

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 8.3×10^8 m³. Spatially, the pan-South Branch was net eroded by 9.7×10^8 m³ whereas the mouth bar zone was net deposited by 18×10^8 m³, 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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**An analysis on half century morphological changes in the
Changjiang Estuary: spatial variability under natural processes
and human intervention**

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63 **Abstract**
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65 18 Examination of large scale, alluvial estuarine morphology and associated time
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68 19 evolution is of particular importance regarding management of channel navigability,
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71 20 ecosystem, etc. In this work, we analyze morphological evolution and changes of the
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73 21 channel-shoal system in the Changjiang Estuary, a river- and tide-controlled coastal
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75 22 plain estuary, based on bathymetric data between 1958 and 2016. We see that its
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77 23 channel-shoal pattern is featured by meandering and bifurcated channels persisting
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79 24 over decades. In the vertical direction, hypsometry curves show that the sand bars and
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82 25 shoals are continuously accreted while the deep channels are eroded, leading to
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85 26 narrower and deeper estuarine channels. Intensive human activities in terms of
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87 27 reclamation, embankment, and dredging play a profound role in controlling the
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89 28 decadal morphological evolution by stabilizing coastlines and narrowing channels.
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92 29 Even though, the present Changjiang Estuary is still a pretty wide and shallow system
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94 30 with channel width-to-depth ratios >1000 , much larger than usual fluvial rivers and
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97 31 small estuaries. In-depth analysis suggests that the Changjiang Estuary as a whole
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99 32 exhibited an overall deposition trend over 59 years, i.e., a net deposition volume of
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101 33 $8.3 \times 10^8 \text{ m}^3$. Spatially, the pan-South Branch was net eroded by $9.7 \times 10^8 \text{ m}^3$ whereas
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104 34 the mouth bar zone was net deposited by $18 \times 10^8 \text{ m}^3$, suggesting that the mouth bar
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107 35 zone is a major sediment sink. Over time there is no directional deposition or erosion
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109 36 trend in the interval though riverine sediment supply has decreased by 2/3 since the
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111 37 mid-1980s. We infer that the pan-South Branch is more fluvial-controlled therefore its
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114 38 morphology responds to riverine sediment load reduction fast while the mouth bar
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122 39 zone is more controlled by both river and tides that its morphological response lags to
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124 40 riverine sediment supply changes at a time scale >10 years, which is an issue largely
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127 41 ignored in previous studies. We argue that the time lag effect needs particular
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129 42 consideration in projecting future estuarine morphological changes under a low
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132 43 sediment supply regime and sea-level rise. Overall, the findings in this work can have
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134 44 implications on management of estuarine ecosystem, navigation channel and coastal
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136 45 flooding in general.
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141 47 **Key words:** Changjiang Estuary; Morphological Evolution; Sediment supply
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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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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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250 62 and waves generally controls the long-term estuarine morphological changes,
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252 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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261
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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266 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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299 80 meandering channel pattern with coexisting flood and ebb channels is observed in
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301 81 tide-dominated systems, such as the Dutch Western Scheldt Estuary (Van Veen, 1950;
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304 82 Van den Berg et al., 1996; Toffolon and Crosato, 2007) and the Chesapeake Bay in
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306 83 the USA (Ahnert, 1960). Distributary channels with multiple bifurcations are
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309 84 observed in river-controlled estuaries and/or delta systems (Andrén, 1994; Edmonds
310
311 85 and Slingerland, 2007; Wang and Ding, 2012). Large scale morphodynamic behavior
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314 86 under combined river and tidal forcing, such as the Changjiang Estuary in China, is
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316 87 insufficiently examined (Guo et al., 2015).

318 88 Morphological evolution of the Changjiang Estuary has been examined by
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321 89 calculating erosion-deposition volumes and analyzing movements of isobaths,
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323 90 shorelines, and thalwegs (Chen et al., 1985 and 1999; Yun, 2004; Wang et al., 2013;
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325 91 Luan et al., 2016). Riverine sediment source availability and human activities are
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327
328 92 widely seen as two important factors in controlling morphological evolution in the
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330 93 Changjiang Estuary, which is also true in other estuaries and deltas such as Niles,
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332 94 Mississippi, and Colorado (Syvitski and Kettner, 2011). Note that previous
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334 95 examinations of the morphological changes in the Changjiang Estuary were mainly at
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336 96 regional scale without taking the estuary as a whole into consideration. For instance,
337
338 97 owing to riverine sediment supply reduction, regional erosion was detected in the
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340 98 South Branch (Wang et al., 2013) and the delta front regions (10 m deep nearshore)
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342 99 (Yang et al., 2003, 2005, 2011) in the recent decades, whereas the examination of a
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347 100 larger region including the sand bars in the mouth bar zone indicates continued
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349 101 deposition (Dai et al., 2014). Moreover, the time scale of large scale estuarine
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358 102 morphodynamic adaptation in responding to external forcing changes is very much
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360 103 ignored in previous studies. The morphological impacts of human activities such as
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363 104 reclamations (Chu et al., 2013; Wei et al., 2015) and the Deep Waterway Channel
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365 105 Project along the North Passage (De Vriend et al., 2011; Jiang et al., 2012, 2013) can
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367 106 also vary in a large space and time scales depending on their location, implementation
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370 107 time, and scales. Sea-level rise is also another factor needs consideration (Wang et al.,
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372 108 2013; Wang et al., 2014; Wei et al., 2015). So far, a comprehensive and quantitative
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375 109 investigation of morphological evolution in the entire Changjiang Estuary is still very
376
377 110 much needed.

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380 111 This study analyzes the morphological changes in the Changjiang Estuary as a
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382 112 whole based on the bathymetric data collected in the period between 1958 and 2016.
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384 113 We will focus on the erosion-deposition processes, changes of hypsometry, and cross-
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386
387 114 section configuration of different branches in the estuary to elaborate the channel
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389 115 patterns and the spatial and temporal variability of the estuarine morphology. The
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391 116 controls of the morphological changes are discussed in terms of natural processes and
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394 117 human activities. The insights obtained from this study are helpful for management
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396 118 and restoration opportunities in the Changjiang Estuary.

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401 120 **2. Data and methods**

403 121 **2.1 Brief introduction to the Changjiang Estuary**

406 122 The Changjiang River and its estuary is one of the biggest on earth with respect
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408 123 to its quantity such as river discharge, sediment load, and space scales. The annual
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417 124 mean river discharge is approximately $28.3 \times 10^3 \text{ m}^3/\text{s}$ (1950-2015) and annual
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419 125 sediment load is 3.7×10^8 tons (1953-2015) (CWRC, 2015). The river and sediment
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421
422 126 discharges exhibit markedly seasonal variations, with about 71% of water flux and
423
424 127 87% of sediment load flushed in the wet season between May and October (Chen et
425
426
427 128 al., 2008). Mean tidal range decreases from about 3.2 m nearshore to 2.4 m at
428
429 129 Xuliujing, the present delta apex, and further to be insignificant 500 km upstream of
430
431 130 Xuliujing. The tidal prism varies between 1.3×10^9 and $5.3 \times 10^9 \text{ m}^3$, with a mean
432
433
434 131 tidal discharge almost 9 times as much as the mean river discharge (Chen et al.,
435
436 132 2002). Thus the Changjiang Estuary is dominantly a partially-mixed, meso-tidal
437
438
439 133 system (Chen et al., 2002). The waves in the Changjiang Estuary are mainly wind
440
441 134 waves with a mean wave height of 0.9 m at Yinshuichuan in the river mouth area (Wu
442
443 135 et al., 2009; Wang et al., 2013). River and tides are the main forcing conditions
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446 136 though wind and waves can affect hydrodynamics and sediment transport over the
447
448 137 shallow tidal flats. The present Changjiang Estuary has four prime inlets connecting
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450
451 138 to the sea, namely the North and South Branch, North and South Channel, and North
452
453 139 and South Passages (Fig. 1). The estuary mouth is as wide as 90 km and the width
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455 140 decreases to approximately 6 km at the apex of the funnel-shaped estuary, i.e.,
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458 141 Xuliujing. Overall the Changjiang Estuary is a complex large scale system with few
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460 142 comparable cases in the world.

