An analysis on half century morphological changes in the Changjiang Estuary: Spatial variability under natural processes and human intervention

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Abstract

Examination of large scale, alluvial estuarine morphology and associated time evolution is of particular importance regarding management of channel navigability, ecosystem, etc. In this work, we analyze morphological evolution and changes of the channel-shoal system in the Changjiang Estuary, a river- and tide-controlled coastal plain estuary, based on bathymetric data between 1958 and 2016. We see that its channel-shoal pattern is featured by meandering and bifurcated channels persisting over decades. In the vertical direction, hypsometry curves show that the sand bars and shoals are continuously accreted while the deep channels are eroded, leading to narrower and deeper estuarine channels. Intensive human activities in terms of reclamation, embankment, and dredging play a profound role in controlling the decadal morphological evolution by stabilizing coastlines and narrowing channels. Even though, the present Changjiang Estuary is still a pretty wide and shallow system with channel width-to-depth ratios >1000 , much larger than usual fluvial rivers and small estuaries. In-depth analysis suggests that the Changjiang Estuary as a whole exhibited an overall deposition trend over 59 years, i.e., a net deposition volume of $8.3 \times 10^8 \text{ m}^3$. Spatially, the pan-South Branch was net eroded by $9.7 \times 10^8 \text{ m}^3$ whereas the mouth bar zone was net deposited by $18 \times 10^8 \text{ m}^3$, suggesting that the mouth bar zone is a major sediment sink. Over time there is no directional deposition or erosion trend in the interval though riverine sediment supply has decreased by 2/3 since the mid-1980s. We infer that the pan-South Branch is more fluvial-controlled therefore its morphology responds to riverine sediment load reduction fast while the mouth bar zone is more controlled by both river and tides that its morphological response lags to riverine sediment supply changes at a time scale >10 years, which is an issue largely ignored in previous studies. We argue that the time lag effect needs particular consideration in projecting future estuarine morphological changes under a low sediment supply regime and sea-level rise. Overall, the findings in this work can have implications on management of estuarine ecosystem, navigation channel and coastal flooding in general.

Keywords	Changjiang Estuary; Morphological Evolution; Sediment supply
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Data will be made available on request

Dear Editors:

Thank you again for handling our work and giving us the opportunity for revising the manuscript. In this revision, we mainly address the misunderstood point regarding the impacts of big river floods on the estuarine morphological changes and its spatial behavior. Please find the response letter and the marked manuscript for the changes.

For any further revisions needed, please feel free to contact us.

Thank you and best regards.

Yours sincerely,

Jie Zhao

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Response letter

Dear Editor,

Thank you very much again for your comments. A slightly revised manuscript with the correction marked is attached for your reference. All comments are addressed point-to-point as in this response letter (see details below). Please feel free to let us know of any further comments and revision needed.

Reviewer 1: Overall, the revised manuscript addressed all of my concerns, I do not have more critical questions. I thus suggest that the manuscript be accepted at its present state.

A: Many thanks for the positive comments and encouragement.

Response to Reviewer 1 (Two questions still to be revised):

1). on Line 375, "600 m" should be "600 km".

A: Thanks for your comments and suggestions. '*600 m*' is corrected as '*600 km*' (line 375).

2). A question remains that during big floods, for Region A and B, the channels experience erosion, with the sand bars and shoals enduring sedimentation. While for the MBZ, the channel is under siltation and shoals are eroded. Could a brief explanation for such a behavior be given in the text?

A: Thanks for your comments and suggestions. There may be some misunderstanding regarding the impacts of big river floods in this case. In Figure 4, we see that the period 1997-2002 was characterized by overall much more severe erosion throughout

the estuary compared to other periods. We argue that this significant erosion could be related to enduring high river discharges and sediment deficiency during big river floods in the interval. The slight net deposition in Region A in this interval is the result of imbalance between channel erosion and shoal accretion, which reflects strong channel migration and shoal movement as a result of big river floods as well. Actually channel erosion and shoal accretion in Region A occurred throughout the ~60 years in this study, thus this morphological behavior is not merely related to big river floods. In the same period, the channels were also largely eroded in Region C, and deposition only dominated in the utmost delta front region, reflecting deposition of seaward flushed sediment by strong river forcing. These clarifications are included in the revision in section 4.3 (Lines 404-438). Please see the marked manuscript for the revision.

We look forward to your findings and thank you for your assistance in handling this work.

With kind regards

Jie Zhao, Leicheng Guo

On behalf of co-authors:

Prof. Qing He

Prof. Zhengbing Wang

Dr. D.S. van Maren

Dr. Xianye Wang

Highlights:

- Distinct morphological behavior between South Branch and mouth bar zone in the Changjiang Estuary.
- Large-scale morphodynamic response lags riverine sediment source reduction by a time scale >10 years.
- Big river floods with long duration and sediment deficiency cause severe erosion.
- Human activities stabilize coastlines and narrow channels.

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2 **An analysis on half century morphological changes in the**

3 **Changjiang Estuary: spatial variability under natural processes**

4 **and human intervention**

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63 **Abstract**
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41 ignored in previous studies. We argue that the time lag effect needs particular
42 consideration in projecting future estuarine morphological changes under a low
43 sediment supply regime and sea-level rise. Overall, the findings in this work can have
44 implications on management of estuarine ecosystem, navigation channel and coastal
45 flooding in general.

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47 **Key words:** Changjiang Estuary; Morphological Evolution; Sediment supply

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- 55 ● Human activities stabilize coastlines and narrow channels.

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240 **58 1. Introduction**
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242 59 Morphological evolutions are critical for socio-economic and ecological
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245 60 environmental development, especially in estuaries where most of the world's famous
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247 61 mega cities and harbors locate. The combined action of fluvial discharge, tidal flows,
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249 62 and waves generally controls the long-term estuarine morphological changes,
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251 63 resulting in a feedback loop between estuarine morphology and hydrodynamics
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254 64 through sediment transport (Cowell and Thom, 1994; Freire et al., 2011; Wang et al,
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257 65 2013). Morphological evolution of large estuaries influenced by more than one
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259 66 primary forcing are insufficiently understood owing to inherent complexity in terms
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262 67 of large space scale and strong spatial and temporal variations. In addition,
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264 68 anthropogenic activities, such as waterway regulation project, dredging, embankment,
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267 69 reclamation, and dam construction, have profound effects on estuaries and human
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269 70 interventions play an increasingly important role in driving estuarine morphological
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271 71 changes (Milliman et al., 1985; Syvitski et al., 2005; Wang et al., 2013). Centennial
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274 72 bathymetric data of estuaries are rare while data at decadal time scales are readily
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276 73 more available, enabling quantitative examinations of medium- to long-term (decades
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278 74 to centuries) estuarine morphological evolution in response to natural forcing and
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281 75 human influences.

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283 76 Morphological evolution and channel pattern changes in rivers, tidal basins,
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286 77 estuaries, and coasts have been broadly discussed at varying time scales. The
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288 78 depositional and morphologic patterns can be quite different under varying single or
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290 79 multiple primary forcing including river, tides, waves, etc (Wright, 1977). A
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meandering channel pattern with coexisting flood and ebb channels is observed in tide-dominated systems, such as the Dutch Western Scheldt Estuary (Van Veen, 1950; Van den Berg et al., 1996; Toffolon and Crosato, 2007) and the Chesapeake Bay in the USA (Ahnert, 1960). Distributary channels with multiple bifurcations are observed in river-controlled estuaries and/or delta systems (Andrn, 1994; Edmonds and Slingerland, 2007; Wang and Ding, 2012). Large scale morphodynamic behavior under combined river and tidal forcing, such as the Changjiang Estuary in China, is insufficiently examined (Guo et al., 2015).

Morphological evolution of the Changjiang Estuary has been examined by calculating erosion-deposition volumes and analyzing movements of isobaths, shorelines, and thalwegs (Chen et al., 1985 and 1999; Yun, 2004; Wang et al., 2013; Luan et al., 2016). Riverine sediment source availability and human activities are widely seen as two important factors in controlling morphological evolution in the Changjiang Estuary, which is also true in other estuaries and deltas such as Niles, Mississippi, and Colorado (Syvitski and Kettner, 2011). Note that previous examinations of the morphological changes in the Changjiang Estuary were mainly at regional scale without taking the estuary as a whole into consideration. For instance, owing to riverine sediment supply reduction, regional erosion was detected in the South Branch (Wang et al., 2013) and the delta front regions (10 m deep nearshore) (Yang et al., 2003, 2005, 2011) in the recent decades, whereas the examination of a larger region including the sand bars in the mouth bar zone indicates continued deposition (Dai et al., 2014). Moreover, the time scale of large scale estuarine

morphodynamic adaptation in responding to external forcing changes is very much ignored in previous studies. The morphological impacts of human activities such as reclamations (Chu et al., 2013; Wei et al., 2015) and the Deep Waterway Channel Project along the North Passage (De Vriend et al., 2011; Jiang et al., 2012, 2013) can also vary in a large space and time scales depending on their location, implementation time, and scales. Sea-level rise is also another factor needs consideration (Wang et al., 2013; Wang et al., 2014; Wei et al., 2015). So far, a comprehensive and quantitative investigation of morphological evolution in the entire Changjiang Estuary is still very much needed.

This study analyzes the morphological changes in the Changjiang Estuary as a whole based on the bathymetric data collected in the period between 1958 and 2016. We will focus on the erosion-deposition processes, changes of hypsometry, and cross-section configuration of different branches in the estuary to elaborate the channel patterns and the spatial and temporal variability of the estuarine morphology. The controls of the morphological changes are discussed in terms of natural processes and human activities. The insights obtained from this study are helpful for management and restoration opportunities in the Changjiang Estuary.

2. Data and methods

2.1 Brief introduction to the Changjiang Estuary

The Changjiang River and its estuary is one of the biggest on earth with respect to its quantity such as river discharge, sediment load, and space scales. The annual

mean river discharge is approximately $28.3 \times 10^3 \text{ m}^3/\text{s}$ (1950-2015) and annual sediment load is 3.7×10^8 tons (1953-2015) (CWRC, 2015). The river and sediment discharges exhibit markedly seasonal variations, with about 71% of water flux and 87% of sediment load flushed in the wet season between May and October (Chen et al., 2008). Mean tidal range decreases from about 3.2 m nearshore to 2.4 m at Xuliujing, the present delta apex, and further to be insignificant 500 km upstream of Xuliujing. The tidal prism varies between 1.3×10^9 and $5.3 \times 10^9 \text{ m}^3$, with a mean tidal discharge almost 9 times as much as the mean river discharge (Chen et al., 2002). Thus the Changjiang Estuary is dominantly a partially-mixed, meso-tidal system (Chen et al., 2002). The waves in the Changjiang Estuary are mainly wind waves with a mean wave height of 0.9 m at Yinshuichuan in the river mouth area (Wu et al., 2009; Wang et al., 2013). River and tides are the main forcing conditions though wind and waves can affect hydrodynamics and sediment transport over the shallow tidal flats. The present Changjiang Estuary has four prime inlets connecting to the sea, namely the North and South Branch, North and South Channel, and North and South Passages (Fig. 1). The estuary mouth is as wide as 90 km and the width decreases to approximately 6 km at the apex of the funnel-shaped estuary, i.e., Xuliujing. Overall the Changjiang Estuary is a complex large scale system with few comparable cases in the world.

2.2 Data and methods

We collect bathymetric data in 1958, 1973, 1986, 1997, 2002, 2010, and 2016, covering the entire regions seaward Xuliujing until 10-15 m deep waters (Fig. 1). The North Branch (NB), nowadays tide-dominated and limitedly influenced by fluvial processes, is excluded in this study due to data scarcity. The bathymetry data in 1958, 1973, and 1986 are obtained from digitization of historical marine charts with a resolution 1/50000 and data in other years are from field sounding measurements with an accuracy of 1-2% for depths <2 m and <1% for depths >2 m (Wang et al., 2011, 2013). All depth data are referenced to the same datum, the Theoretical Lowest Astronomical Tide (TLAT), which is basically below local mean water level by a half maximum tidal range (~ 2 m). A digital elevation model (DEM) by 20×20 m is created using Kriging interpolation.

