to July. It also varies on the inter-annual time scale, with sometimes continuous high or low flow years (Han et al., 2003). The tidal wave deforms rapidly landward due to estuarine convergence and shallowing water depth. The mean tidal range increases upstream from about 3.2 m at the mouth to about 6 m at Ganpu, and then gradually decreases landward. The tidal wave evolves into a tidal bore at the Yanguan section, with an average bore height being 1–2 m and a maximum exceeding 3 m (Bartsch-Winkler and Lynch, 1988; Pan and Huang, 2010).

Since the 1960s, a large-scale coastal embankment in the QE has been built for the purposes of flood defense and land requirements, etc. (Li and Dai, 1986; Han et al., 2003). So far, more than 1000 km^2 land has been reclaimed and the width of the estuary has been largely narrowed, especially in the middle reach, i.e., between Zakou and Ganpu (Fig. 1a).

3. Data and analysis

The bathymetry in the middle reach has been investigated in every April, July and November since the 1980s, representing the periods before and after flood season and low river discharge of the year (Han et al., 2003). During each bathymetric investigation, the bed elevation along 60 cross-sections was observed using an Odom Hydrotrac echo-sounder. The error of the measured bed level is 0.1 m, and a global positioning system (GPS) by Trimble was used that gave the positioning error within 1 m. After each investigation, the volumes below multi-year averaged high water level (MHL) between the cross-sections were calculated. In this contribution, we collect the volume data of the reaches Zakou-Yanguan (ZY) and Yanguan-Ganpu (YG), as well as the monthly river discharge from FPS since 1981, in order to provide a comprehensive picture of the inter-annual and seasonal changes of the large sedimentary system.

A detailed hydrographical survey was conducted during 9–17th October 2015, at YG01 station located at the Yanguan section, where the tidal bore is strongest (Fig. 1a). The flow velocity was measured by an Acoustic Doppler Current Profiler (ADCP), and SSC was measured using an Optical Back Scatter (OBS). The OBS instrument was calibrated against water samples collected at the same site. Because both flow velocity and SSC increase drastically at the bore arrival, the records were at one minute intervals in the hour around the bore arrival, and half an hour in the rest of the tidal period. No extreme conditions like flood events or storms occurred during the survey.

Furthermore, the daily river discharge from FPS and the detailed bathymetric data in April, July and November in 2015 at the Zakou-Ganpu reach, were collected in order to relate the short-term hydrodynamics to long-term bathymetrical changes. The digital elevation models (DEM) were reconstructed by interpolation of the data using the Surfer software package, making use of the Kriging interpolation technique, which has been widely used in previous studies (e.g. van der Wal et al., 2002; Blott et al., 2006; Dai et al., 2014). Spatial deposition and erosion patterns and associated volume changes were calculated by subtraction of the DEMs.

4. Results

The volumes of ZY and YG reaches are characterized by seasonal and inter-annual variations (Fig. 2a and b). Over the ZY reach, the volume in July is apparently larger than that in April and November, and the volume in November is smaller than in July and a little larger than in April. The mean values since 1981 in April, July and November are 294, 364 and 312 × 10^6 m^3, respectively. Moreover, the volumes in wet years (1987–1999 and 2010–2016) are larger than in dry years (1981–1986 and 2003–2009), by about 1.5 times on average. The volume in July at the ZY section correlates well with the mean river discharge during April–July (Fig. 2c):

$$V = 7.57Q^{0.54} \quad (1)$$

where V is volume in 10^6 m^3, and Q is river discharge in m^3/s. The correlation coefficient is 0.91, indicating the river flow dominance on the morphology during the high discharge season.