461 462 463 464 465 144 **2.2 Data and methods**

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476 145 We collect bathymetric data in 1958, 1973, 1986, 1997, 2002, 2010, and 2016,
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478 146 covering the entire regions seaward Xuliujing until 10-15 m deep waters (Fig. 1). The
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481 147 North Branch (NB), nowadays tide-dominated and limitedly influenced by fluvial
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483 148 processes, is excluded in this study due to data scarcity. The bathymetry data in 1958,
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485
486 149 1973, and 1986 are obtained from digitization of historical marine charts with a
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488 150 resolution 1/50000 and data in other years are from field sounding measurements with
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490
491 151 an accuracy of 1-2% for depths <2 m and <1% for depths >2 m (Wang et al., 2011,
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493 152 2013). All depth data are referenced to the same datum, the Theoretical Lowest
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495 153 Astronomical Tide (TLAT), which is basically below local mean water level by a half
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498 154 maximum tidal range (~ 2 m). A digital elevation model (DEM) by 20×20 m is
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500 155 created using Kriging interpolation.

502 156 Considering spatial variations of hydrodynamics, sediment properties, and
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505 157 morphological features (Fig. 3), we divide the study area into three regions for the
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507 158 benefit of clarification. Region A includes the South Branch (SB) and region B
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509 159 includes the South Channel (SC) and the upper section of the North Channel (NC),
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512 160 while region C indicates the mouth bar zone (MBZ) which includes the lower section
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514 161 of the North Channel, the North Passage (NP), and the South Passage (SP). Regions A
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516 162 and B together are also named pan-South Branch (PSB) region as a counterpart of
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518
519 163 region C (Fig. 1). Erosion and deposition volumes of different regions and the estuary
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521 164 as a whole are calculated for different time intervals. Hypsometry curves are also
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524 165 derived by linking channel volumes and planar areas at different depths. The
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526 166 hypsometric curves help to uncover morphological change of channels and shoals in
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167 the vertical direction. Moreover, we also estimate variations of width, depth, and
168 width-to-depth ratio and examine cross-section profile variations in different regions.

169

170 **3. Results**

171 **3.1 Overall morphological evolution (1958-2016)**

172 We see that there is no new channel bifurcation in the Changjiang Estuary since
173 1958. The three-level bifurcation and four-outlet configuration persists and the
174 channels and shoals develop toward mature conditions by strong erosion and
175 deposition evolution (Fig. 4). The middle-channel channel-shoal pattern is featured by
176 meandering channels and sand bars. The entire estuary becomes narrower and deeper
177 owing to deposition over the shoals and tidal flats and erosion along the channels.

178

179 **3.2 Erosion and deposition patterns**

180 The study area as a whole (including regions A, B, and C) had experienced
181 deposition from 1958 to 2016. The total net deposition amount of the study area
182 reached 8.3×10^8 m³ over 59 years, which equals a net deposition rate of 14.3×10^6
183 m³/year.

184 Temporally, the estuary did not exhibit directional persistent deposition or
185 erosion over 59 years (Table 1, Fig. 4). The entire study area first experienced fast
186 deposition in 1958-1973 (98.2×10^6 m³/year), followed by slight erosion in 1973-1986
187 (9.2×10^6 m³/year), deposition in 1986-1997 (56.3×10^6 m³/year), erosion in 1997-2002
188 again (40×10^6 m³/year), slight deposition in 2002-2010 (13.9×10^6 m³/year), and
189 recently fast erosion in 2010-2016 (175.7×10^6 m³/year).

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593
594 190 Spatially, the net erosion volume was $9.7 \times 10^8 \text{ m}^3$ in the pan-South Branch
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596 191 between 1958 and 2016. Approximately 52% of that occurred in region A and 48% in
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599 192 region B. To the contrast, the MBZ was deposited by $18 \times 10^8 \text{ m}^3$ in the interval,
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601 193 indicating that the MBZ is a major sediment sink. The erosion and deposition patterns
602
603 194 are different in different regions (Table 1). Region A had changed from deposition
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606 195 (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
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608 196 variation behavior was also observed in region B by slight deposition (1958-1973,
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610 197 $5.5 \times 10^6 \text{ m}^3/\text{year}$) and moderate erosion (2010-2016, $31.7 \times 10^6 \text{ m}^3/\text{year}$). However,
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613 198 region C showed a strong deposition trend from 1958 to 2010 and the deposition rates
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615 199 reached up to $75 \times 10^6 \text{ m}^3/\text{year}$ most of the time, followed by significant erosion of
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618 200 $1.15 \times 10^8 \text{ m}^3/\text{year}$ since 2010.
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622 623 202 **3.3 Changes of hypsometry**

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625 203 Hypsometric curve is a concise and quantitative way to understand vertical
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627 204 morphological characteristics. According to the hypsometric curves of the study area
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630 205 as a whole from 1958 to 2016 (Fig. 5D), both the total water volume and area of the
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632 206 study area decreased due to deposition and human activities. Specifically, the total
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634
635 207 water volume of the region below +2 m isobaths was $31.6 \times 10^9 \text{ m}^3$ in 1958. It
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637 208 decreased to $30 \times 10^9 \text{ m}^3$ in 2016, indicating 5% reduction compared to 1958. The total
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639 209 area at +2 m isobaths also decreased by about 514 km^2 from 1958 to 2016, i.e., 13%
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641
642 210 of that in 1958, mainly owing to reclamations and embankment for the Qingcao Shoal
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645 211 reservoir.
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653 212 In the vertical direction, the erosion and deposition patterns of the sand bars and
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655 213 shoals and the deep channels were quite different from each other during the past 59
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658 214 years. By comparing the water volumes and areas of the channels under different
659
660 215 isobaths in both 1958 and 2016 (Fig. 5D), we see that the entire study area was
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662 216 confined by -8 m isobaths. The water volume of the region above -8 m (-8~+2 m)
663
664 217 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
665
666 218 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
667
668 219 and shoals, which includes intertidal zone (0~+2 m). The water volume of the region
669
670 220 below -8 m isobaths (-8~ -20 m) increased by about $1.49 \times 10^9 \text{ m}^3$ and the area
671
672 221 increased by $0.1 \times 10^9 \text{ m}^2$. In the deep part of the channels below -12 m isobaths, the
673
674 222 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.
675
676 223 Thus the channels, especially the deep parts of them, were continuously eroded from
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678 224 1958 to 2016.
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684 225 For three regions of the estuary, deposited sand bars and shoals and eroded deep
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686 226 channels were also detected from 1958 to 2016, but the depth thresholds for shallow
687
688 227 (deposited) and deep (eroded) areas were different. Region A as a whole was
689
690 228 separated by -7 m isobaths while region C was separated by -8 m isobaths. The shape
691
692 229 of the hypsometric curves in different years was similar to each other, for both regions
693
694 230 A and C (Fig. 5A and 5B). However, region B was separated by -1 m isobaths. The
695
696 231 hypsometric curves in region B had significantly changes during the past 59 years,
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698 232 especially after 2002, mainly owing to embankment for the Qingcao Shoal reservoir
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701 233 (Fig. 5C).
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714 235 **3.4 Changes of cross-section**
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716
717 236 The width of the cross-sections in region C increases in the seaward direction.
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719 237 The depth of the cross-sections has a significant seaward decrease trend and has a
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721
722 238 minimum value on the top of the mouth bar. They are quite different from those in
723
724 239 regions A and B which do not have such a significant seaward depth variation along
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726
727 240 the river.
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729 241 For the chosen 6 cross-sections in the Changjiang Estuary (Fig. 6), the width and
730
731 242 average depth at 0 m of the cross-section 1 in region A were 11.1 km and 8 m in
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733
734 243 1958, respectively. They changed to 11.5 km and 8.6 m in 2016. And the width to
735
736 244 depth ratio (B/H) reduced by 4% from 1958 to 2016. The average depths of the cross-
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738
739 245 sections 2 and 3 in region B both increased by 0.2 m and 3.1 m, respectively. The
740
741 246 width of the former increased by about 5% while the latter reduced by 16%. The B/H
742
743 247 of the cross-section 2 in the South Channel had no obvious change, but that of the
744
745
746 248 cross-section 3 in the upper section of the North Channel significantly decreased by
747
748 249 40%, due to embankment for the Qingcao Shoal reservoir. The above-mentioned
749
750 250 parameters of cross-sections 4, 5 and 6 in region C also had a similar variation
751
752
753 251 tendency as those in the upper section of the North Channel. From 1958 to 2016, the
754
755 252 mean width and width to depth ratio of the three cross-sections in region C reduced by
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757
758 253 42% and 60%, respectively, while the mean depth increased by almost 50%. The
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760 254 reclamations in both East Nanhui shoal and East Hengsha shoal and the Deep
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763 255 Waterway Channel Project in the North Passage were the main reasons for such
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771 256 changes (Fig. 6B and 6C).
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773 257 So far, the width at 0 m of the most cross-sections in the Changjiang Estuary had
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775
776 258 a decreasing trend while the average depth had an increasing trend from 1958 to 2016,
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778 259 especially in the regions where human activities occurred frequently. Thus the mean
780
781 260 width to depth ratio of the cross-sections decreased obviously during the past 59
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783 261 years. It indicated that the cross-sections in the Changjiang Estuary became much
784
785 262 narrower and deeper from 1958 to 2016, corresponding to deposition in the sand bars
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787
788 263 and shoals and erosion in the deep channels.
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790 264