Considering spatial variations of hydrodynamics, sediment properties, and morphological features (Fig. 3), we divide the study area into three regions for the benefit of clarification. Region A includes the South Branch (SB) and region B includes the South Channel (SC) and the upper section of the North Channel (NC), while region C indicates the mouth bar zone (MBZ) which includes the lower section of the North Channel, the North Passage (NP), and the South Passage (SP). Regions A and B together are also named pan-South Branch (PSB) region as a counterpart of region C (Fig. 1). Erosion and deposition volumes of different regions and the estuary as a whole are calculated for different time intervals. Hypsometry curves are also derived by linking channel volumes and planar areas at different depths. The hypsometric curves help to uncover morphological change of channels and shoals in

the vertical direction. Moreover, we also estimate variations of width, depth, and width-to-depth ratio and examine cross-section profile variations in different regions.

3. Results

3.1 Overall morphological evolution (1958-2016)

We see that there is no new channel bifurcation in the Changjiang Estuary since 1958. The three-level bifurcation and four-outlet configuration persists and the channels and shoals develop toward mature conditions by strong erosion and deposition evolution (Fig. 4). The middle-channel channel-shoal pattern is featured by meandering channels and sand bars. The entire estuary becomes narrower and deeper owing to deposition over the shoals and tidal flats and erosion along the channels.

3.2 Erosion and deposition patterns

The study area as a whole (including regions A, B, and C) had experienced deposition from 1958 to 2016. The total net deposition amount of the study area reached $8.3 \times 10^8 \text{ m}^3$ over 59 years, which equals a net deposition rate of $14.3 \times 10^6 \text{ m}^3/\text{year}$.

Temporally, the estuary did not exhibit directional persistent deposition or erosion over 59 years (Table 1, Fig. 4). The entire study area first experienced fast deposition in 1958-1973 ($98.2 \times 10^6 \text{ m}^3/\text{year}$), followed by slight erosion in 1973-1986 ($9.2 \times 10^6 \text{ m}^3/\text{year}$), deposition in 1986-1997 ($56.3 \times 10^6 \text{ m}^3/\text{year}$), erosion in 1997-2002 again ($40 \times 10^6 \text{ m}^3/\text{year}$), slight deposition in 2002-2010 ($13.9 \times 10^6 \text{ m}^3/\text{year}$), and recently fast erosion in 2010-2016 ($175.7 \times 10^6 \text{ m}^3/\text{year}$).

Spatially, the net erosion volume was $9.7 \times 10^8 \text{ m}^3$ in the pan-South Branch between 1958 and 2016. Approximately 52% of that occurred in region A and 48% in region B. To the contrast, the MBZ was deposited by $18 \times 10^8 \text{ m}^3$ in the interval, indicating that the MBZ is a major sediment sink. The erosion and deposition patterns are different in different regions (Table 1). Region A had changed from deposition (1958-1973, $19.2 \times 10^6 \text{ m}^3/\text{year}$) to erosion (2010-2016, $28.8 \times 10^6 \text{ m}^3/\text{year}$). Similar variation behavior was also observed in region B by slight deposition (1958-1973, $5.5 \times 10^6 \text{ m}^3/\text{year}$) and moderate erosion (2010-2016, $31.7 \times 10^6 \text{ m}^3/\text{year}$). However, region C showed a strong deposition trend from 1958 to 2010 and the deposition rates reached up to $75 \times 10^6 \text{ m}^3/\text{year}$ most of the time, followed by significant erosion of $1.15 \times 10^8 \text{ m}^3/\text{year}$ since 2010.

3.3 Changes of hypsometry

Hypsometric curve is a concise and quantitative way to understand vertical morphological characteristics. According to the hypsometric curves of the study area as a whole from 1958 to 2016 (Fig. 5D), both the total water volume and area of the study area decreased due to deposition and human activities. Specifically, the total water volume of the region below +2 m isobaths was $31.6 \times 10^9 \text{ m}^3$ in 1958. It decreased to $30 \times 10^9 \text{ m}^3$ in 2016, indicating 5% reduction compared to 1958. The total area at +2 m isobaths also decreased by about 514 km^2 from 1958 to 2016, i.e., 13% of that in 1958, mainly owing to reclamations and embankment for the Qingcao Shoal reservoir.

In the vertical direction, the erosion and deposition patterns of the sand bars and shoals and the deep channels were quite different from each other during the past 59 years. By comparing the water volumes and areas of the channels under different isobaths in both 1958 and 2016 (Fig. 5D), we see that the entire study area was confined by -8 m isobaths. The water volume of the region above -8 m (-8~+2 m) isobaths reduced from $28.1 \times 10^9 \text{ m}^3$ in 1958 to $25 \times 10^9 \text{ m}^3$ in 2016, and the area decreased from $2.76 \times 10^9 \text{ m}^2$ to $2.15 \times 10^9 \text{ m}^2$. Deposition took place in the sand bars and shoals, which includes intertidal zone (0~+2 m). The water volume of the region below -8 m isobaths (-8~-20 m) increased by about $1.49 \times 10^9 \text{ m}^3$ and the area increased by $0.1 \times 10^9 \text{ m}^2$. In the deep part of the channels below -12 m isobaths, the water volume and the area increased by $0.9 \times 10^9 \text{ m}^3$ and $0.11 \times 10^9 \text{ m}^2$, respectively. Thus the channels, especially the deep parts of them, were continuously eroded from 1958 to 2016.

For three regions of the estuary, deposited sand bars and shoals and eroded deep channels were also detected from 1958 to 2016, but the depth thresholds for shallow (deposited) and deep (eroded) areas were different. Region A as a whole was separated by -7 m isobaths while region C was separated by -8 m isobaths. The shape of the hypsometric curves in different years was similar to each other, for both regions A and C (Fig. 5A and 5B). However, region B was separated by -1 m isobaths. The hypsometric curves in region B had significantly changes during the past 59 years, especially after 2002, mainly owing to embankment for the Qingcao Shoal reservoir (Fig. 5C).

235 3.4 Changes of cross-section

236 The width of the cross-sections in region C increases in the seaward direction.
 237 The depth of the cross-sections has a significant seaward decrease trend and has a
 238 minimum value on the top of the mouth bar. They are quite different from those in
 239 regions A and B which do not have such a significant seaward depth variation along
 240 the river.

241 For the chosen 6 cross-sections in the Changjiang Estuary (Fig. 6), the width and
 242 average depth at 0 m of the cross-section 1 in region A were 11.1 km and 8 m in
 243 1958, respectively. They changed to 11.5 km and 8.6 m in 2016. And the width to
 244 depth ratio (B/H) reduced by 4% from 1958 to 2016. The average depths of the cross-
 245 sections 2 and 3 in region B both increased by 0.2 m and 3.1 m, respectively. The
 246 width of the former increased by about 5% while the latter reduced by 16%. The B/H
 247 of the cross-section 2 in the South Channel had no obvious change, but that of the
 248 cross-section 3 in the upper section of the North Channel significantly decreased by
 249 40%, due to embankment for the Qingcao Shoal reservoir. The above-mentioned
 250 parameters of cross-sections 4, 5 and 6 in region C also had a similar variation
 251 tendency as those in the upper section of the North Channel. From 1958 to 2016, the
 252 mean width and width to depth ratio of the three cross-sections in region C reduced by
 253 42% and 60%, respectively, while the mean depth increased by almost 50%. The
 254 reclamations in both East Nanhui shoal and East Hengsha shoal and the Deep
 255 Waterway Channel Project in the North Passage were the main reasons for such

changes (Fig. 6B and 6C).

So far, the width at 0 m of the most cross-sections in the Changjiang Estuary had a decreasing trend while the average depth had an increasing trend from 1958 to 2016, especially in the regions where human activities occurred frequently. Thus the mean width to depth ratio of the cross-sections decreased obviously during the past 59 years. It indicated that the cross-sections in the Changjiang Estuary became much narrower and deeper from 1958 to 2016, corresponding to deposition in the sand bars and shoals and erosion in the deep channels.

4. Discussion

4.1 Spatially varying hydrodynamics and sediment characteristics

The Changjiang Estuary covers so large area that hydrodynamics and sediment transport dynamics present strong spatial variations from upstream to downstream due to the combined effect of river and tides (Liu et al., 2010; He et al., 2015). Most of the main channels in the Changjiang Estuary are ebb-dominated with stronger ebb currents than flood currents (Fig. 3A). The ratios of river discharge to tidally mean discharge (Q_r/Q_t) present an obvious decreasing tendency in the seaward direction. For instance, the Q_r/Q_t ratios are 0.44 and 0.12 in regions A and C, respectively (Fig. 3B). From the South Branch to the MBZ, the Q_r/Q_t ratio reduces by 73%. It indicates that the South Branch is more river-influenced while the MBZ is much more tidal-influenced than the South Branch.

The suspended sediment concentration (SSC) exhibits an increasing trend from

upstream (region A) to downstream (region C). For example, the mean SSC was only 0.43 kg/m³ between 2003 and 2007 in the South Branch (region A), while the mean SSC increased to 0.99 kg/m³ in the South Passage (region C), which is twice more than that in the South Branch (Fig. 3C; Liu et al., 2010; He et al., 2015).

The grain size of suspended sediment presents an increasing trend from the South Branch to the MBZ (Fig. 3D). In 2003, the median grain size of suspended sediment in region A was 6.5 μ m while it was 8~9.5 μ m in the MBZ. In contrast, the grain size of bottom sediments decreases seaward along the river. In the main channel of the South Branch, the median grain sizes of bottom sediments were >200 μ m while such values were far <50 μ m in the main channel of the MBZ in 2003 (Fig. 3E).

All these differences between regions A and C (region B is in transition between them) suggest that they are controlled by different hydrodynamic conditions thus potentially explaining different morphological behavior between them.

4.2 Spatially varying morphodynamic behavior of the Changjiang Estuary

Riverine input is a major source of water and sediment fluxes that influence the estuarine morphological evolution. Sediment source reductions below pristine conditions are observed in many estuaries creating new challenges to estuaries and deltas under sea level rise (Syvitski et al., 2011). For the Changjiang Estuary, it was obvious that the morphological changes were influenced by riverine sediment load reduction (Yang et al., 2005, 2011; Kuang et al., 2013; Wang et al., 2008, 2013; Wang et al., 2014), but some parts of the estuary, such as the MBZ, had little response

to riverine sediment load reduction within a short time (Dai et al., 2014), owing to the complex spatio-temporal variations of hydrodynamics and sediment characters in such a large estuary. The effects of sediment source reduction caused by the Three Gorges Dam in the watershed on estuarine morphological change are still in dispute. How different branches in the Changjiang Estuary responded to sediment source reduction needs further clarification.

It is widely known that river discharge acting on the Changjiang Estuary did not show significant decreasing or increasing trend from 1958 to 2016, but the sediment load at Datong had significantly reduced since the mid-1980s, mainly attributed to dam constructions in the drainage basin. The annual river discharge at Datong remained about $890 \times 10^9 \text{ m}^3/\text{year}$ in the total six periods while the annual sediment load had continuously reduced from $4.82 \times 10^8 \text{ t/year}$ (1958-1973) to $1.28 \times 10^8 \text{ t/year}$ (2010-2016), a 2/3 reduction (Fig. 2A; Chen et al., 2008; He et al., 2015). However, there was no directional deposition or erosion trend of the entire study area in the estuary (Table 1), suggesting that estuarine morphological changes are not linearly or simply correlated with riverine sediment supply changes as widely documented in previous studies. We will discuss potential factors acting on the inconsistent change behavior, including spatially varying estuarine morphological response behavior, time lag effect, etc.

Both regions A and B were featured by an obvious switch change from deposition to erosion over time. A positive linear relationship was found between the annual mean erosion or deposition rates in region A ($R^2=0.48$) and region B ($R^2=0.56$)

and the annual mean sediment load at Datong (Fig. 7A and 7B), indicating that the morphological changes of these two regions had a good relationship with riverine sediment source variations. We infer that the pan-South Branch is more fluvial-influenced that its morphology is sensitive to riverine sediment supply reduction. On the other hand, the MBZ presented a persisting deposition trend prior 2010 and turned to be afterward erosion. The annual mean erosion or deposition rates of the MBZ had poor relationship with the annual mean sediment load at Datong over 59 years ($R^2=0.19$) (Fig. 7C). We think the MBZ is controlled by both river and tides that its morphological changes can have resilience to sediment source changes and/or are out of phase of sediment source changes.