The volume over the YG reach has a trend of decrease, which is related to the large-scale embankment building in the Qiantang Estuary in the last decades (Xie et al., 2017b). Overall, the seasonal variation of the volume of the YG reach is opposite to that of the ZY reach, with the mean volumes being 3304, 3173 and 3285 × 10^6 m^3, in April, July and November, respectively, indicating active sediment exchange between the two reaches. The maximum volume change in the wet season of 1995 over the ZY and YG reaches were 200 and 400 × 10^6 m^3, respectively. It should be noted that the volume changes of the two reaches are not always comparable because there exists active sediment

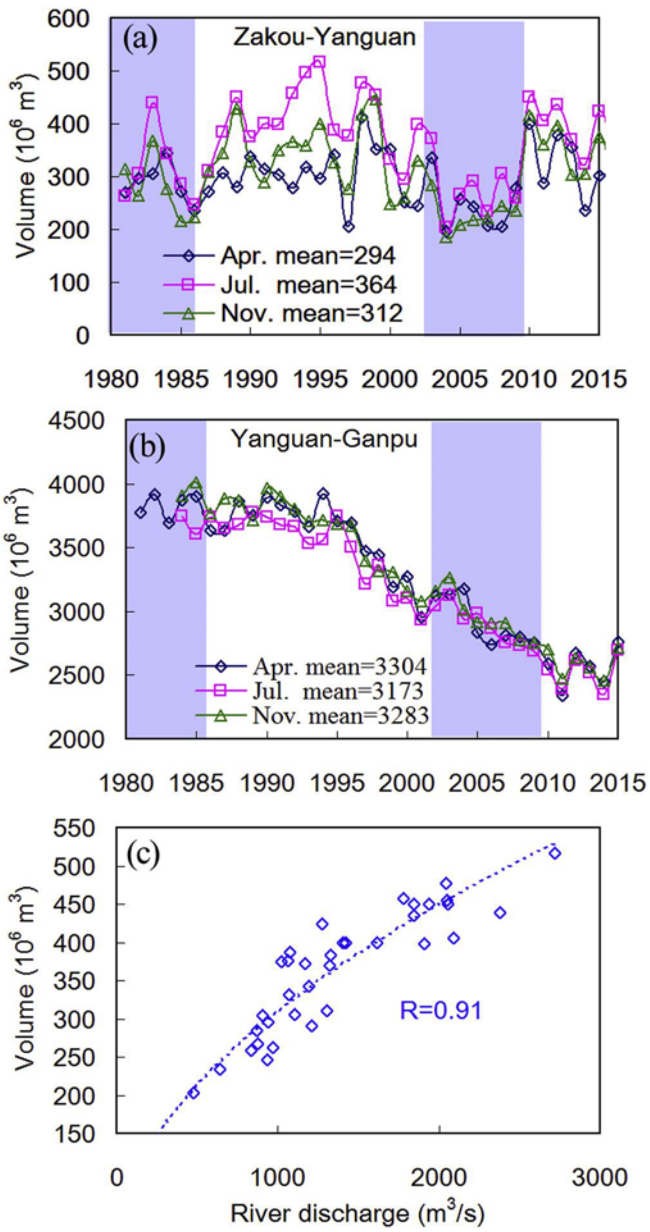

Fig. 2. (a, b) The volumes of the ZY and YG reaches in every April, July and November since 1981. The shades denote the continuous dry years. (c) Relationship between the volume of ZY reach in July and the average river discharge from April to July.
Data in April of panels A and B from Xie et al. (2017b).

exchange between the YG reach and the lower estuary, i.e., the Hangzhou Bay (Chen et al., 1990; Han et al., 2003; Xie et al., 2017b).