792 265 **4. Discussion**

794 266 **4.1 Spatially varying hydrodynamics and sediment characteristics**

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796
797 267 The Changjiang Estuary covers so large area that hydrodynamics and sediment
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800 268 transport dynamics present strong spatial variations from upstream to downstream due
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802 269 to the combined effect of river and tides (Liu et al., 2010; He et al., 2015). Most of the
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804
805 270 main channels in the Changjiang Estuary are ebb-dominated with stronger ebb
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807 271 currents than flood currents (Fig. 3A). The ratios of river discharge to tidally mean
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809 272 discharge (Q_r/Q_t) present an obvious decreasing tendency in the seaward direction.
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811
812 273 For instance, the Q_r/Q_t ratios are 0.44 and 0.12 in regions A and C, respectively (Fig.
813
814 274 3B). From the South Branch to the MBZ, the Q_r/Q_t ratio reduces by 73%. It indicates
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816
817 275 that the South Branch is more river-influenced while the MBZ is much more tidal-
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819 276 influenced than the South Branch.

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821 277 The suspended sediment concentration (SSC) exhibits an increasing trend from
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830 278 upstream (region A) to downstream (region C). For example, the mean SSC was only
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832 279 0.43 kg/m³ between 2003 and 2007 in the South Branch (region A), while the mean
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834
835 280 SSC increased to 0.99 kg/m³ in the South Passage (region C), which is twice more
836
837 281 than that in the South Branch (Fig. 3C; Liu et al., 2010; He et al., 2015).

838
839 282 The grain size of suspended sediment presents an increasing trend from the
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841
842 283 South Branch to the MBZ (Fig. 3D). In 2003, the median grain size of suspended
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845 284 sediment in region A was 6.5 μm while it was 8~9.5 μm in the MBZ. In contrast, the
846
847 285 grain size of bottom sediments decreases seaward along the river. In the main channel
848
849 286 of the South Branch, the median grain sizes of bottom sediments were >200 μm while
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851
852 287 such values were far <50 μm in the main channel of the MBZ in 2003 (Fig. 3E).

853
854 288 All these differences between regions A and C (region B is in transition between
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856 289 them) suggest that they are controlled by different hydrodynamic conditions thus
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858
859 290 potentially explaining different morphological behavior between them.

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862 863 292 **4.2 Spatially varying morphodynamic behavior of the Changjiang Estuary**

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865
866 293 Riverine input is a major source of water and sediment fluxes that influence the
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868 294 estuarine morphological evolution. Sediment source reductions below pristine
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871 295 conditions are observed in many estuaries creating new challenges to estuaries and
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873 296 deltas under sea level rise (Syvitski et al., 2011). For the Changjiang Estuary, it was
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876 297 obvious that the morphological changes were influenced by riverine sediment load
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878 298 reduction (Yang et al., 2005, 2011; Kuang et al., 2013; Wang et al., 2008, 2013;
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880 299 Wang et al., 2014), but some parts of the estuary, such as the MBZ, had little response
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889 300 to riverine sediment load reduction within a short time (Dai et al., 2014), owing to the
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891 301 complex spatio-temporal variations of hydrodynamics and sediment characters in
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893
894 302 such a large estuary. The effects of sediment source reduction caused by the Three
895
896 303 Gorges Dam in the watershed on estuarine morphological change are still in dispute.
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899 304 How different branches in the Changjiang Estuary responded to sediment source
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901 305 reduction needs further clarification.

903 306 It is widely known that river discharge acting on the Changjiang Estuary did not
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905
906 307 show significant decreasing or increasing trend from 1958 to 2016, but the sediment
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908 308 load at Datong had significantly reduced since the mid-1980s, mainly attributed to
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910 309 dam constructions in the drainage basin. The annual river discharge at Datong
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912
913 310 remained about 890×10^9 m³/year in the total six periods while the annual sediment
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915 311 load had continuously reduced from 4.82×10^8 t/year (1958-1973) to 1.28×10^8 t/year
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917 312 (2010-2016), a 2/3 reduction (Fig. 2A; Chen et al., 2008; He et al., 2015). However,
918
919 313 there was no directional deposition or erosion trend of the entire study area in the
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921 314 estuary (Table 1), suggesting that estuarine morphological changes are not linearly or
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923 315 simply correlated with riverine sediment supply changes as widely documented in
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925 316 previous studies. We will discuss potential factors acting on the inconsistent change
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927 317 behavior, including spatially varying estuarine morphological response behavior, time
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929 318 lag effect, etc.

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935 319 Both regions A and B were featured by an obvious switch change from
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937 320 deposition to erosion over time. A positive linear relationship was found between the
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939 321 annual mean erosion or deposition rates in region A ($R^2=0.48$) and region B ($R^2=0.56$)
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948 322 and the annual mean sediment load at Datong (Fig. 7A and 7B), indicating that the
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950 323 morphological changes of these two regions had a good relationship with riverine
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953 324 sediment source variations. We infer that the pan-South Branch is more fluvial-
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955 325 influenced that its morphology is sensitive to riverine sediment supply reduction. On
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957
958 326 the other hand, the MBZ presented a persisting deposition trend prior 2010 and turned
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960 327 to be afterward erosion. The annual mean erosion or deposition rates of the MBZ had
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963 328 poor relationship with the annual mean sediment load at Datong over 59 years
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965 329 ($R^2=0.19$) (Fig. 7C). We think the MBZ is controlled by both river and tides that its
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967
968 330 morphological changes can have resilience to sediment source changes and/or are out
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970 331 of phase of sediment source changes.