Specifically, region A turned to be moderately eroded from 1986 to 1997, but region B still showed a slight deposition at that time and shifted to moderate erosion from 1997 to 2002. The response of the South Branch and region B to riverine sediment source reduction thus did not occur simultaneously. We see that both the mean annual erosion or deposition rates of region A and region B are positively correlated to the annual mean sediment load at Datong, suggesting erosion happened in these zones due to riverine sediment source reduction. For region A, the correlation changes little ($R^2<0.48$) when considering a 2 year time lag between estuarine morphology and riverine sediment supply. The correlation significantly improves ($R^2=0.77$) in region B considering a time lag of 5 years (Table 2). It indicates that there is a ~ 5 years of time lag for the response of morphological changes in region B, while the time lag of region A is in the order of ~ 2 years,

which is shorter than that in region B. The annual mean erosion or deposition rates of region C (the MBZ) has little ($R^2=0.19$) relationship with the annual mean sediment load at Datong. The correlationship also improves ($R^2=0.53$) considering a time lag of 5 years (Table 2). Though limited data about sediment load at Datong before 1953 is available, we believe that the time lag of morphological changes in the MBZ can be >10 years considering its large scale and tidal influence.

The presence of a time lag between large scale estuarine morphological responses to riverine sediment supply variations is understandable. The Changjiang Estuary is primarily controlled by river and tides. River discharge transports a large amount of suspended sediment seaward and flushes bottom sediments downward. Tidal waves and currents propagate landward and create stratification and gravitational circulations particularly in region C, which have effects in trapping sediment in the mouth bar (turbidity maximum zone) and even inducing landward sediment transport in the bottom layers. Tidal asymmetry and tidal pumping can also favor landward sediment transport though it may be of secondary importance due to high river discharge (Guo et al., 2015). Sediment redistribution within the estuary, e.g., by channel erosion and flat accretion, explains the large scale morphological resilience to external source changes (Guo, 2014). Spatially, region A is overall well-mixed and more river-influenced and its sediment source and transport processes are directly affected by river forcing first (He et al., 2015), explaining why the South Branch is sensitive to riverine input and a small time lag. Region C is dominantly partially-mixed and both river and tides are of equal importance. Region C is strongly

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1066 366 affected by density currents, horizontal circulations, tidal asymmetry, etc. (Guo, 2014;
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1068 367 Wu et al., 2010, 2012; Jiang et al., 2013), that its morphology has large resilience and
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1070 368 inherent buffering effects to riverine sediment source changes. Region C, facing to the
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1075 370 to be transported and deposited in channels. Overall these processes explain why a
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1077 371 large time lag is present in the MBZ compared to the inner estuary, e.g., the South
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1083 373 The time scale of sediment transport in such a large estuary system may also play
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1085 374 a role though it is difficult to quantify accurately. The riverine sediment flux
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1089 376 transported seaward step by step while along river morphological changes have
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1091 377 buffering effects. It can explain the seaward increasing time lag. The SSC in both
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1093 378 regions A and B had decreased significantly over time. For instance, the depth-
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1095 379 averaged SSC in the South Branch and the South Channel reduced by 84% and 64%
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1097 380 from 2003 to 2013, respectively (Fig. 3C). However, the depth-averaged SSC in the
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1101 382 and 75% in the lower section of the North Channel (Fig. 3C). It suggests that the
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1105 384 The overall erosion since 2010 in all the three regions may suggest that the
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1107 385 estuary undergoes a shift from overall deposition to erosion after a time lag (Fig. 4,
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1109 386 Table 1). Comparing with the previous period (2002-2010), the erosion rate of region
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MBZ sustained a high deposition rate from 2002 to 2010, even the sediment load at Datong had reduced by 2/3 since 2003. It suggests that the effects of riverine sediment source reduction on the MBZ are only detectable in the very recent years. It again supports the argument of a time lag $\sim$ 10 years for the response of the morphological changes in region C to riverine sediment source reduction. The time lag effect is easily ignored in the morphological examination in previous studies, which can explain why the controversial conclusions reached.

So far the time lag is only quantitatively discussed due to large bathymetric data interval. Future work by morphodynamic modeling can help to better quantify the time lag and its spatial variability. Actually a large estuarine morphodynamic adaptation time scale is reported in schematized long-term estuarine and deltaic morphodynamic studies and it merits careful consideration in real world as well when predicting future morphological changes in response to a low sediment influx regime and sea level rise.

4.3 Spatially varying morphological changes under big river floods

Estuarine morphological evolution is so complex that it is influenced by a variety of factors other than riverine sediment load changes. River flow is just one prominent process governing estuarine morphodynamics. Though the annually mean river discharge changes little and is not expected to cause directional estuarine morphological changes (Table 1), changes of the frequency and magnitude of episodic big river floods can play a role in shaping morphological evolution (Yun, 2004; Guo,

2014; Luan et al., 2016). At long-term time scales, catastrophic river floods with a peak river discharge $\geq 70,000 \text{ m}^3/\text{s}$ were thought to play a prominent role in stimulating new channel bifurcation in the Changjiang Estuary, such as the formation of the North Passage due to the big flood in 1954 (Yun, 2004). At decadal time scales, we identify five years with flood peak discharges $\geq 70,000 \text{ m}^3/\text{s}$ from 1958 to 2016, including a catastrophic flood in 1998. We see that most of the high river discharges occurred in the period of 1997-2002 (Fig. 2B). Accordingly, the estuary displayed severe erosion in the same interval (1997-2002) compared to other periods though net deposition was detected in region A due to the accretion over the shoals (Fig. 4). This change pattern was inconsistent with the long-term tendency between 1958 and 1997 (Table 1). Linear riverine sediment source reduction since the mid-1980s failed to explain such intense changes.

We argue that enduring high river discharges exert strong influence on estuarine morphological changes. The high river discharges ($>70,000 \text{ m}^3/\text{s}$) persisted 1-2 months in 1998 and 1999, and post-flood discharges maintained at a relatively high level ($>45,000 \text{ m}^3/\text{s}$) for 2-3 months in these two years. The river discharge hydrographs were quite different from normal conditions. It provided a continuous strong river force in flushing sediment seaward. Moreover, based on the historical data from 1951 to 1984, Yin et al. (2009) found significant sediment deficiency for river discharges $>60,000 \text{ m}^3/\text{s}$ at Datong. High river flow has a larger sediment transport capacity but the sediment source-limited condition in the river upstream Datong restricts sediment availability to the estuary, thus triggering erosion in the

estuary considering further by enhanced sediment transport capacity thru river-tide interactions (Guo, 2014). The net deposition in region A in 1997-2002 reflects the imbalance between channel erosion and shoal accretion which is very much related to channel migration and shoal movement caused by big river floods as well. Overall we think that it is not only the magnitude of the flood peak discharges, but also its duration and associated sediment deficiency, matter in causing strong estuarine morphological changes.

4.4 The influence of human activities

Extensive human activities in the estuary locally, such as the Deep Waterway Channel Project, dredging, reclamation, and embankment for reservoir construction, also exert strong impacts in estuarine morphological evolution at decadal time scales (Fig. 8A).

Reclamation and embankment is one of the main factors in stabilizing coastlines and narrowing channels in historic periods. The width of the Xuliujing section narrowed from 15.7 km in 1958 to 5.7 km in 1970s due to reclamation and the narrowed Xuliujing section became a controlling point in stabilizing the division between the South Branch and the North Branch (Yun, 2004; Guo, 2014). As a result of it, the old Baimao Shoal moved northward and merged with the Chongming Island in 1970s and the entrance of the South Branch became much narrower and deeper from 1958 to 1973. For the entire study area, a reduction of 571 km² of the water surface area resulted from reclamation and embankment from 1958 to 2016,

accounting for almost 14% of that in 1958, which meant 11 man-made Hengsha Islands formed in the Changjiang Estuary (Fig. 8A). Due to the reclamation and embankment, the channels in the estuary become much narrower and deeper, especially around the regions reclamation or embankment occurred nearby. For instance, the width and width to depth ratio of the cross-section 3 obviously decreased by 16% and 40%, respectively, especially after 2009 owing to embankment for the Qingcao Shoal reservoir (Fig. 6).

The Deep Waterway Channel Project was carried out in the North Passage of the Changjiang Estuary since 1998 and almost $50\text{-}80 \times 10^6 \text{ m}^3$ of sediment was dredged each year from the navigation channel (Fig. 8B). The morphological changes of the MBZ, including the North Passage, were intensely impacted by these human interventions. The North Passage tended to be a man-controlled bifurcation channel owing to the navigational works and dredging. The cross-section of the North Passage also became narrower and deeper. Taking cross-section 5 as an example, a 53% reduction in width and a 35% growth in average-depth were observed from 1958 to 2016 and a dramatic change mainly occurred since 2002 because of the navigational works and dredging. Other changes such as local erosion in the middle reach of the North Channel and the upper section of the South Passage and reduced horizontal growth and enhanced vertical accretion of the Jiuduan Shoal from 2002 to 2010 were also attributed to the navigational works (Jiang et al., 2010).

Human activities play a more important role in driving abrupt changes of estuarine morphology by stabilizing coastlines and narrowing channels in relatively

short time and their impacts can persist for long time, overlapped by slow changes under natural evolution processes. Overall the Changjiang Estuary is becoming more constrained and human-influenced due to extensive reclamation, embankment, and navigational works and the channel-shoal system of the estuary will be more stabilized under human interventions in the future.

5. Conclusions

We analyzed and interpreted 59-year's morphological evolution of the Changjiang Estuary as a whole from 1958 to 2016 and inferred the causes and implications. We see that its channel-shoal pattern featured by meandering and bifurcated channels does not change over decades though there is strong erosion and deposition. The Changjiang Estuary exhibits an overall deposition trend but with strong temporal and spatial variations. The net deposition volume of the whole study area was $8.3 \times 10^8 \text{ m}^3$ from 1958 to 2016, or a net deposition rate of $14.3 \times 10^6 \text{ m}^3/\text{year}$.

Spatially both regions A and B, the inner part of the estuary, turned from deposition to erosion, i.e., by totally $5 \times 10^8 \text{ m}^3$ and $4.7 \times 10^8 \text{ m}^3$ eroded, respectively, over 59 years. However, there was $18 \times 10^8 \text{ m}^3$ of deposition in region C, i.e., the mouth bar zone, from 1958 to 2016. Erosion had been also detected since 2010 in the MBZ. The strong spatial variability can be explained by the differences in their hydrodynamic forcing and morphological features owing to along river distribution of river and tide energy. In the vertical direction, the hypsometric curves showed that deposition happened over the sand bars and shoals, whereas erosion mainly occurred

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1425 500 The non-directional deposition and erosion trend of estuarine morphological
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1427 501 changes is consistent with directionally decreasing riverine sediment supply. The
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1429 502 morphological change of the pan-South Branch had a good relationship with riverine
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1431 503 sediment source reduction. We infer that the pan-South Branch is more fluvial
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1435 505 mouth bar zone is controlled by both river and tides thus its morphology does not
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1437 506 show a clear linkage with sediment supply. Seaward sediment flushing takes time and
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1439 507 there is a time lag between estuarine morphological changes and riverine sediment
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1441 508 source variations in the different regions. The time lag increases in the seaward
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1443 509 direction and it is >10 years in the mouth bar zone. Sediment redistribution has
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1445 510 buffering effect and the estuarine circulation, tidal pumping, waves, etc. can also
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1447 511 explain sediment trapping in the mouth bar zone which has a large morphological
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by stabilizing coastlines and narrowing channels. Overall the Changjiang Estuary is becoming more constrained and man-influenced due to extensive reclamation, embankment, and the navigational works and the channel-shoal system of the estuary will be more stabilized in the future.

Future work by using morphodynamic modeling is needed to better quantify the time lag and explain the controls of spatial morphological variability.

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References

- Ahnert, F., 1960. Estuarine meanders in the Chesapeake Bay area. *Geographical Review*, 50 (3), 390-401.
- Andrén, H., 1994. Development of the Laitaure delta, Swedish Lapland: A study of growth, distributary forms, and processes. Ph.D. Dissertation of Uppsala University, Uppsala, Sweden.
- Changjiang Water Resources Commission (CWRC)(ed.), 2015. Changjiang River Sediment Bulletin. Changjiang Press, Wuhan, China (in Chinese).