The hydrodynamics at the YG01 station during spring and intermediate tides in October 2015 were characterized by the tidal bore (Fig. 3). Upon the arrival of the bore, the water level increased by about 3 m within 1 min. The velocity reversed from ebb current of less than 1.5 m/s to flood currents of 2.7 m/s in 1 min and the maximum of 4.2 m/s was reached within half an hour. The SSC increased from less than 2 kg/m^3 to about 15 kg/m^3. This is consistent with Pan and Huang (2010) and Chanson (2012) that sudden velocity and SSC changes occur at the bore arrival. Accordingly, the sediment flux, a function of velocity, water depth and SSC, reversed from less than 60 kg/s/m seawards to more than 300 kg/s/m landwards. The sediment fluxes during ebb tides were comparable to that of the adjacent Changjiang Estuary, which is normally less than 50 kg/s/m (Milliman et al., 1985; Su and Wang, 1986; Li et al., 2011). During neap tides, undular bores were present and the capacity of sediment transport decreased significantly. The sediment mass transport during flood and ebb on spring tides can be around 900 and 500 t/m, respectively. The sediment fluxes during flood or ebb tides correlated well with the tidal range at Ganpu (Fig. 3c). In estuaries the net flux over a tidal cycle may be difficult to measure or compute using field data because it is a very small number based on the difference between the very large flood and ebb fluxes (Townend and Whitehead, 2003). However, in this study the net sediment transport was distinctly directed landward during spring and intermediate tides, because of the large landward sediment fluxes induced by the tidal bore; whereas it was seaward during neap tides due to the much longer duration of the ebb tides. In the spring-neap tidal cycle, the net landward sediment mass transport per m width was around 2000 t, indicating that accretion would occur in the dry season.

Fig. 4a and b illustrate the erosion and deposition patterns during April–July and July–November 2015. Only one river flood event occurred in June, with the peak discharge being 12,600 m^3/s. Despite the short duration of the river flood (about 10 days), the bed upstream of Yanguan was seriously eroded. The erosion mainly occurred around the thalweg, and the maximum erosion was more than 5 m. The volume over the ZY section increased from 301 × 10^6 to 424 × 10^6 m^3, indicating an erosion of 123 × 10^6 m^3. The eroded sediment was transported seaward and deposited in the YG reach and the Hangzhou Bay. The volume over the YG reach decreased from 2762 × 10^6 to 2692 × 10^6 m^3, indicating a decrease of 70 × 10^6 m^3. The bed level changes from July to November were opposite: sedimentation of 46 × 10^6 m^3 over the ZY reach and erosion of 25 × 10^6 m^3 over the YG reach.

Assuming that the observed data during October 2015 can represent the period between July and November, and considering that the width at Yanguan reach is about 2.5 km, the cumulative landward sediment transport from July to November was about 80 × 10^6 t. Given that the dry density of the sediment is 1650 kg/m^3, the net sedimentation at the upstream of Yanguan was about 48 × 10^6 m^3, consistent with the volume change over the ZY reach based on the DEM comparison.

5. Discussion

Results in this study support the conceptual model proposed by Hoitink et al. (2017) that seasonal variations of river flow can play an important role on the estuarine morphodynamic equilibrium. Under usual flow discharge conditions, sediment transport is directed landwards. The role of the tidal bore on the landward sediment transport is not intrinsically different from the flood dominance in other estuaries (Dronkers, 1986; Wang et al., 2002; Bolle et al., 2010). On the other hand, the capacity of sediment transport of the bore is much larger than normal tidal currents. The flood current velocities during spring and intermediate tides can be more than 4 m/s, about twice the maximum velocity of ebb tides, which results in extreme flood dominance. Furthermore, when the bore arrives, SSC also increases drastically because of the fine sediment that can be easily resuspended and, therefore, the sediment flux during flood tides is very large. Whereas the current velocity and SSC during ebb tides are much lower, and the sediment flux during ebb is less despite the much longer ebb duration. As a result, the net sediment transport over a tidal cycle is directed landward. The river flood events produce remarkable erosion. The larger the river discharge, the more sediment can be transported seaward. In a seasonal timescale, the morphology in the estuary is apparently deviated from its equilibrium; but within a whole year the two opposite processes can be balanced, and subsequently a dynamic equilibrium can be maintained.