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972 332 Specifically, region A turned to be moderately eroded from 1986 to 1997, but
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974 333 region B still showed a slight deposition at that time and shifted to moderate erosion
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976
977 334 from 1997 to 2002. The response of the South Branch and region B to riverine
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980 335 sediment source reduction thus did not occur simultaneously. We see that both the
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982 336 mean annual erosion or deposition rates of region A and region B are positively
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984 337 correlated to the annual mean sediment load at Datong, suggesting erosion happened
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986
987 338 in these zones due to riverine sediment source reduction. For region A, the
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989 339 relationship changes little ($R^2<0.48$) when considering a 2 year time lag between
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992 340 estuarine morphology and riverine sediment supply. The relationship significantly
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994 341 improves ($R^2=0.77$) in region B considering a time lag of 5 years (Table 2). It
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996 342 indicates that there is a ~ 5 years of time lag for the response of morphological
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999 343 changes in region B, while the time lag of region A is in the order of ~ 2 years,

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1007 344 which is shorter than that in region B. The annual mean erosion or deposition rates of
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1009 345 region C (the MBZ) has little ($R^2=0.19$) relationship with the annual mean sediment
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1011
1012 346 load at Datong. The correlation also improves ($R^2=0.53$) considering a time lag of
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1014 347 5 years (Table 2). Though limited data about sediment load at Datong before 1953 is
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1016 348 available, we believe that the time lag of morphological changes in the MBZ can
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1019 349 be >10 years considering its large scale and tidal influence.

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1021 350 The presence of a time lag between large scale estuarine morphological
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1024 351 responses to riverine sediment supply variations is understandable. The Changjiang
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1026 352 Estuary is primarily controlled by river and tides. River discharge transports a large
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1029 353 amount of suspended sediment seaward and flushes bottom sediments downward.
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1031 354 Tidal waves and currents propagate landward and create stratification and
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1033 355 gravitational circulations particularly in region C, which have effects in trapping
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1036 356 sediment in the mouth bar (turbidity maximum zone) and even inducing landward
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1038 357 sediment transport in the bottom layers. Tidal asymmetry and tidal pumping can also
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1040
1041 358 favor landward sediment transport though it may be of secondary importance due to
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1043 359 high river discharge (Guo et al., 2015). Sediment redistribution within the estuary,
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1045 360 e.g., by channel erosion and flat accretion, explains the large scale morphological
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1048 361 resilience to external source changes (Guo, 2014). Spatially, region A is overall well-
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1050 362 mixed and more river-influenced and its sediment source and transport processes are
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1052 363 directly affected by river forcing first (He et al., 2015), explaining why the South
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1054
1055 364 Branch is sensitive to riverine input and a small time lag. Region C is dominantly
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1057 365 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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1072
1073 369 open sea, is also influenced by wind and waves which can rework tidal flats sediments
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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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1079
1080 372 Branch.

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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1087 375 monitored at Datong, 600 km upstream of region C, may take quite a while to be
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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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1099 381 MBZ was still high ($>0.5 \text{ kg/m}^3$) and even increased by 36% in the North Passage
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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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1103 383 response behavior in region C is quite different from regions A and B.

1109 384 The overall erosion since 2010 in all the three regions may suggest that the
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1111 385 estuary undergoes a shift from overall deposition to erosion after a time lag (Fig. 4,
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1113 386 Table 1). Comparing with the previous period (2002-2010), the erosion rate of region
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1115 387 A decreased while the erosion rate of region B increased (Table 1). However, the
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1125 388 MBZ sustained a high deposition rate from 2002 to 2010, even the sediment load at
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1127 389 Datong had reduced by 2/3 since 2003. It suggests that the effects of riverine sediment
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1130 390 source reduction on the MBZ are only detectable in the very recent years. It again
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1132 391 supports the argument of a time lag \approx 10 years for the response of the morphological
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1134 392 changes in region C to riverine sediment source reduction. The time lag effect is
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1136
1137 393 easily ignored in the morphological examination in previous studies, which can
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1139 394 explain why the controversial conclusions reached.

1142 395 So far the time lag is only quantitatively discussed due to large bathymetric data
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1144 396 interval. Future work by morphodynamic modeling can help to better quantify the
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1146 397 time lag and its spatial variability. Actually a large estuarine morphodynamic
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1148 398 adaptation time scale is reported in schematized long-term estuarine and deltaic
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1150 399 morphodynamic studies and it merits careful consideration in real world as well when
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1152 400 predicting future morphological changes in response to a low sediment influx regime
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1154 401 and sea level rise.

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1158 402

1161 403 **4.3 Spatially varying morphological changes under big river floods**

1162
1163 404 Estuarine morphological evolution is so complex that it is influenced by a variety
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1165
1166 405 of factors other than riverine sediment load changes. River flow is just one prominent
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1168 406 process governing estuarine morphodynamics. Though the annually mean river
1169
1170 407 discharge changes little and is not expected to cause directional estuarine
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1172 408 morphological changes (Table 1), changes of the frequency and magnitude of episodic
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1174 409 big river floods can play a role in shaping morphological evolution (Yun, 2004; Guo,
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1184 410 2014; Luan et al., 2016). At long-term time scales, catastrophic river floods with a
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1186 411 peak river discharge $\geq 70,000 \text{ m}^3/\text{s}$ were thought to play an prominent role in
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1188
1189 412 stimulating new channel bifurcation in the Changjiang Estuary, such as the formation
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1191 413 of the North Passage due to the big flood in 1954 (Yun, 2004). At decadal time scales,
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1193 414 we identify five years with flood peak discharges $\geq 70,000 \text{ m}^3/\text{s}$ from 1958 to 2016,
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1196 415 including a catastrophic flood in 1998. We see that most of the high river discharges
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1198 416 occurred in the period of 1997-2002 (Fig. 2B). Accordingly, the estuary displayed
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1200
1201 417 severe erosion in the same interval (1997-2002) compared to other periods though net
1202
1203 418 deposition was detected in region A due to the accretion over the shoals (Fig. 4). This
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1205
1206 419 change pattern was inconsistent with the long-term tendency between 1958 and 1997
1207
1208 420 (Table 1). Linear riverine sediment source reduction since the mid-1980s failed to
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1210 421 explain such intense changes.

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1213 422 We argue that enduring high river discharges exert strong influence on estuarine
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1215 423 morphological changes. The high river discharges ($>70,000 \text{ m}^3/\text{s}$) persisted 1-2
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1218 424 months in 1998 and 1999, and post-flood discharges maintained at a relatively high
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1220 425 level ($>45,000 \text{ m}^3/\text{s}$) for 2-3 months in these two years. The river discharge
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1222 426 hydrographs were quite different from normal conditions. It provided a continuous
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1225 427 strong river force in flushing sediment seaward. Moreover, based on the historical
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1227 428 data from 1951 to 1984, Yin et al. (2009) found significant sediment deficiency for
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1229
1230 429 river discharges $>60,000 \text{ m}^3/\text{s}$ at Datong. High river flow has a larger sediment
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1233 430 transport capacity but the sediment source-limited condition in the river upstream
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1235 431 Datong restricts sediment availability to the estuary, thus triggering erosion in the
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1243 432 estuary considering further by enhanced sediment transport capacity thru river-tide
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1245 433 interactions (Guo, 2014). The net deposition in region A in 1997-2002 reflects the
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1247
1248 434 imbalance between channel erosion and shoal accretion which is very much related to
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1250 435 channel migration and shoal movement caused by big river floods as well. Overall we
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1252
1253 436 think that it is not only the magnitude of the flood peak discharges, but also its
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1255 437 duration and associated sediment deficiency, matter in causing strong estuarine
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1257 438 morphological changes.
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1261 440 **4.4 The influence of human activities**