- Chen, J.Y., Yun, C.X., Xu, H.G., 1982. The model of development of the Changjiang Estuary during the last 2000 years. In: V.S. Kennedy (ed.), *Estuarine Comparisons*, Academic Press, New York, 655-666.
- Chen, J.Y., Zhu, H.F., Dong, Y.F., Sun, J.M., 1985. Development of the Changjiang estuary and its submerged delta. *Continental Shelf Research*, 4(1-2), 47-56.
- Chen, J., Li, D., Chen, B., Hu, F., Zhu, H., Liu, C., 1999. The processes of dynamic sedimentation in the Changjiang Estuary. *Journal of Sea Research*, 41(1), 129-140.
- Chen, J., Li, D., 2002. *Regulation of the Changjiang Estuary: Past, Present and Future. Engineered Coasts*. Springer Netherlands, 185-197.
- Chen, X., Yan, Y., Fu, R., Dou, X., Zhang, E., 2008. Sediment transport from the Yangtze River, China, into the sea over the post-Three Gorge Dam period: A discussion. *Quaternary International*, 186(1), 55-64.
- Chen, Z., Song, B., Wang, Z., Cai, Y., 2000. Late Quaternary evolution of the sub-aqueous Yangtze Delta, China: sedimentation, stratigraphy, palynology, and deformation. *Marine Geology*, 162(2-4):423-441.
- Chen, Z., Xu, K., Masataka, W., 2008. Dynamic hydrology and geomorphology of the Yangtze River. In: Gupta A. (ed.), *Large Rivers: Geomorphology and Management*, 457-469.
- Chu, Z., Yang, X., Feng, X., Fan, D., Li, Y., Shen, X., et al., 2013. Temporal and spatial changes in coastline movement of the Yangtze delta during 1974-2010. *Journal of Asian Earth Sciences*, 66, 166-174.
- Cowell, P. J. and Thom, B. G., 1994. Morphodynamics of coastal evolution. In: Carter, R.W.G. and Woodroffe, C. D. (ed.), *Coastal Evolution. Late quaternary shoreline morphodynamics*. Cambridge: Cambridge University Press, 33-86.
- 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), 6600.
- De Vriend, H.J., Wang, Z.B., Ysebaert, T., Herman, P.M., Ding, P.X., 2011. Eco-morphological problems in the Yangtze Estuary and the Western Scheldt. *Wetlands*, 31 (6), 1033-1042.
- Edmonds, D.A., Slingerland, R.L., 2007. Mechanics of river mouth bar formation: implications for the morphodynamics of delta distributary networks. *Journal of Geophysical Research Earth Surface*, 112 (F2), 237-254.

- Edmonds, D.A., Slingerland, R.L., Best, J., Dan, P., Smith, N., 2010. Response of river-dominated delta channel networks to permanent changes in river discharge. *Geophysical Research Letters*, 37(12), doi: 10.1029/2010GL043269.
- Freire, P., Taborda, R., Bertin, X., Guerreiro, M., Fortunato, A. B., Silva, A. M., Andrade, C., Oliveira, A., Antunes, C., Freitas, M. C., Nahon, A., Rodrigues, M. and Bruneau, N., 2011. Medium-term morphodynamic evolution of a small coastal inlet. *Journal of Coastal Research*, 56(SI 64), 666-670.
- Guo, L.C., 2014. Modeling estuarine morphodynamics under combined river and tidal forcing. PH.D. Dissertation of Delft University of Technology, CRC Press.
- Guo, L., Wegen, M., Roelvink, J.A., He, Q., 2015. The role of river flow and tidal asymmetry on 1-D estuarine morphodynamics. *Journal of Geophysical Research: Earth Surface*, 119(11), 2315-2334.
- Guo, L., Mick, V.D.W., Jay, D.A., Matte, P., Wang, Z.B., Roelvink, D., He, Q., 2015. River-tide dynamics: Exploration of nonstationary and nonlinear tidal behavior in the Yangtze River estuary. *Journal of Geophysical Research: Oceans*, 120(5), 3499-3521.
- He, Q., Guo, L., Liu, H., Wang, Y., 2015. Changjiang Estuary Sediment Transport Dynamics. Ecological Continuum from the Changjiang (Yangtze River) Watersheds to the East China Sea Continental Margin. Springer International Publishing, 47-69.
- Jiang, C.J., Li, J.F., de Swart, H.E., 2012. Effects of navigational works on morphological changes in the bar area of the Yangtze Estuary. *Geomorphology*, 139, 205-219.
- Jiang, C.J., de Swart, H.E., Li, J.F., Liu, G.F., 2013. Mechanisms of along-channel sediment transport in the north passage of the Yangtze Estuary and their response to large-scale interventions. *Ocean Dynamics*, 63(2-3), 283-305.
- Kuang, C., Liu, X., Gu, J., Guo, Y., Huang, S., Liu, S., Yu, W., Huang, J., Sun, B., 2013. Numerical prediction of medium-term tidal flat evolution in the Yangtze Estuary: impacts of the Three Gorges project. *Continental Shelf Research*, 52(1), 12-26.
- Li, W., Cheng, H.Q., Li, J., Ping, D., 2008. Temporal and spatial changes of dunes in the Changjiang (Yangtze) Estuary, China. *Estuarine Coastal and Shelf Science*, 77(1), 169-174.
- Liu, H., He, Q., Wang, Z.B., 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.

- Liu, J.P., Li, A.C., Xu, K.H., Velozzi, D.M., Yang, Z.S., Milliman, J.D., DeMaster, D.J., 2006. Sedimentary features of the Yangtze River-derived along-shelf clinoform deposit in the East China Sea. *Continental Shelf Research*, 26(17), 2141-2156.
- 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.
- Marciano, R., Wang, Z.B., Hibma, A., De Vriend, H.J., Defina, A., 2005. Modeling of channel patterns in short tidal basins. *Journal of Geophysical Research: Earth Surface*, 110(F1), 67-106.
- Milliman, J.D., Shen, H.T., Yang, Z.S., Mead, R.H., 1985. Transport and deposition of river sediment in the Changjiang estuary and adjacent continental shelf. *Continental Shelf Research*, 4(1-2), 37-45.
- Syvitski, J.P.M., Kettner, A.J., Correggiari, A., Nelson, B.W., 2005. Distributary channels and their impact on sediment dispersal. *Marine Geology*, 222, 75-94.
- Syvitski, J.P.M., Kettner, A., 2011. Sediment flux and the Anthropocene. *Philosophical Transactions, Series A, Mathematical, physical, and engineering sciences*, 369(1938), 957.
- Toffolon, M., and Crosato, A., 2007. Developing macroscale indicators for estuarine morphology: the case of the Scheldt Estuary. *Journal of Coastal Research*, 23(1), 195-212.
- Van den Berg, J.H., Jeuken, M.C.J.L., Van der Spek, A.J.F., 1996. Hydraulic processes affecting the morphology and evolution of the Westerschelde estuary. In: Nordstorm, K.F. et al. (ed.) *Estuarine Shores: Evolution. Environments and Human Alterations*, John Wiley, London, 157-184.
- Van Veen, J., van der Spek, A.J., Stive, M.J., Zitman, T., 2005. Ebb and flood channel systems in the Netherlands tidal waters. *Journal of Coastal Research*, 21, 1107-1120.
- Walcott, R.C., Summerfield, M.A., 2008. Scale dependence of hypsometric integrals: An analysis of southeast African basins. *Geomorphology*, 96(1-2), 174-186.
- Wang, Y., Shen, J., He, Q., 2010. A numerical model study of the transport timescale and change of estuarine circulation due to waterway constructions in the Changjiang Estuary, China. *Journal of Marine Systems*, 82(3), 154-170.
- Wang, H., Ge, Z., Yuan, L., Zhang, L., 2014. Evaluation of the combined threat from sea-level rise and sedimentation reduction to the coastal wetlands in the Yangtze Estuary, China. *Ecological Engineering*, 71(71), 346-354.

- Wang, Y.H., Ridd, P.V., Wu, H.L., Wu, J.X., Shen, H.T., 2008. Long-term morphodynamic evolution and the equilibrium mechanism of a flood channel in the Yangtze Estuary (China). *Geomorphology*, 99(1-4), 130-138.
- Wang, Y.H., Shen, H.T., LI, J.F., Mao, Z.C., 2011. Geomorphologic features and transport of sandwaves in the flood and ebb channels of the Changjiang Estuary. *Oceanologia et Limnologia Sinica*, 42(2), 330-336.
- Wang, Y.H., Dong, P., Oguchi, T., Chen, S.L., Shen, H.T., 2013. Long-term (1842-2006) morphological change and equilibrium state of the Changjiang (Yangtze) Estuary, China. *Continental Shelf Research*, 56, 71-81.
- Wang, Z.B., Ding, P.X., 2012. The branching channel network in the Yangtze Estuary. *Coastal Engineering Research Council*, 1(33).
- Wright, L.D., 1977. Sediment transport and deposition at river mouths: a synthesis. *Geological Society of America Bulletin*, 88(6), 857-868.
- Wu, H., Zhu, J.R., Choi, B.H., 2010. Links between saltwater intrusion and subtidal circulation in the Changjiang Estuary: a model-guided study. *Continental Shelf Research*, 30(17), 1891-1905.
- Wu, J.X., Liu, J.T., Wang, X., 2012. Sediment trapping of turbidity maxima in the Changjiang Estuary. *Marine Geology*, 303-306(1), 14-25.
- Wu, J., Wang, Y., Cheng, H., 2009. Bedforms and bed material transport pathways in the Changjiang (Yangtze) Estuary. *Geomorphology*, 104(3), 175-184.
- Yang, S.L., Ding, P.X., Chen, S.L., 2001. Changes in progradation rate of the tidal flats at the mouth of the Changjiang (Yangtze) River, China. *Geomorphology*, 38(1), 167-180.
- Yang, S.L., Belkin, I.M., Belkina, A.I., Zhao, Q.Y., Zhu, J., Ding, P.X., 2003. Delta response to decline in sediment supply from the Yangtze River: evidence of the recent four decades and expectations for the next half-century. *Estuarine Coastal and Shelf Science*, 57(4), 689-699.
- Yang, S.L., Zhang, J., Zhu, J., Smith, J.P., Dai, S.B., Gao, A., Li, P., 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), 247-275.
- 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), 14-20.

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1818
1819
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1827
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1829

719 Yin, D.W., Chen, Z.Y., 2009. The Changjiang sediment flux into the seas: measurability and
720 predictability. *Frontier of Earth Science in China*, 3(2), 146-153.
721
722 Yu, Q., Wang, Y., Flemming, B., Gao, S., 2012. Modelling the equilibrium hypsometry of
723 back-barrier tidal flats in the German Wadden Sea (southern North Sea). *Continental Shelf*
724 *Research*, 49(49), 90-99.
725
726 Yun, C.X., 2004. Recent developments of the Changjiang Estuary. China Ocean Press,
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Fig. 1. A sketch map of the study area and division of different branches in the Changjiang Estuary with its bathymetry (depth in meters) in 2016. The whole study area is divided into three parts by brown solid lines, i.e., region A (the South Branch (1[#])), region B (the South Channel (2[#])) and the upper section of the North Channel (5[#]), and region C (the North Passage (3[#]), the South Passage (4[#]), and the lower section of the North Channel (6[#])).

Fig. 2. (A) Annual river discharge and sediment load at Datong from 1950 to 2015 (Blue dotted line: annual river discharge from 1950 to 2015, Brown solid line: annual sediment loads from 1951 to 2015, Brown dotted lines: the annual mean sediment loads during different periods which indicated the riverine sediment load reduction mainly due to dam constructions in the Changjiang River basin (4.7×10^8 t/year 1953-1984, 3.4×10^8 t/year 1986-2002, 1.4×10^8 t/year 2004-2015), Green square solid points: the years that catastrophic floods happened in both 1954 and 1998). (B) The number of the days that daily water discharge is greater than 60,000 m^3/s (blue), 65,000 m^3/s (red), and 70,000 m^3/s (green) each year at Datong from 1958 to 2015.

Fig. 3. Longitudinal distribution of the depth-averaged flood and ebb current velocity during a neap-spring tidal cycle (A), ratio of river discharge to tidally mean discharge (Q_r/Q_t) during a neap-spring tidal cycle (B), depth-averaged suspended sediment concentration (C) (yellow bar: 2003; blue bar: 2013), depth-averaged suspended sediment D_{50} (D), and bottom sediments D_{50} (E) in wet season in 2003 (data from Liu et al., 2010 and He et al., 2015).

Fig. 4. Bathymetry changes of the study area during different periods (1958-1973, 1973-1986, 1986-1997, 1997-2002, 2002-2010, and 2010-2016) (unit: m/year).