One of the most striking features of Qiantang Estuary is bed erosion during river flood events, especially in the upper reach of the estuary (Fig. 4b). The serious bed degradation can be explained by the fact that the discharge during a river flood event is much larger than the normal discharge which is around 1000 m^3/s (Chen et al., 2006). Previous

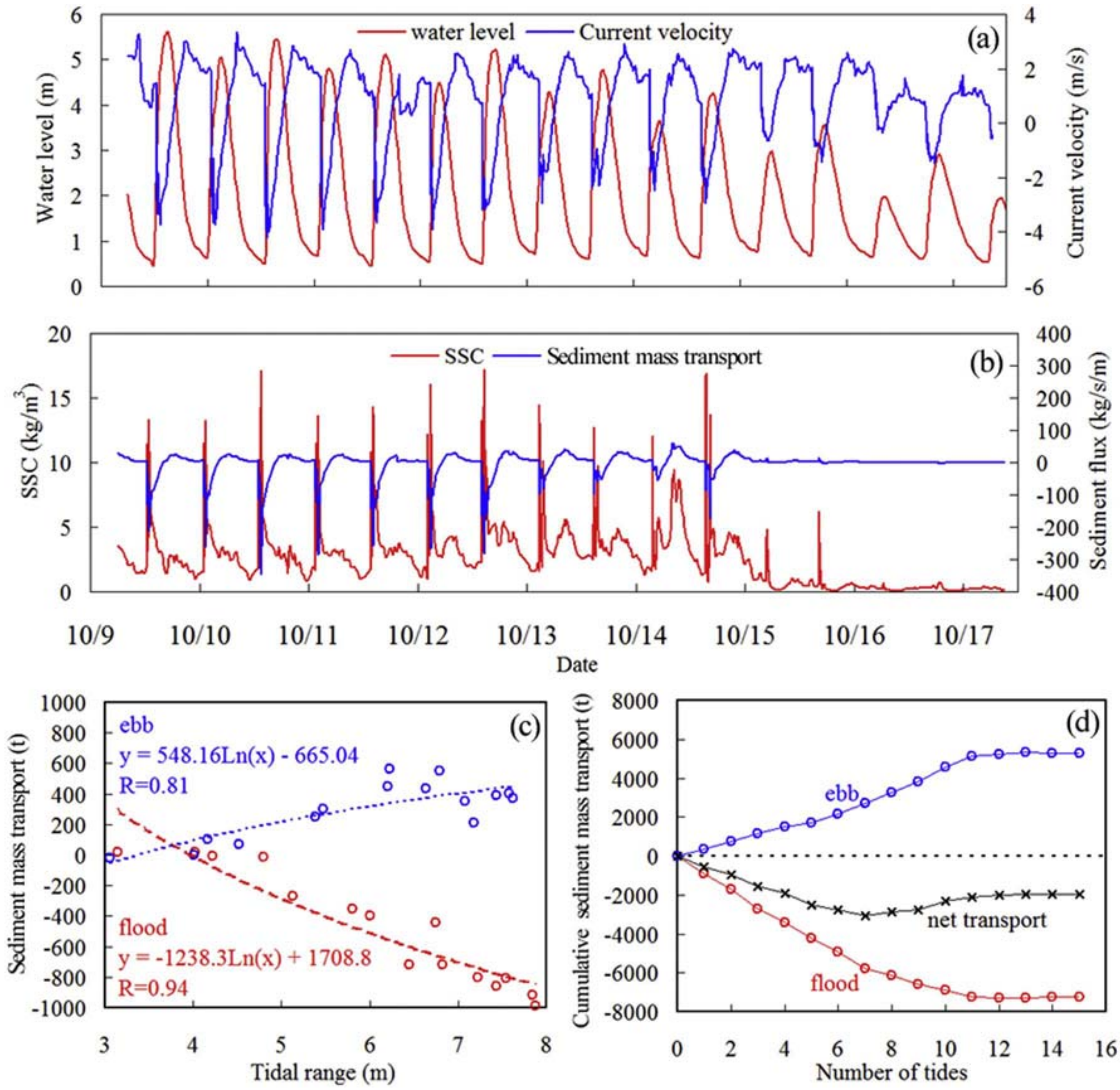

Fig. 3. (a, b) Time series of tidal level, depth-averaged current velocity, SSC and sediment flux at YG01 station during 9–17th October 2015. (c) Relationship between flood and ebb sediment fluxes and tidal range at Ganpu station. (d) The cumulative and net sediment mass transport during the measurement.

studies have found that the cross-sectional area and the cross-sectional averaged depth of estuaries are power functions of the river discharge (Leopold and Maddock, 1953; Smith, 1974; Han et al., 2009). Considering that the volume is a function of cross-sectional area and the length, it is reasonable that the volume adjusts in a power-law relationship with the changes of river discharge, as fitted by Eq. (1). Such a formula provides a simple tool to predict the bathymetry of the estuary at the end of the high discharge season, given the averaged river discharge of the high discharge season is available.