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1263
1264 441 Extensive human activities in the estuary locally, such as the Deep Waterway
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1266
1267 442 Channel Project, dredging, reclamation, and embankment for reservoir construction,
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1269 443 also exert strong impacts in estuarine morphological evolution at decadal time scales
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1271
1272 444 (Fig. 8A).
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1274 445 Reclamation and embankment is one of the main factors in stabilizing coastlines
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1276 446 and narrowing channels in historic periods. The width of the Xuliujing section
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1278
1279 447 narrowed from 15.7 km in 1958 to 5.7 km in 1970s due to reclamation and the
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1281 448 narrowed Xuliujing section became a controlling point in stabilizing the division
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1283
1284 449 between the South Branch and the North Branch (Yun, 2004; Guo, 2014). As a result
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1286 450 of it, the old Baimao Shoal moved northward and merged with the Chongming Island
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1288
1289 451 in 1970s and the entrance of the South Branch became much narrower and deeper
1290
1291 452 from 1958 to 1973. For the entire study area, a reduction of 571 km² of the water
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1293
1294 453 surface area resulted from reclamation and embankment from 1958 to 2016,
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1302 454 accounting for almost 14% of that in 1958, which meant 11 man-made Hengsha
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1304 455 Islands formed in the Changjiang Estuary (Fig. 8A). Due to the reclamation and
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1306 embankment, the channels in the estuary become much narrower and deeper,
1307 456
1308 especially around the regions reclamation or embankment occurred nearby. For
1309 457
1310 instance, the width and width to depth ratio of the cross-section 3 obviously decreased
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1312 by 16% and 40%, respectively, especially after 2009 owing to embankment for the
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1314 Qingcao Shoal reservoir (Fig. 6).
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1319 461 The Deep Waterway Channel Project was carried out in the North Passage of the
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1321 462 Changjiang Estuary since 1998 and almost $50-80 \times 10^6$ m³ of sediment was dredged
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1323 each year from the navigation channel (Fig. 8B). The morphological changes of the
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1325 MBZ, including the North Passage, were intensely impacted by these human
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1327 interventions. The North Passage tended to be a man-controlled bifurcation channel
1328 465
1329 owing to the navigational works and dredging. The cross-section of the North Passage
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1331 also became narrower and deeper. Taking cross-section 5 as an example, a 53%
1332 467
1333 reduction in width and a 35% growth in average-depth were observed from 1958 to
1334 468
1335 2016 and a dramatic change mainly occurred since 2002 because of the navigational
1336 469
1337 works and dredging. Other changes such as local erosion in the middle reach of the
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1339 North Channel and the upper section of the South Passage and reduced horizontal
1340 471
1341 growth and enhanced vertical accretion of the Jiudian Shoal from 2002 to 2010 were
1342 472
1343 also attributed to the navigational works (Jiang et al., 2010).
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1350 474 Human activities play a more important role in driving abrupt changes of
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1352 475 estuarine morphology by stabilizing coastlines and narrowing channels in relatively
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1361 476 short time and their impacts can persist for long time, overlapped by slow changes
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1363 477 under natural evolution processes. Overall the Changjiang Estuary is becoming more
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1365 478 constrained and human-influenced due to extensive reclamation, embankment, and
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1367
1368 479 navigational works and the channel-shoal system of the estuary will be more
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1370 480 stabilized under human interventions in the future.
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1375 482 **5. Conclusions**

1378 483 We analyzed and interpreted 59-year's morphological evolution of the
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1380 484 Changjiang Estuary as a whole from 1958 to 2016 and inferred the causes and
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1382 485 implications. We see that its channel-shoal pattern featured by meandering and
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1384 486 bifurcated channels does not change over decades though there is strong erosion and
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1386 487 deposition. The Changjiang Estuary exhibits an overall deposition trend but with
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1388 488 strong temporal and spatial variations. The net deposition volume of the whole study
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1390 489 area was $8.3 \times 10^8 \text{ m}^3$ from 1958 to 2016, or a net deposition rate of $14.3 \times 10^6 \text{ m}^3/\text{year}$.
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1394 490 Spatially both regions A and B, the inner part of the estuary, turned from
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1396 491 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,
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1398 492 over 59 years. However, there was $18 \times 10^8 \text{ m}^3$ of deposition in region C, i.e., the
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1400 493 mouth bar zone, from 1958 to 2016. Erosion had been also detected since 2010 in the
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1402 494 MBZ. The strong spatial variability can be explained by the differences in their
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1404 495 hydrodynamic forcing and morphological features owing to along river distribution of
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1406 496 river and tide energy. In the vertical direction, the hypsometric curves showed that
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1408 497 deposition happened over the sand bars and shoals, whereas erosion mainly occurred
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1420 498 in the deep channels since 1958. As a result, the channels of the estuary became much
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1422 499 narrower and deeper.

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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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1433 504 influenced and its morphology is sensitive to riverine sediment supply reduction. The
1434
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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1449 512 resilience to external source changes. We argue that the time lag effects need to be
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1451 513 considered when examining large scale estuarine morphological changes in response
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1453 514 to riverine sediment supply variations which is not well understood but an important
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1455 515 issue given projection of future changes.

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1458 516 Big river flows with long duration and sediment deficiency may also explain the
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1460 517 erosion in periods from the late 1990s to early 2000s.

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1462
1463 518 Human activities such as the Deep Waterway Channel Project, reclamation, and
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1465 519 embankment play an important role in driving morphological evolution in the estuary
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1479 520 by stabilizing coastlines and narrowing channels. Overall the Changjiang Estuary is
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1481 521 becoming more constrained and man-influenced due to extensive reclamation,
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1484 522 embankment, and the navigational works and the channel-shoal system of the estuary
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1486 523 will be more stabilized in the future.

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1489 524 Future work by using morphodynamic modeling is needed to better quantify the
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1491 525 time lag and explain the controls of spatial morphological variability.