Fig. 5. Hypsometry changes of region A (A), region B (B), region C (C), and entire study area (D) from 1958 to 2016.

Fig. 6. (A) Location of 6 chosen cross-sections in the Changjiang Estuary. (B) Width to depth ratios of 6 cross-sections based at 0 m referenced to the TLAT in 1958 and 2016. (C) Morphological variations of 6 cross-sectional profiles in both 1958 and 2016.

Fig. 7. Comparison of mean annual erosion/deposition rates in region A (A), region B (B), and the MBZ (C) with mean annual sediment load at Datong during the different periods.

Table 1. Annual mean river discharge and sediment load at Datong and the erosion or deposition parameters (net rates, area and net thickness) in region A, B, C, and whole study area (A+B+C) during different periods (1958-1973, 1973-1986, 1986-1997, 1997-2002, 2002-2010, 2010-2016) (positive values stand for deposition while negative values stand for erosion).

				1958-1973	1973-1986	1986-1997	1997-2002	2002-2010	2010-2016
	Location		Unit						
Annual-mean river discharge	Datong		10 ⁸ m ³ /year	8632	8925	8805	10018	8401	8588
Annual-mean sediment load	Datong		10 ⁸ t/year	4.88	4.53	3.60	3.36	1.84	1.28
Erosion / deposition parameters	region A	net rates	10 ⁶ m ³ /year	19.2	-0.4	-35.9	16.0	-37.7	-28.8
		area	10 ⁸ m ²	6.9	6.8	6.6	6.7	6.3	6.3
		net thickness	mm/year	27.7	-0.5	-54.3	23.9	-59.6	-45.8
	region B	net rates	10 ⁶ m ³ /year	5.5	-11.1	8.4	-23.5	-23.7	-31.7
		area	10 ⁸ m ²	3.6	3.6	3.5	3.5	2.9	2.9
		net thickness	mm/year	15.1	-31.1	24.4	-67.8	-81.9	-110.8
	region C	net rates	10 ⁶ m ³ /year	73.5	2.3	83.7	-32.5	75.3	-115.3
		area	10 ⁸ m ²	29.0	28.9	28.6	27.9	27.3	25.4
		net thickness	mm/year	25.3	0.8	29.3	-11.6	27.6	-45.3
	A+B+C	rates	10 ⁶ m ³ /year	98.2	-9.2	56.3	-40.0	13.9	-175.7
		area	10 ⁸ m ²	39.6	39.3	38.7	38.1	36.5	34.6
		thickness	mm/year	24.8	-2.3	14.5	-10.5	3.8	-50.8

Table 2. Linear correlation coefficients between the mean annual erosion/deposition rates in region A (A) (i.e., the South Branch), region B (B), and region C (C) (i.e., the MBZ) and the mean annual sediment load at Datong in current periods or 1-5 years before the current periods.

R^2						
Region	corresponding year	previous 1 year	previous 2 years	previous 3 years	previous 4 years	previous 5 years
A	0.48	0.48	0.45	0.35	0.28	0.23
B	0.56	0.58	0.63	0.71	0.73	0.77
C	0.19	0.23	0.29	0.38	0.51	0.53

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**An analysis on half century morphological changes in the
Changjiang Estuary: spatial variability under natural processes
and human intervention**

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Abstract

Examination of large scale, alluvial estuarine morphology and associated time evolution is of particular importance regarding management of channel navigability, ecosystem, etc. In this work, we analyze morphological evolution and changes of the channel-shoal system in the Changjiang Estuary, a river- and tide-controlled coastal plain estuary, based on bathymetric data between 1958 and 2016. We see that its channel-shoal pattern is featured by meandering and bifurcated channels persisting over decades. In the vertical direction, hypsometry curves show that the sand bars and shoals are continuously accreted while the deep channels are eroded, leading to narrower and deeper estuarine channels. Intensive human activities in terms of reclamation, embankment, and dredging play a profound role in controlling the decadal morphological evolution by stabilizing coastlines and narrowing channels. Even though, the present Changjiang Estuary is still a pretty wide and shallow system with channel width-to-depth ratios >1000 , much larger than usual fluvial rivers and small estuaries. In-depth analysis suggests that the Changjiang Estuary as a whole exhibited an overall deposition trend over 59 years, i.e., a net deposition volume of $8.3 \times 10^8 \text{ m}^3$. Spatially, the pan-South Branch was net eroded by $9.7 \times 10^8 \text{ m}^3$ whereas the mouth bar zone was net deposited by $18 \times 10^8 \text{ m}^3$, suggesting that the mouth bar zone is a major sediment sink. Over time there is no directional deposition or erosion trend in the interval though riverine sediment supply has decreased by 2/3 since the mid-1980s. We infer that the pan-South Branch is more fluvial-controlled therefore its morphology responds to riverine sediment load reduction fast while the mouth bar

zone is more controlled by both river and tides that its morphological response lags to riverine sediment supply changes at a time scale >10 years, which is an issue largely ignored in previous studies. We argue that the time lag effect needs particular consideration in projecting future estuarine morphological changes under a low sediment supply regime and sea-level rise. Overall, the findings in this work can have implications on management of estuarine ecosystem, navigation channel and coastal flooding in general.

Key words: Changjiang Estuary; Morphological Evolution; Sediment supply

49 **Highlights:**

- 50 ● Distinct morphological behavior between South Branch and mouth bar zone in
- 51 the Changjiang Estuary.
- 52 ● Large-scale morphodynamic response lags riverine sediment source reduction by
- 53 a time scale >10 years.
- 54 ● Big river floods with long duration and sediment deficiency cause severe erosion.
- 55 ● Human activities stabilize coastlines and narrow channels.

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1. Introduction

Morphological evolutions are critical for socio-economic and ecological environmental development, especially in estuaries where most of the world's famous mega cities and harbors locate. The combined action of fluvial discharge, tidal flows, and waves generally controls the long-term estuarine morphological changes, resulting in a feedback loop between estuarine morphology and hydrodynamics through sediment transport (Cowell and Thom, 1994; Freire et al., 2011; Wang et al, 2013). Morphological evolution of large estuaries influenced by more than one primary forcing are insufficiently understood owing to inherent complexity in terms of large space scale and strong spatial and temporal variations. In addition, anthropogenic activities, such as waterway regulation project, dredging, embankment, reclamation, and dam construction, have profound effects on estuaries and human interventions play an increasingly important role in driving estuarine morphological changes (Milliman et al., 1985; Syvitski et al., 2005; Wang et al., 2013). Centennial bathymetric data of estuaries are rare while data at decadal time scales are readily more available, enabling quantitative examinations of medium- to long-term (decades to centuries) estuarine morphological evolution in response to natural forcing and human influences.

Morphological evolution and channel pattern changes in rivers, tidal basins, estuaries, and coasts have been broadly discussed at varying time scales. The depositional and morphologic patterns can be quite different under varying single or multiple primary forcing including river, tides, waves, etc (Wright, 1977). A

meandering channel pattern with coexisting flood and ebb channels is observed in tide-dominated systems, such as the Dutch Western Scheldt Estuary (Van Veen, 1950; Van den Berg et al., 1996; Toffolon and Crosato, 2007) and the Chesapeake Bay in the USA (Ahnert, 1960). Distributary channels with multiple bifurcations are observed in river-controlled estuaries and/or delta systems (Andrn, 1994; Edmonds and Slingerland, 2007; Wang and Ding, 2012). Large scale morphodynamic behavior under combined river and tidal forcing, such as the Changjiang Estuary in China, is insufficiently examined (Guo et al., 2015).

Morphological evolution of the Changjiang Estuary has been examined by calculating erosion-deposition volumes and analyzing movements of isobaths, shorelines, and thalwegs (Chen et al., 1985 and 1999; Yun, 2004; Wang et al., 2013; Luan et al., 2016). Riverine sediment source availability and human activities are widely seen as two important factors in controlling morphological evolution in the Changjiang Estuary, which is also true in other estuaries and deltas such as Niles, Mississippi, and Colorado (Syvitski and Kettner, 2011). Note that previous examinations of the morphological changes in the Changjiang Estuary were mainly at regional scale without taking the estuary as a whole into consideration. For instance, owing to riverine sediment supply reduction, regional erosion was detected in the South Branch (Wang et al., 2013) and the delta front regions (10 m deep nearshore) (Yang et al., 2003, 2005, 2011) in the recent decades, whereas the examination of a larger region including the sand bars in the mouth bar zone indicates continued deposition (Dai et al., 2014). Moreover, the time scale of large scale estuarine

morphodynamic adaptation in responding to external forcing changes is very much ignored in previous studies. The morphological impacts of human activities such as reclamations (Chu et al., 2013; Wei et al., 2015) and the Deep Waterway Channel Project along the North Passage (De Vriend et al., 2011; Jiang et al., 2012, 2013) can also vary in a large space and time scales depending on their location, implementation time, and scales. Sea-level rise is also another factor needs consideration (Wang et al., 2013; Wang et al., 2014; Wei et al., 2015). So far, a comprehensive and quantitative investigation of morphological evolution in the entire Changjiang Estuary is still very much needed.

This study analyzes the morphological changes in the Changjiang Estuary as a whole based on the bathymetric data collected in the period between 1958 and 2016. We will focus on the erosion-deposition processes, changes of hypsometry, and cross-section configuration of different branches in the estuary to elaborate the channel patterns and the spatial and temporal variability of the estuarine morphology. The controls of the morphological changes are discussed in terms of natural processes and human activities. The insights obtained from this study are helpful for management and restoration opportunities in the Changjiang Estuary.

2. Data and methods

2.1 Brief introduction to the Changjiang Estuary

The Changjiang River and its estuary is one of the biggest on earth with respect to its quantity such as river discharge, sediment load, and space scales. The annual

mean river discharge is approximately $28.3 \times 10^3 \text{ m}^3/\text{s}$ (1950-2015) and annual sediment load is 3.7×10^8 tons (1953-2015) (CWRC, 2015). The river and sediment discharges exhibit markedly seasonal variations, with about 71% of water flux and 87% of sediment load flushed in the wet season between May and October (Chen et al., 2008). Mean tidal range decreases from about 3.2 m nearshore to 2.4 m at Xuliujing, the present delta apex, and further to be insignificant 500 km upstream of Xuliujing. The tidal prism varies between 1.3×10^9 and $5.3 \times 10^9 \text{ m}^3$, with a mean tidal discharge almost 9 times as much as the mean river discharge (Chen et al., 2002). Thus the Changjiang Estuary is dominantly a partially-mixed, meso-tidal system (Chen et al., 2002). The waves in the Changjiang Estuary are mainly wind waves with a mean wave height of 0.9 m at Yinshuichuan in the river mouth area (Wu et al., 2009; Wang et al., 2013). River and tides are the main forcing conditions though wind and waves can affect hydrodynamics and sediment transport over the shallow tidal flats. The present Changjiang Estuary has four prime inlets connecting to the sea, namely the North and South Branch, North and South Channel, and North and South Passages (Fig. 1). The estuary mouth is as wide as 90 km and the width decreases to approximately 6 km at the apex of the funnel-shaped estuary, i.e., Xuliujing. Overall the Changjiang Estuary is a complex large scale system with few comparable cases in the world.

2.2 Data and methods

We collect bathymetric data in 1958, 1973, 1986, 1997, 2002, 2010, and 2016, covering the entire regions seaward Xuliujing until 10-15 m deep waters (Fig. 1). The North Branch (NB), nowadays tide-dominated and limitedly influenced by fluvial processes, is excluded in this study due to data scarcity. The bathymetry data in 1958, 1973, and 1986 are obtained from digitization of historical marine charts with a resolution 1/50000 and data in other years are from field sounding measurements with an accuracy of 1-2% for depths <2 m and <1% for depths >2 m (Wang et al., 2011, 2013). All depth data are referenced to the same datum, the Theoretical Lowest Astronomical Tide (TLAT), which is basically below local mean water level by a half maximum tidal range (~ 2 m). A digital elevation model (DEM) by 20×20 m is created using Kriging interpolation.