In general, river flood events induces active channel morphodynamics such as bank erosion and point bar deposition due to increased discharge and enhanced sediment concentrations (e.g. Mutti et al., 1985; Dalrymple and Choi, 2007). However, such channel morphological behavior is apparently not the case in the present Qiantang Estuary. Instead, the bed level rises and falls in response to sediment import and export. This is because the estuary has been significantly influenced by the construction of unerodible artificial levee (Fig. 1a). Actually, before the large-scale embankment in the estuary, pronounced lateral migration of the thalweg occurred frequently, especially at the bends like Qibao and Cao'E (Chien et al., 1964). This is mainly caused by the inconsistence of flood and ebb current routes, which would adjust according to the seasonal changes of the relative strength of river flow to tidal current.

6. Conclusions

The big dataset obtained from the long-term bathymetry and hydrological survey in the Qiantang Estuary provided a quantitative illustration of how a dynamic equilibrium of morphology is maintained over a seasonal and inter-annual scale. The active morphological behaviors are controlled by river flood events and the extreme flood tide dominance associated with tidal bores. The tidal bore transports a large amount of sediment landward, causing accumulation during normal river discharge periods. Conversely, river flood events erode the bed severely. Furthermore, a power function was built between the averaged river discharge and the channel volume of the upper part in high flow season. The estuary has also been significantly influenced by the large-scale embankment in last decades, which constrained the lateral migration of thalweg and point bar deposition.

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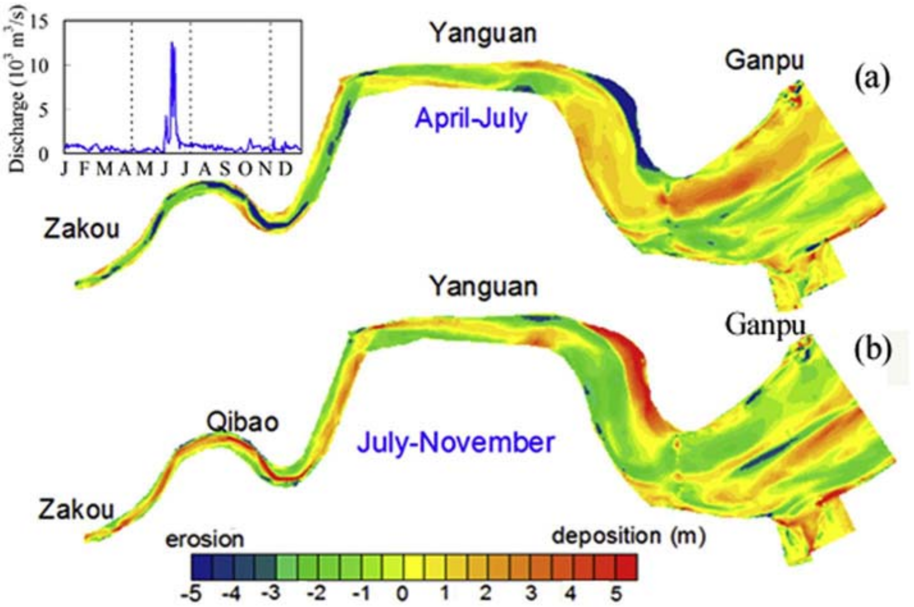

Fig. 4. Bed erosion and accretion patterns from April to July (a) and from July to November (b) in 2015. The upper left panel of panel a shows the time series of daily river discharge from FPS in 2015 and survey periods (dashed lines).

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