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1493 526

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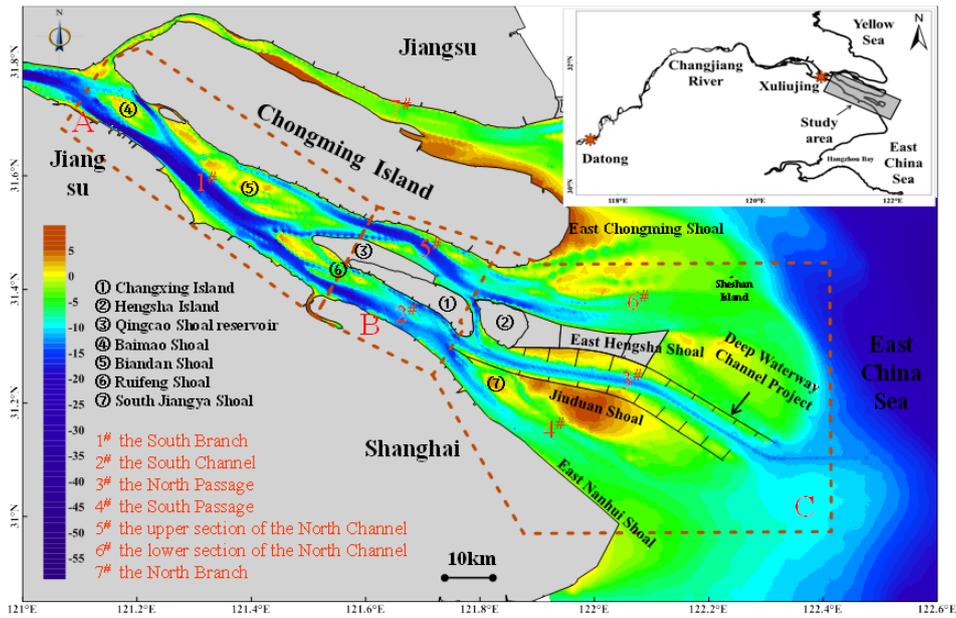
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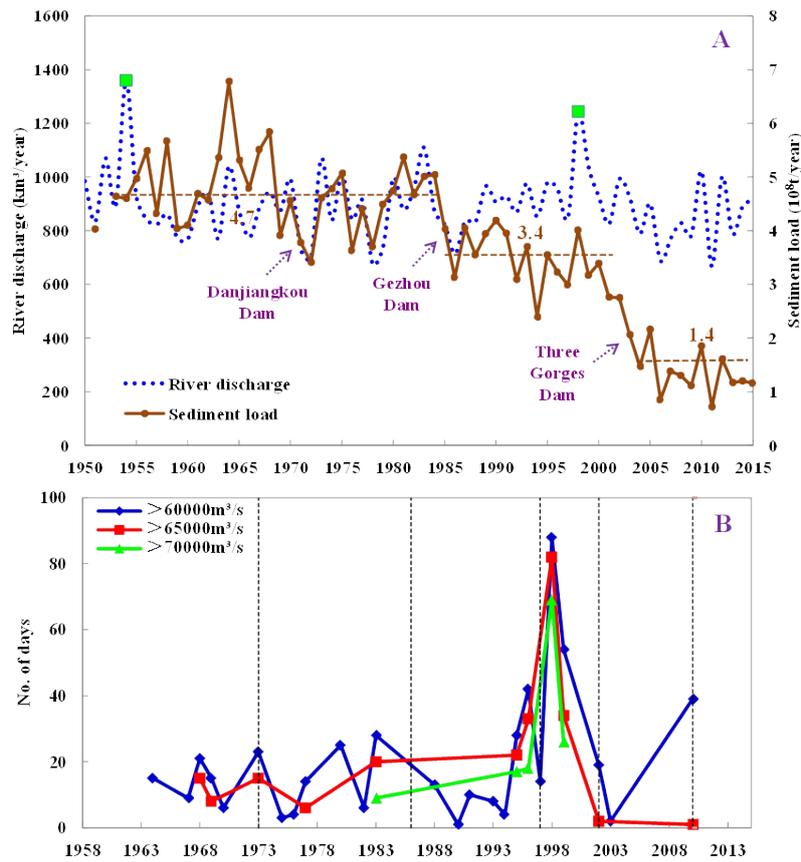
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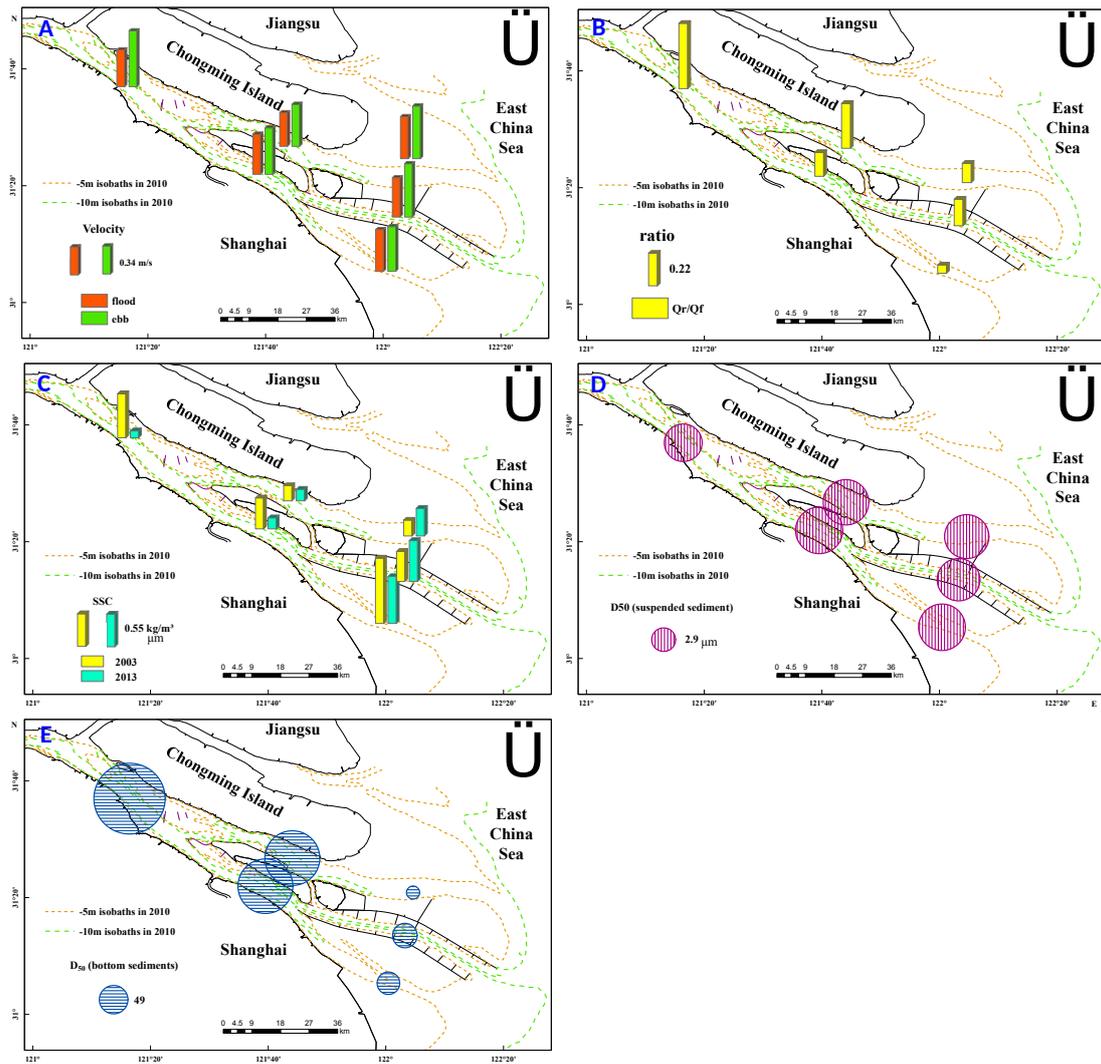
741 Fig. 1. A sketch map of the study area and division of different branches in the Changjiang Estuary with its
 742 bathymetry (depth in meters) in 2016. The whole study area is divided into three parts by brown solid lines, i.e.,
 743 region A (the South Branch (1[#])), region B (the South Channel (2[#]) and the upper section of the North Channel
 744 (5[#]), and region C (the North Passage (3[#]), the South Passage (4[#]), and the lower section of the North Channel
 745 (6[#])).

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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.