Considering spatial variations of hydrodynamics, sediment properties, and morphological features (Fig. 3), we divide the study area into three regions for the benefit of clarification. Region A includes the South Branch (SB) and region B includes the South Channel (SC) and the upper section of the North Channel (NC), while region C indicates the mouth bar zone (MBZ) which includes the lower section of the North Channel, the North Passage (NP), and the South Passage (SP). Regions A and B together are also named pan-South Branch (PSB) region as a counterpart of region C (Fig. 1). Erosion and deposition volumes of different regions and the estuary as a whole are calculated for different time intervals. Hypsometry curves are also derived by linking channel volumes and planar areas at different depths. The hypsometric curves help to uncover morphological change of channels and shoals in

the vertical direction. Moreover, we also estimate variations of width, depth, and width-to-depth ratio and examine cross-section profile variations in different regions.

3. Results

3.1 Overall morphological evolution (1958-2016)

We see that there is no new channel bifurcation in the Changjiang Estuary since 1958. The three-level bifurcation and four-outlet configuration persists and the channels and shoals develop toward mature conditions by strong erosion and deposition evolution (Fig. 4). The middle-channel channel-shoal pattern is featured by meandering channels and sand bars. The entire estuary becomes narrower and deeper owing to deposition over the shoals and tidal flats and erosion along the channels.

3.2 Erosion and deposition patterns

The study area as a whole (including regions A, B, and C) had experienced deposition from 1958 to 2016. The total net deposition amount of the study area reached $8.3 \times 10^8 \text{ m}^3$ over 59 years, which equals a net deposition rate of $14.3 \times 10^6 \text{ m}^3/\text{year}$.

Temporally, the estuary did not exhibit directional persistent deposition or erosion over 59 years (Table 1, Fig. 4). The entire study area first experienced fast deposition in 1958-1973 ($98.2 \times 10^6 \text{ m}^3/\text{year}$), followed by slight erosion in 1973-1986 ($9.2 \times 10^6 \text{ m}^3/\text{year}$), deposition in 1986-1997 ($56.3 \times 10^6 \text{ m}^3/\text{year}$), erosion in 1997-2002 again ($40 \times 10^6 \text{ m}^3/\text{year}$), slight deposition in 2002-2010 ($13.9 \times 10^6 \text{ m}^3/\text{year}$), and recently fast erosion in 2010-2016 ($175.7 \times 10^6 \text{ m}^3/\text{year}$).

Spatially, the net erosion volume was $9.7 \times 10^8 \text{ m}^3$ in the pan-South Branch between 1958 and 2016. Approximately 52% of that occurred in region A and 48% in region B. To the contrast, the MBZ was deposited by $18 \times 10^8 \text{ m}^3$ in the interval, indicating that the MBZ is a major sediment sink. The erosion and deposition patterns are different in different regions (Table 1). Region A had changed from deposition (1958-1973, $19.2 \times 10^6 \text{ m}^3/\text{year}$) to erosion (2010-2016, $28.8 \times 10^6 \text{ m}^3/\text{year}$). Similar variation behavior was also observed in region B by slight deposition (1958-1973, $5.5 \times 10^6 \text{ m}^3/\text{year}$) and moderate erosion (2010-2016, $31.7 \times 10^6 \text{ m}^3/\text{year}$). However, region C showed a strong deposition trend from 1958 to 2010 and the deposition rates reached up to $75 \times 10^6 \text{ m}^3/\text{year}$ most of the time, followed by significant erosion of $1.15 \times 10^8 \text{ m}^3/\text{year}$ since 2010.

3.3 Changes of hypsometry

Hypsometric curve is a concise and quantitative way to understand vertical morphological characteristics. According to the hypsometric curves of the study area as a whole from 1958 to 2016 (Fig. 5D), both the total water volume and area of the study area decreased due to deposition and human activities. Specifically, the total water volume of the region below +2 m isobaths was $31.6 \times 10^9 \text{ m}^3$ in 1958. It decreased to $30 \times 10^9 \text{ m}^3$ in 2016, indicating 5% reduction compared to 1958. The total area at +2 m isobaths also decreased by about 514 km^2 from 1958 to 2016, i.e., 13% of that in 1958, mainly owing to reclamations and embankment for the Qingcao Shoal reservoir.

In the vertical direction, the erosion and deposition patterns of the sand bars and shoals and the deep channels were quite different from each other during the past 59 years. By comparing the water volumes and areas of the channels under different isobaths in both 1958 and 2016 (Fig. 5D), we see that the entire study area was confined by -8 m isobaths. The water volume of the region above -8 m (-8~+2 m) isobaths reduced from $28.1 \times 10^9 \text{ m}^3$ in 1958 to $25 \times 10^9 \text{ m}^3$ in 2016, and the area decreased from $2.76 \times 10^9 \text{ m}^2$ to $2.15 \times 10^9 \text{ m}^2$. Deposition took place in the sand bars and shoals, which includes intertidal zone (0~+2 m). The water volume of the region below -8 m isobaths (-8~-20 m) increased by about $1.49 \times 10^9 \text{ m}^3$ and the area increased by $0.1 \times 10^9 \text{ m}^2$. In the deep part of the channels below -12 m isobaths, the water volume and the area increased by $0.9 \times 10^9 \text{ m}^3$ and $0.11 \times 10^9 \text{ m}^2$, respectively. Thus the channels, especially the deep parts of them, were continuously eroded from 1958 to 2016.

For three regions of the estuary, deposited sand bars and shoals and eroded deep channels were also detected from 1958 to 2016, but the depth thresholds for shallow (deposited) and deep (eroded) areas were different. Region A as a whole was separated by -7 m isobaths while region C was separated by -8 m isobaths. The shape of the hypsometric curves in different years was similar to each other, for both regions A and C (Fig. 5A and 5B). However, region B was separated by -1 m isobaths. The hypsometric curves in region B had significantly changes during the past 59 years, especially after 2002, mainly owing to embankment for the Qingcao Shoal reservoir (Fig. 5C).

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235 **3.4 Changes of cross-section**

236 The width of the cross-sections in region C increases in the seaward direction.
237 The depth of the cross-sections has a significant seaward decrease trend and has a
238 minimum value on the top of the mouth bar. They are quite different from those in
239 regions A and B which do not have such a significant seaward depth variation along
240 the river.

241 For the chosen 6 cross-sections in the Changjiang Estuary (Fig. 6), the width and
242 average depth at 0 m of the cross-section 1 in region A were 11.1 km and 8 m in
243 1958, respectively. They changed to 11.5 km and 8.6 m in 2016. And the width to
244 depth ratio (B/H) reduced by 4% from 1958 to 2016. The average depths of the cross-
245 sections 2 and 3 in region B both increased by 0.2 m and 3.1 m, respectively. The
246 width of the former increased by about 5% while the latter reduced by 16%. The B/H
247 of the cross-section 2 in the South Channel had no obvious change, but that of the
248 cross-section 3 in the upper section of the North Channel significantly decreased by
249 40%, due to embankment for the Qingcao Shoal reservoir. The above-mentioned
250 parameters of cross-sections 4, 5 and 6 in region C also had a similar variation
251 tendency as those in the upper section of the North Channel. From 1958 to 2016, the
252 mean width and width to depth ratio of the three cross-sections in region C reduced by
253 42% and 60%, respectively, while the mean depth increased by almost 50%. The
254 reclamations in both East Nanhui shoal and East Hengsha shoal and the Deep
255 Waterway Channel Project in the North Passage were the main reasons for such

changes (Fig. 6B and 6C).

So far, the width at 0 m of the most cross-sections in the Changjiang Estuary had a decreasing trend while the average depth had an increasing trend from 1958 to 2016, especially in the regions where human activities occurred frequently. Thus the mean width to depth ratio of the cross-sections decreased obviously during the past 59 years. It indicated that the cross-sections in the Changjiang Estuary became much narrower and deeper from 1958 to 2016, corresponding to deposition in the sand bars and shoals and erosion in the deep channels.

4. Discussion

4.1 Spatially varying hydrodynamics and sediment characteristics

The Changjiang Estuary covers so large area that hydrodynamics and sediment transport dynamics present strong spatial variations from upstream to downstream due to the combined effect of river and tides (Liu et al., 2010; He et al., 2015). Most of the main channels in the Changjiang Estuary are ebb-dominated with stronger ebb currents than flood currents (Fig. 3A). The ratios of river discharge to tidally mean discharge (Q_r/Q_t) present an obvious decreasing tendency in the seaward direction. For instance, the Q_r/Q_t ratios are 0.44 and 0.12 in regions A and C, respectively (Fig. 3B). From the South Branch to the MBZ, the Q_r/Q_t ratio reduces by 73%. It indicates that the South Branch is more river-influenced while the MBZ is much more tidal-influenced than the South Branch.

The suspended sediment concentration (SSC) exhibits an increasing trend from

upstream (region A) to downstream (region C). For example, the mean SSC was only 0.43 kg/m³ between 2003 and 2007 in the South Branch (region A), while the mean SSC increased to 0.99 kg/m³ in the South Passage (region C), which is twice more than that in the South Branch (Fig. 3C; Liu et al., 2010; He et al., 2015).

The grain size of suspended sediment presents an increasing trend from the South Branch to the MBZ (Fig. 3D). In 2003, the median grain size of suspended sediment in region A was 6.5 μ m while it was 8~9.5 μ m in the MBZ. In contrast, the grain size of bottom sediments decreases seaward along the river. In the main channel of the South Branch, the median grain sizes of bottom sediments were >200 μ m while such values were far <50 μ m in the main channel of the MBZ in 2003 (Fig. 3E).

All these differences between regions A and C (region B is in transition between them) suggest that they are controlled by different hydrodynamic conditions thus potentially explaining different morphological behavior between them.

4.2 Spatially varying morphodynamic behavior of the Changjiang Estuary

Riverine input is a major source of water and sediment fluxes that influence the estuarine morphological evolution. Sediment source reductions below pristine conditions are observed in many estuaries creating new challenges to estuaries and deltas under sea level rise (Syvitski et al., 2011). For the Changjiang Estuary, it was obvious that the morphological changes were influenced by riverine sediment load reduction (Yang et al., 2005, 2011; Kuang et al., 2013; Wang et al., 2008, 2013; Wang et al., 2014), but some parts of the estuary, such as the MBZ, had little response

to riverine sediment load reduction within a short time (Dai et al., 2014), owing to the complex spatio-temporal variations of hydrodynamics and sediment characters in such a large estuary. The effects of sediment source reduction caused by the Three Gorges Dam in the watershed on estuarine morphological change are still in dispute. How different branches in the Changjiang Estuary responded to sediment source reduction needs further clarification.

It is widely known that river discharge acting on the Changjiang Estuary did not show significant decreasing or increasing trend from 1958 to 2016, but the sediment load at Datong had significantly reduced since the mid-1980s, mainly attributed to dam constructions in the drainage basin. The annual river discharge at Datong remained about $890 \times 10^9 \text{ m}^3/\text{year}$ in the total six periods while the annual sediment load had continuously reduced from $4.82 \times 10^8 \text{ t/year}$ (1958-1973) to $1.28 \times 10^8 \text{ t/year}$ (2010-2016), a 2/3 reduction (Fig. 2A; Chen et al., 2008; He et al., 2015). However, there was no directional deposition or erosion trend of the entire study area in the estuary (Table 1), suggesting that estuarine morphological changes are not linearly or simply correlated with riverine sediment supply changes as widely documented in previous studies. We will discuss potential factors acting on the inconsistent change behavior, including spatially varying estuarine morphological response behavior, time lag effect, etc.

Both regions A and B were featured by an obvious switch change from deposition to erosion over time. A positive linear relationship was found between the annual mean erosion or deposition rates in region A ($R^2=0.48$) and region B ($R^2=0.56$)

and the annual mean sediment load at Datong (Fig. 7A and 7B), indicating that the morphological changes of these two regions had a good relationship with riverine sediment source variations. We infer that the pan-South Branch is more fluvial-influenced that its morphology is sensitive to riverine sediment supply reduction. On the other hand, the MBZ presented a persisting deposition trend prior 2010 and turned to be afterward erosion. The annual mean erosion or deposition rates of the MBZ had poor relationship with the annual mean sediment load at Datong over 59 years ($R^2=0.19$) (Fig. 7C). We think the MBZ is controlled by both river and tides that its morphological changes can have resilience to sediment source changes and/or are out of phase of sediment source changes.

Specifically, region A turned to be moderately eroded from 1986 to 1997, but region B still showed a slight deposition at that time and shifted to moderate erosion from 1997 to 2002. The response of the South Branch and region B to riverine sediment source reduction thus did not occur simultaneously. We see that both the mean annual erosion or deposition rates of region A and region B are positively correlated to the annual mean sediment load at Datong, suggesting erosion happened in these zones due to riverine sediment source reduction. For region A, the correlation changes little ($R^2<0.48$) when considering a 2 year time lag between estuarine morphology and riverine sediment supply. The correlation significantly improves ($R^2=0.77$) in region B considering a time lag of 5 years (Table 2). It indicates that there is a ~ 5 years of time lag for the response of morphological changes in region B, while the time lag of region A is in the order of ~ 2 years,

which is shorter than that in region B. The annual mean erosion or deposition rates of region C (the MBZ) has little ($R^2=0.19$) relationship with the annual mean sediment load at Datong. The correlationship also improves ($R^2=0.53$) considering a time lag of 5 years (Table 2). Though limited data about sediment load at Datong before 1953 is available, we believe that the time lag of morphological changes in the MBZ can be >10 years considering its large scale and tidal influence.

The presence of a time lag between large scale estuarine morphological responses to riverine sediment supply variations is understandable. The Changjiang Estuary is primarily controlled by river and tides. River discharge transports a large amount of suspended sediment seaward and flushes bottom sediments downward. Tidal waves and currents propagate landward and create stratification and gravitational circulations particularly in region C, which have effects in trapping sediment in the mouth bar (turbidity maximum zone) and even inducing landward sediment transport in the bottom layers. Tidal asymmetry and tidal pumping can also favor landward sediment transport though it may be of secondary importance due to high river discharge (Guo et al., 2015). Sediment redistribution within the estuary, e.g., by channel erosion and flat accretion, explains the large scale morphological resilience to external source changes (Guo, 2014). Spatially, region A is overall well-mixed and more river-influenced and its sediment source and transport processes are directly affected by river forcing first (He et al., 2015), explaining why the South Branch is sensitive to riverine input and a small time lag. Region C is dominantly partially-mixed and both river and tides are of equal importance. Region C is strongly

affected by density currents, horizontal circulations, tidal asymmetry, etc. (Guo, 2014; Wu et al., 2010, 2012; Jiang et al., 2013), that its morphology has large resilience and inherent buffering effects to riverine sediment source changes. Region C, facing to the open sea, is also influenced by wind and waves which can rework tidal flats sediments to be transported and deposited in channels. Overall these processes explain why a large time lag is present in the MBZ compared to the inner estuary, e.g., the South Branch.

The time scale of sediment transport in such a large estuary system may also play a role though it is difficult to quantify accurately. The riverine sediment flux monitored at Datong, 600 km upstream of region C, may take quite a while to be transported seaward step by step while along river morphological changes have buffering effects. It can explain the seaward increasing time lag. The SSC in both regions A and B had decreased significantly over time. For instance, the depth-averaged SSC in the South Branch and the South Channel reduced by 84% and 64% from 2003 to 2013, respectively (Fig. 3C). However, the depth-averaged SSC in the MBZ was still high ($>0.5 \text{ kg/m}^3$) and even increased by 36% in the North Passage and 75% in the lower section of the North Channel (Fig. 3C). It suggests that the response behavior in region C is quite different from regions A and B.

The overall erosion since 2010 in all the three regions may suggest that the estuary undergoes a shift from overall deposition to erosion after a time lag (Fig. 4, Table 1). Comparing with the previous period (2002-2010), the erosion rate of region A decreased while the erosion rate of region B increased (Table 1). However, the

MBZ sustained a high deposition rate from 2002 to 2010, even the sediment load at Datong had reduced by 2/3 since 2003. It suggests that the effects of riverine sediment source reduction on the MBZ are only detectable in the very recent years. It again supports the argument of a time lag ≈ 10 years for the response of the morphological changes in region C to riverine sediment source reduction. The time lag effect is easily ignored in the morphological examination in previous studies, which can explain why the controversial conclusions reached.

So far the time lag is only quantitatively discussed due to large bathymetric data interval. Future work by morphodynamic modeling can help to better quantify the time lag and its spatial variability. Actually a large estuarine morphodynamic adaptation time scale is reported in schematized long-term estuarine and deltaic morphodynamic studies and it merits careful consideration in real world as well when predicting future morphological changes in response to a low sediment influx regime and sea level rise.

4.3 Spatially varying morphological changes under ~~catastrophic~~big river floods

Estuarine morphological evolution is so complex that it is influenced by a variety of factors, ~~not just other than the~~ riverine sediment load changes. River flow is just one prominent process governing estuarine morphodynamics. Though the ~~mean-~~ annually mean river discharge changes little and is not ~~suppose-expected~~ to cause ~~strong-directional~~ estuarine morphological changes (Table 1), changes of the frequency and magnitude of episodic ~~large-big~~ river floods ~~may-can~~ play a role in

shaping morphological evolution (Yun, 2004; ~~Edmonds et al., 2010~~; Guo, 2014; Luan et al., 2016). At long-term time scales, catastrophic river floods with a peak river discharge $\geq 70,000$ m³/s were thought to play an prominent role in stimulating new channel bifurcation in the Changjiang Estuary, such as the formation of the North Passage due to the big flood in 1954 (Yun, 2004; ~~Luan et al., 2016~~). At decadal time scales, we

~~In this work we~~ identify five years with flood peak discharges $\geq 70,000$ m³/s from 1958 to 2016, including a catastrophic flood in 1998. We see that most of the high river discharges occurred in the period of 1997-2002 (Fig. 2B). Accordingly, the estuary displayed severe erosion in the same interval (1997-2002) compared to other periods though net deposition was detected in region A due to the accretion over the shoals (Fig. 4). This change pattern was inconsistent with the long-term tendency between 1958 and 1997 (Table 1). The entire lower estuary was overwhelmingly eroded while deposition was detected in the South Branch in this period (Table 1). In the South Branch, deposition mostly happened in the deep channels while erosion took place in the sand bars and shoals, with an amplitude of >0.5 m/year. In contrast, the deep channels in regions B and C were eroded obviously, especially along the main channels in the North Channel while depositions were observed in the sand bars and shoals (Fig. 4). Linear riverine sediment source reduction since the mid-1980s failed to explain ~~all~~ such intense changes.

We argue that enduring the high river discharges exert strong influence on estuarine morphological changes. The high river discharges ($>70,000$ m³/s) persisted

1-2 months in ~~both~~ 1998 and 1999, and ~~also the~~ post-flood discharges maintained at a relatively high level ($>45,000 \text{ m}^3/\text{s}$) for 2-3 months in these two years. ~~which~~ The river discharge hydrographs were quite different from ~~the~~ normal ~~years~~ conditions. It provided a continuous strong river force ~~to~~ in flushing sediment seaward ~~and may cause erosion in the estuary~~. Moreover, based on the historical data from 1951 to 1984, Yin et al. (2009) found significant sediment deficiency for river discharges $>60,000 \text{ m}^3/\text{s}$ at Datong. ~~The~~ High river flow has a larger sediment transport ~~carrying~~ capacity but ~~there is not enough sediment to be transported (the sediment source-limited limited condition in the river upstream Datong restricts sediment availability to the estuary)~~, thus triggering erosion in the estuary considering further by enhanced sediment transport capacity thru river-tide interactions (Guo, 2014). The net deposition in region A in 1997-2002 reflects the imbalance between channel erosion and shoal accretion which is very much related to channel migration and shoal movement caused by big river floods as well. Overall ~~w~~ We ~~also~~ think that it is not only the magnitude of the flood peak discharges, but also its duration and associated sediment deficiency, matter in causing strong estuarine morphological changes ~~during large river floods~~.

4.4 The influence of human activities

Extensive human activities in the estuary locally, such as the Deep Waterway Channel Project, dredging, reclamation, and embankment for reservoir construction, also exert strong impacts in estuarine morphological evolution at decadal time scales

(Fig. 8A).

Reclamation and embankment is one of the main factors in stabilizing coastlines and narrowing channels in historic periods. The width of the Xuliujing section narrowed from 15.7 km in 1958 to 5.7 km in 1970s due to reclamation and the narrowed Xuliujing section became a controlling point in stabilizing the division between the South Branch and the North Branch (Yun, 2004; Guo, 2014). As a result of it, the old Baimao Shoal moved northward and merged with the Chongming Island in 1970s and the entrance of the South Branch became much narrower and deeper from 1958 to 1973. For the entire study area, a reduction of 571 km² of the water surface area resulted from reclamation and embankment from 1958 to 2016, accounting for almost 14% of that in 1958, which meant 11 man-made Hengsha Islands formed in the Changjiang Estuary (Fig. 8A). Due to the reclamation and embankment, the channels in the estuary become much narrower and deeper, especially around the regions reclamation or embankment occurred nearby. For instance, the width and width to depth ratio of the cross-section 3 obviously decreased by 16% and 40%, respectively, especially after 2009 owing to embankment for the Qingcao Shoal reservoir (Fig. 6).

The Deep Waterway Channel Project was carried out in the North Passage of the Changjiang Estuary since 1998 and almost 50-80×10⁶ m³ of sediment was dredged each year from the navigation channel (Fig. 8B). The morphological changes of the MBZ, including the North Passage, were intensely impacted by these human interventions. The North Passage tended to be a man-controlled bifurcation channel

owing to the navigational works and dredging. The cross-section of the North Passage also became narrower and deeper. Taking cross-section 5 as an example, a 53% reduction in width and a 35% growth in average-depth were observed from 1958 to 2016 and a dramatic change mainly occurred since 2002 because of the navigational works and dredging. Other changes such as local erosion in the middle reach of the North Channel and the upper section of the South Passage and reduced horizontal growth and enhanced vertical accretion of the Jiudian Shoal from 2002 to 2010 were also attributed to the navigational works (Jiang et al., 2010).

Human activities play a more important role in driving abrupt changes of estuarine morphology by stabilizing coastlines and narrowing channels in relatively short time and their impacts can persist for long time, overlapped by slow changes under natural evolution processes. Overall the Changjiang Estuary is becoming more constrained and human-influenced due to extensive reclamation, embankment, and navigational works and the channel-shoal system of the estuary will be more stabilized under human interventions in the future.

5. Conclusions

We analyzed and interpreted 59-year's morphological evolution of the Changjiang Estuary as a whole from 1958 to 2016 and inferred the causes and implications. We see that its channel-shoal pattern featured by meandering and bifurcated channels does not change over decades though there is strong erosion and deposition. The Changjiang Estuary exhibits an overall deposition trend but with

strong temporal and spatial variations. The net deposition volume of the whole study area was $8.3 \times 10^8 \text{ m}^3$ from 1958 to 2016, or a net deposition rate of $14.3 \times 10^6 \text{ m}^3/\text{year}$.

Spatially both regions A and B, the inner part of the estuary, turned from deposition to erosion, i.e., by totally $5 \times 10^8 \text{ m}^3$ and $4.7 \times 10^8 \text{ m}^3$ eroded, respectively, over 59 years. However, there was $18 \times 10^8 \text{ m}^3$ of deposition in region C, i.e., the mouth bar zone, from 1958 to 2016. Erosion had been also detected since 2010 in the MBZ. The strong spatial variability can be explained by the differences in their hydrodynamic forcing and morphological features owing to along river distribution of river and tide energy. In the vertical direction, the hypsometric curves showed that deposition happened over the sand bars and shoals, whereas erosion mainly occurred in the deep channels since 1958. As a result, the channels of the estuary became much narrower and deeper.

The non-directional deposition and erosion trend of estuarine morphological changes is consistent with directionally decreasing riverine sediment supply. The morphological change of the pan-South Branch had a good relationship with riverine sediment source reduction. We infer that the pan-South Branch is more fluvial influenced and its morphology is sensitive to riverine sediment supply reduction. The mouth bar zone is controlled by both river and tides thus its morphology does not show a clear linkage with sediment supply. Seaward sediment flushing takes time and there is a time lag between estuarine morphological changes and riverine sediment source variations in the different regions. The time lag increases in the seaward direction and it is >10 years in the mouth bar zone. Sediment redistribution has

buffering effect and the estuarine circulation, tidal pumping, waves, etc. can also explain sediment trapping in the mouth bar zone which has a large morphological resilience to external source changes. We argue that the time lag effects need to be considered when examining large scale estuarine morphological changes in response to riverine sediment supply variations which is not well understood but an important issue given projection of future changes.

Big river flows with long duration and sediment deficiency may also explain the erosion in periods from the late 1990s to early 2000s.