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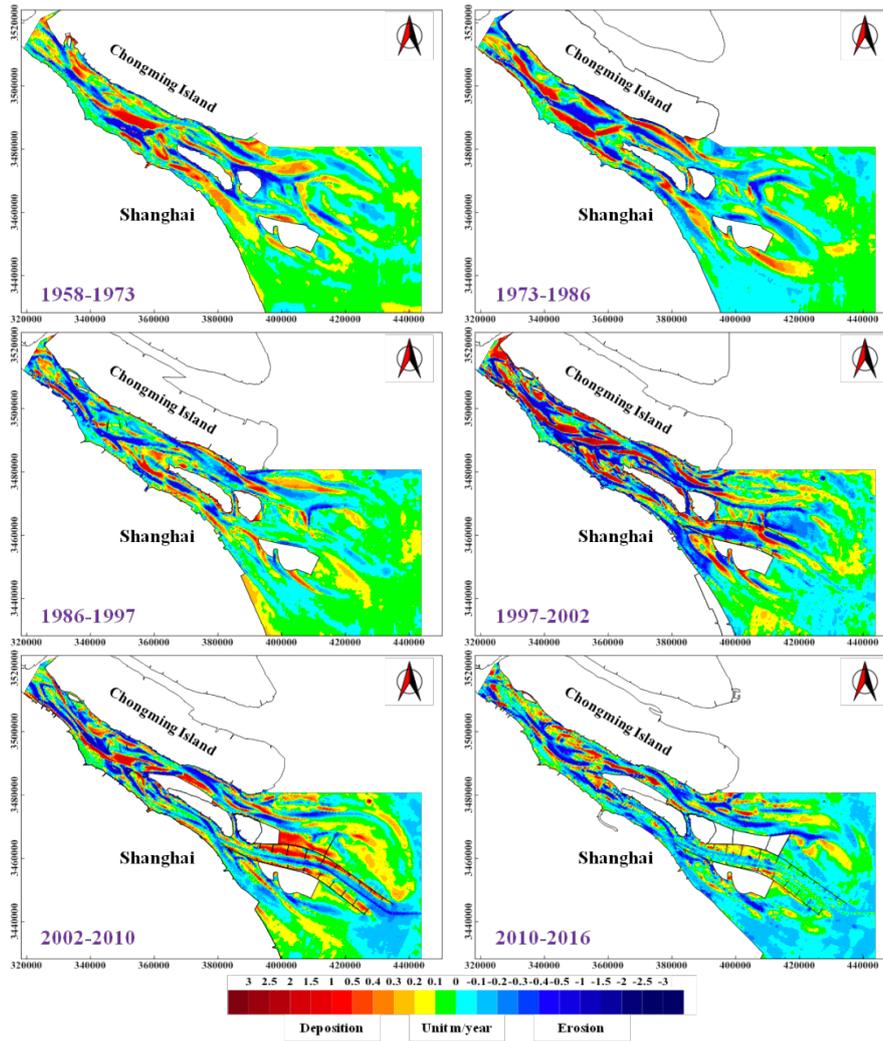
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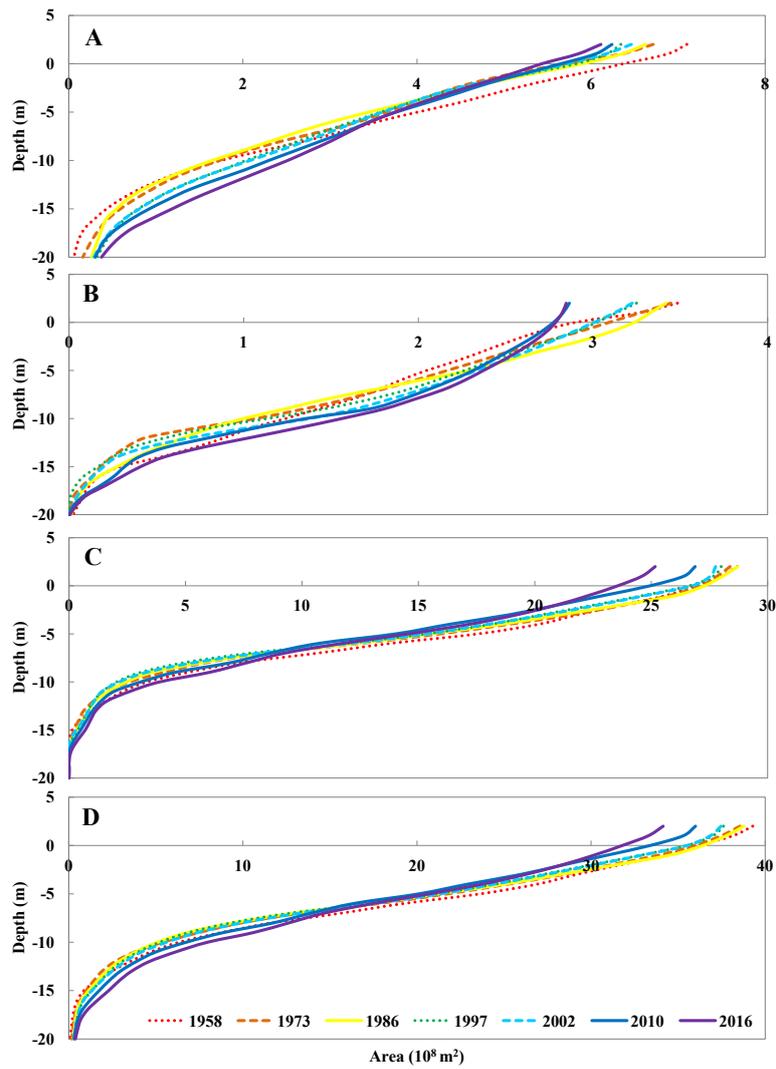
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Fig. 3. Longitudinal distribution of the depth-averaged flood and ebb current velocity during a neap-spring tidal cycle (A), ratio of river discharge to tidally mean discharge (Q_r/Q_t) during a neap-spring tidal cycle (B), depth-averaged suspended 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).



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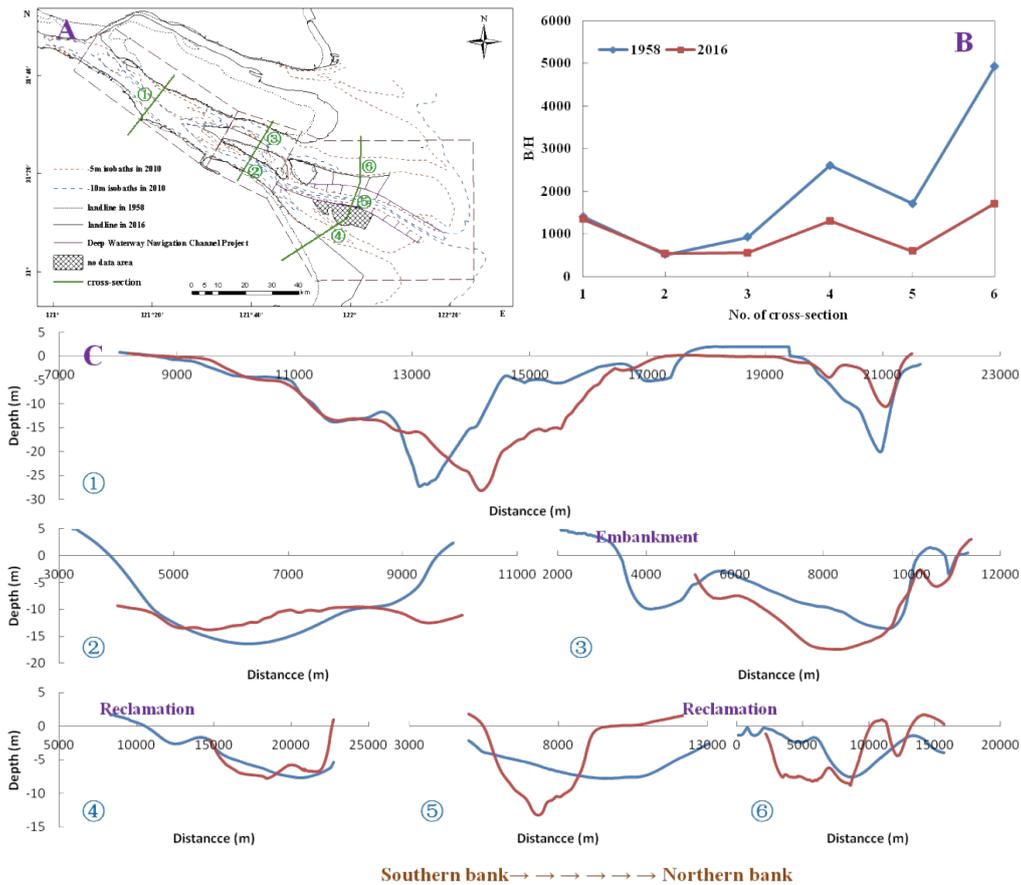
Fig. 4. Bathymetry changes of the study area during different periods (1958-1973, 1973-1986, 1986-1997, 1997-2002, 2002-2010, and 2010-2016) (unit: m/year).



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

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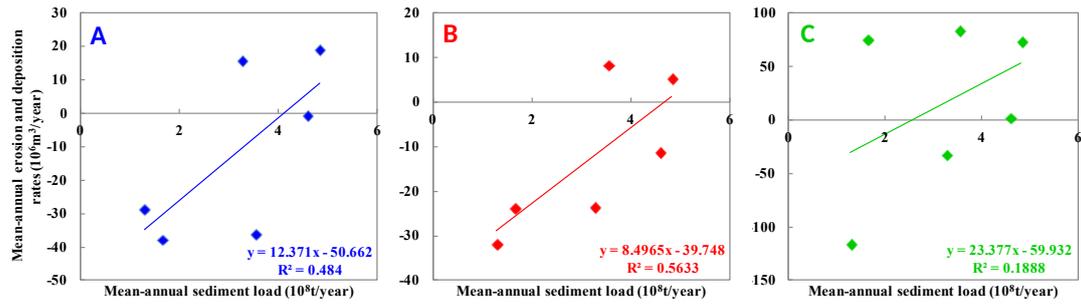
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Fig. 6. (A) Location of 6 chosen cross-sections in the Changjiang Estuary. (B) Width to depth ratios of 6 cross-sections based at 0 m referenced to the TLAT in 1958 and 2016. (C) Morphological variations of 6 cross-sectional profiles in both 1958 and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



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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.