Human activities such as the Deep Waterway Channel Project, reclamation, and embankment play an important role in driving morphological evolution in the estuary by stabilizing coastlines and narrowing channels. Overall the Changjiang Estuary is becoming more constrained and man-influenced due to extensive reclamation, embankment, and the navigational works and the channel-shoal system of the estuary will be more stabilized in the future.

Future work by using morphodynamic modeling is needed to better quantify the time lag and explain the controls of spatial morphological variability.

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References

- Ahnert, F., 1960. Estuarine meanders in the Chesapeake Bay area. *Geographical Review*, 50 (3), 390-401.
- Andrén, H., 1994. Development of the Laitaure delta, Swedish Lapland: A study of growth, distributary forms, and processes. Ph.D. Dissertation of Uppsala University, Uppsala, Sweden.
- Changjiang Water Resources Commission (CWRC)(ed.), 2015. Changjiang River Sediment Bulletin. Changjiang Press, Wuhan, China (in Chinese).
- Chen, J.Y., Yun, C.X., Xu, H.G., 1982. The model of development of the Changjiang Estuary during the last 2000 years. In: V.S. Kennedy (ed.), *Estuarine Comparisons*, Academic Press, New York, 655-666.
- Chen, J.Y., Zhu, H.F., Dong, Y.F., Sun, J.M., 1985. Development of the Changjiang estuary and its submerged delta. *Continental Shelf Research*, 4(1-2), 47-56.
- Chen, J., Li, D., Chen, B., Hu, F., Zhu, H., Liu, C., 1999. The processes of dynamic sedimentation in the Changjiang Estuary. *Journal of Sea Research*, 41(1), 129-140.
- Chen, J., Li, D., 2002. Regulation of the Changjiang Estuary: Past, Present and Future. *Engineered Coasts*. Springer Netherlands, 185-197.
- Chen, X., Yan, Y., Fu, R., Dou, X., Zhang, E., 2008. Sediment transport from the Yangtze River, China, into the sea over the post-Three Gorge Dam period: A discussion. *Quaternary International*, 186(1), 55-64.
- Chen, Z., Song, B., Wang, Z., Cai, Y., 2000. Late Quaternary evolution of the sub-aqueous Yangtze Delta, China: sedimentation, stratigraphy, palynology, and deformation. *Marine Geology*, 162(2-4):423-441.
- Chen, Z., Xu, K., Masataka, W., 2008. Dynamic hydrology and geomorphology of the Yangtze River. In: Gupta A. (ed.), *Large Rivers: Geomorphology and Management*, 457-469.

- Chu, Z., Yang, X., Feng, X., Fan, D., Li, Y., Shen, X., et al., 2013. Temporal and spatial changes in coastline movement of the Yangtze delta during 1974-2010. *Journal of Asian Earth Sciences*, 66, 166-174.
- Cowell, P. J. and Thom, B. G., 1994. Morphodynamics of coastal evolution. In: Carter, R.W.G. and Woodroffe, C. D. (ed.), *Coastal Evolution. Late quaternary shoreline morphodynamics*. Cambridge: Cambridge University Press, 33-86.
- 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), 6600.
- De Vriend, H.J., Wang, Z.B., Ysebaert, T., Herman, P.M., Ding, P.X., 2011. Eco-morphological problems in the Yangtze Estuary and the Western Scheldt. *Wetlands*, 31 (6), 1033-1042.
- Edmonds, D.A., Slingerland, R.L., 2007. Mechanics of river mouth bar formation: implications for the morphodynamics of delta distributary networks. *Journal of Geophysical Research Earth Surface*, 112 (F2), 237-254.
- Edmonds, D.A., Slingerland, R.L., Best, J., Dan, P., Smith, N., 2010. Response of river-dominated delta channel networks to permanent changes in river discharge. *Geophysical Research Letters*, 37(12), doi: 10.1029/2010GL043269.
- Freire, P., Taborda, R., Bertin, X., Guerreiro, M., Fortunato, A. B., Silva, A. M., Andrade, C., Oliveira, A., Antunes, C., Freitas, M. C., Nahon, A., Rodrigues, M. and Bruneau, N., 2011. Medium-term morphodynamic evolution of a small coastal inlet. *Journal of Coastal Research*, 56(SI 64), 666-670.
- Guo, L.C., 2014. Modeling estuarine morphodynamics under combined river and tidal forcing. PH.D. Dissertation of Delft University of Technology, CRC Press.
- Guo, L., Wegen, M., Roelvink, J.A., He, Q., 2015. The role of river flow and tidal asymmetry on 1-D estuarine morphodynamics. *Journal of Geophysical Research: Earth Surface*, 119(11), 2315-2334.
- Guo, L., Mick, V.D.W., Jay, D.A., Matte, P., Wang, Z.B., Roelvink, D., He, Q., 2015. River-tide dynamics: Exploration of nonstationary and nonlinear tidal behavior in the Yangtze River estuary. *Journal of Geophysical Research: Oceans*, 120(5), 3499-3521.
- He, Q., Guo, L., Liu, H., Wang, Y., 2015. Changjiang Estuary Sediment Transport Dynamics. *Ecological Continuum from the Changjiang (Yangtze River) Watersheds to the East China Sea Continental Margin*. Springer International Publishing, 47-69.

- 624 Jiang, C.J., Li, J.F., de Swart, H.E., 2012. Effects of navigational works on morphological
625 changes in the bar area of the Yangtze Estuary. *Geomorphology*, 139, 205-219.
- 626
- 627 Jiang, C.J., de Swart, H.E., Li, J.F., Liu, G.F., 2013. Mechanisms of along-channel sediment
628 transport in the north passage of the Yangtze Estuary and their response to large-scale
629 interventions. *Ocean Dynamics*, 63(2-3), 283-305.
- 630
- 631 Kuang, C., Liu, X., Gu, J., Guo, Y., Huang, S., Liu, S., Yu, W., Huang, J., Sun, B., 2013.
632 Numerical prediction of medium-term tidal flat evolution in the Yangtze Estuary: impacts of
633 the Three Gorges project. *Continental Shelf Research*, 52(1), 12-26.
- 634
- 635 Li, W., Cheng, H.Q., Li, J., Ping, D., 2008. Temporal and spatial changes of dunes in the
636 Changjiang (Yangtze) Estuary, China. *Estuarine Coastal and Shelf Science*, 77(1), 169-174.
- 637
- 638 Liu, H., He, Q., Wang, Z.B., Weltje, G.J., Zhang, J., 2010. Dynamics and spatial variability of
639 near-bottom sediment exchange in the Yangtze Estuary, China. *Estuarine Coastal and Shelf
640 Science*, 86(3), 322-330.
- 641
- 642 Liu, J.P., Li, A.C., Xu, K.H., Velozzi, D.M., Yang, Z.S., Milliman, J.D., DeMaster, D.J.,
643 2006. Sedimentary features of the Yangtze River-derived along-shelf clinoform deposit in the
644 East China Sea. *Continental Shelf Research*, 26(17), 2141-2156.
- 645
- 646 Luan, H.L., Ding, P.X., Wang, Z.B., Ge, J.Z., Yang, S.L., 2016. Decadal morphological
647 evolution of the Yangtze Estuary in response to river input changes and estuarine engineering
648 projects. *Geomorphology*, 265, 12-23.
- 649
- 650 Marciano, R., Wang, Z.B., Hibma, A., De Vriend, H.J., Defina, A., 2005. Modeling of
651 channel patterns in short tidal basins. *Journal of Geophysical Research: Earth
652 Surface*, 110(F1), 67-106.
- 653
- 654 Milliman, J.D., Shen, H.T., Yang, Z.S., Mead, R.H., 1985. Transport and deposition of river
655 sediment in the Changjiang estuary and adjacent continental shelf. *Continental Shelf
656 Research*, 4(1-2), 37-45.
- 657
- 658 Syvitski, J.P.M., Kettner, A.J., Correggiari, A., Nelson, B.W., 2005. Distributary channels
659 and their impact on sediment dispersal. *Marine Geology*, 222, 75-94.
- 660
- 661 Syvitski, J.P.M., Kettner, A., 2011. Sediment flux and the Anthropocene. *Philosophical
662 Transactions, Series A, Mathematical, physical, and engineering sciences*, 369(1938), 957.
- 663
- 664 Toffolon, M., and Crosato, A., 2007. Developing macroscale indicators for estuarine
665 morphology: the case of the Scheldt Estuary. *Journal of Coastal Research*, 23(1), 195-212.
- 666

- Van den Berg, J.H., Jeuken, M.C.J.L., Van der Spek, A.J.F., 1996. Hydraulic processes affecting the morphology and evolution of the Westerschelde estuary. In: Nordstorm, K.F. et al. (ed.) *Estuarine Shores: Evolution. Environments and Human Alterations*, John Wiley, London, 157-184.
- Van Veen, J., van der Spek, A.J., Stive, M.J., Zitman, T., 2005. Ebb and flood channel systems in the Netherlands tidal waters. *Journal of Coastal Research*, 21, 1107-1120.
- Walcott, R.C., Summerfield, M.A., 2008. Scale dependence of hypsometric integrals: An analysis of southeast African basins. *Geomorphology*, 96(1-2), 174-186.
- Wang, Y., Shen, J., He, Q., 2010. A numerical model study of the transport timescale and change of estuarine circulation due to waterway constructions in the Changjiang Estuary, China. *Journal of Marine Systems*, 82(3), 154-170.
- Wang, H., Ge, Z., Yuan, L., Zhang, L., 2014. Evaluation of the combined threat from sea-level rise and sedimentation reduction to the coastal wetlands in the Yangtze Estuary, China. *Ecological Engineering*, 71(71), 346-354.
- Wang, Y.H., Ridd, P.V., Wu, H.L., Wu, J.X., Shen, H.T., 2008. Long-term morphodynamic evolution and the equilibrium mechanism of a flood channel in the Yangtze Estuary (China). *Geomorphology*, 99(1-4), 130-138.
- Wang, Y.H., Shen, H.T., LI, J.F., Mao, Z.C., 2011. Geomorphologic features and transport of sandwaves in the flood and ebb channels of the Changjiang Estuary. *Oceanologia et Limnologia Sinica*, 42(2), 330-336.
- Wang, Y.H., Dong, P., Oguchi, T., Chen, S.L., Shen, H.T., 2013. Long-term (1842-2006) morphological change and equilibrium state of the Changjiang (Yangtze) Estuary, China. *Continental Shelf Research*, 56, 71-81.
- Wang, Z.B., Ding, P.X., 2012. The branching channel network in the Yangtze Estuary. *Coastal Engineering Research Council*, 1(33).
- Wright, L.D., 1977. Sediment transport and deposition at river mouths: a synthesis. *Geological Society of America Bulletin*, 88(6), 857-868.
- Wu, H., Zhu, J.R., Choi, B.H., 2010. Links between saltwater intrusion and subtidal circulation in the Changjiang Estuary: a model-guided study. *Continental Shelf Research*, 30(17), 1891-1905.
- Wu, J.X., Liu, J.T., Wang, X., 2012. Sediment trapping of turbidity maxima in the Changjiang Estuary. *Marine Geology*, 303-306(1), 14-25.

- Wu, J., Wang, Y., Cheng, H., 2009. Bedforms and bed material transport pathways in the Changjiang (Yangtze) Estuary. *Geomorphology*, 104(3), 175-184.
- Yang, S.L., Ding, P.X., Chen, S.L., 2001. Changes in progradation rate of the tidal flats at the mouth of the Changjiang (Yangtze) River, China. *Geomorphology*, 38(1), 167-180.
- Yang, S.L., Belkin, I.M., Belkina, A.I., Zhao, Q.Y., Zhu, J., Ding, P.X., 2003. Delta response to decline in sediment supply from the Yangtze River: evidence of the recent four decades and expectations for the next half-century. *Estuarine Coastal and Shelf Science*, 57(4), 689-699.
- Yang, S.L., Zhang, J., Zhu, J., Smith, J.P., Dai, S.B., Gao, A., Li, P., 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), 247-275.
- 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), 14-20.
- Yin, D.W., Chen, Z.Y., 2009. The Changjiang sediment flux into the seas: measurability and predictability. *Frontier of Earth Science in China*, 3(2), 146-153.
- Yu, Q., Wang, Y., Flemming, B., Gao, S., 2012. Modelling the equilibrium hypsometry of back-barrier tidal flats in the German Wadden Sea (southern North Sea). *Continental Shelf Research*, 49(49), 90-99.
- Yun, C.X., 2004. Recent developments of the Changjiang Estuary. China Ocean Press, Beijing.