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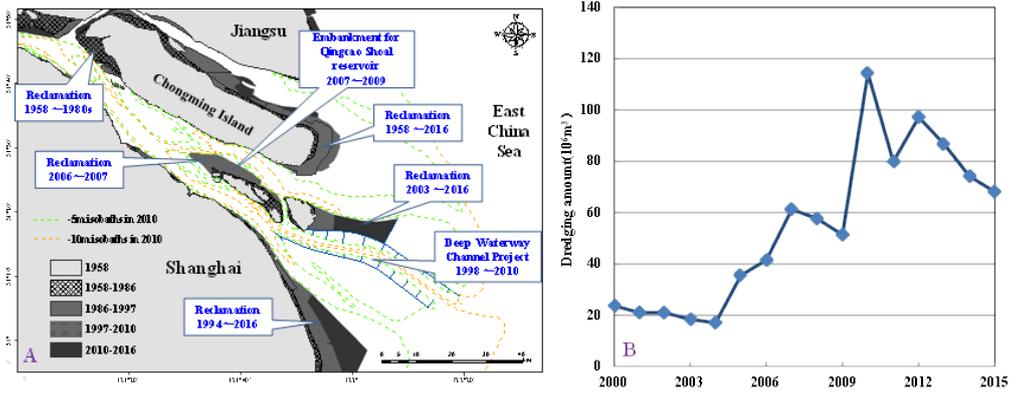
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 799 Fig. 8. (A) Change of the shorelines and main large hydraulic constructions in the Changjiang Estuary different
 800 periods. (B) Annual dredging amount in the North Passage in the Changjiang Estuary.

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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).

	Location	Unit	1958-1973	1973-1986	1986-1997	1997-2002	2002-2010	2010-2016	
Annual-mean river discharge	Datong	$10^8 \text{ m}^3/\text{year}$	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	$10^6 \text{ m}^3/\text{year}$	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	$10^6 \text{ m}^3/\text{year}$	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	$10^6 \text{ m}^3/\text{year}$	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	$10^6 \text{ m}^3/\text{year}$	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

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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

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Changjiang Estuary: spatial variability under natural processes

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and human intervention

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16

17 **Abstract**

18 Examination of large scale, alluvial estuarine morphology and associated time
19 evolution is of particular importance regarding management of channel navigability,
20 ecosystem, etc. In this work, we analyze morphological evolution and changes of the
21 channel-shoal system in the Changjiang Estuary, a river- and tide-controlled coastal
22 plain estuary, based on bathymetric data between 1958 and 2016. We see that its
23 channel-shoal pattern is featured by meandering and bifurcated channels persisting
24 over decades. In the vertical direction, hypsometry curves show that the sand bars and
25 shoals are continuously accreted while the deep channels are eroded, leading to
26 narrower and deeper estuarine channels. Intensive human activities in terms of
27 reclamation, embankment, and dredging play a profound role in controlling the
28 decadal morphological evolution by stabilizing coastlines and narrowing channels.
29 Even though, the present Changjiang Estuary is still a pretty wide and shallow system
30 with channel width-to-depth ratios >1000 , much larger than usual fluvial rivers and
31 small estuaries. In-depth analysis suggests that the Changjiang Estuary as a whole
32 exhibited an overall deposition trend over 59 years, i.e., a net deposition volume of
33 $8.3 \times 10^8 \text{ m}^3$. Spatially, the pan-South Branch was net eroded by $9.7 \times 10^8 \text{ m}^3$ whereas
34 the mouth bar zone was net deposited by $18 \times 10^8 \text{ m}^3$, suggesting that the mouth bar
35 zone is a major sediment sink. Over time there is no directional deposition or erosion
36 trend in the interval though riverine sediment supply has decreased by $2/3$ since the
37 mid-1980s. We infer that the pan-South Branch is more fluvial-controlled therefore its
38 morphology responds to riverine sediment load reduction fast while the mouth bar

39 zone is more controlled by both river and tides that its morphological response lags to
40 riverine sediment supply changes at a time scale >10 years, which is an issue largely
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.

46

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

48

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.

56

57

58 **1. Introduction**

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

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

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

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

102 morphodynamic adaptation in responding to external forcing changes is very much
103 ignored in previous studies. The morphological impacts of human activities such as
104 reclamations (Chu et al., 2013; Wei et al., 2015) and the Deep Waterway Channel
105 Project along the North Passage (De Vriend et al., 2011; Jiang et al., 2012, 2013) can
106 also vary in a large space and time scales depending on their location, implementation
107 time, and scales. Sea-level rise is also another factor needs consideration (Wang et al.,
108 2013; Wang et al., 2014; Wei et al., 2015). So far, a comprehensive and quantitative
109 investigation of morphological evolution in the entire Changjiang Estuary is still very
110 much needed.

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

119

120 **2. Data and methods**

121 **2.1 Brief introduction to the Changjiang Estuary**

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

124 mean river discharge is approximately $28.3 \times 10^3 \text{ m}^3/\text{s}$ (1950-2015) and annual
125 sediment load is 3.7×10^8 tons (1953-2015) (CWRC, 2015). The river and sediment
126 discharges exhibit markedly seasonal variations, with about 71% of water flux and
127 87% of sediment load flushed in the wet season between May and October (Chen et
128 al., 2008). Mean tidal range decreases from about 3.2 m nearshore to 2.4 m at
129 Xuliujing, the present delta apex, and further to be insignificant 500 km upstream of
130 Xuliujing. The tidal prism varies between 1.3×10^9 and $5.3 \times 10^9 \text{ m}^3$, with a mean
131 tidal discharge almost 9 times as much as the mean river discharge (Chen et al.,
132 2002). Thus the Changjiang Estuary is dominantly a partially-mixed, meso-tidal
133 system (Chen et al., 2002). The waves in the Changjiang Estuary are mainly wind
134 waves with a mean wave height of 0.9 m at Yinshuichuan in the river mouth area (Wu
135 et al., 2009; Wang et al., 2013). River and tides are the main forcing conditions
136 though wind and waves can affect hydrodynamics and sediment transport over the
137 shallow tidal flats. The present Changjiang Estuary has four prime inlets connecting
138 to the sea, namely the North and South Branch, North and South Channel, and North
139 and South Passages (Fig. 1). The estuary mouth is as wide as 90 km and the width
140 decreases to approximately 6 km at the apex of the funnel-shaped estuary, i.e.,
141 Xuliujing. Overall the Changjiang Estuary is a complex large scale system with few
142 comparable cases in the world.

143

144 **2.2 Data and methods**

145 We collect bathymetric data in 1958, 1973, 1986, 1997, 2002, 2010, and 2016,
146 covering the entire regions seaward Xuliujing until 10-15 m deep waters (Fig. 1). The
147 North Branch (NB), nowadays tide-dominated and limitedly influenced by fluvial
148 processes, is excluded in this study due to data scarcity. The bathymetry data in 1958,
149 1973, and 1986 are obtained from digitization of historical marine charts with a
150 resolution 1/50000 and data in other years are from field sounding measurements with
151 an accuracy of 1-2% for depths <2 m and <1% for depths >2 m (Wang et al., 2011,
152 2013). All depth data are referenced to the same datum, the Theoretical Lowest
153 Astronomical Tide (TLAT), which is basically below local mean water level by a half
154 maximum tidal range (~ 2 m). A digital elevation model (DEM) by 20×20 m is
155 created using Kriging interpolation.

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

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

169

170 **3. Results**

171 **3.1 Overall morphological evolution (1958-2016)**

172 We see that there is no new channel bifurcation in the Changjiang Estuary since
173 1958. The three-level bifurcation and four-outlet configuration persists and the
174 channels and shoals develop toward mature conditions by strong erosion and
175 deposition evolution (Fig. 4). The middle-channel channel-shoal pattern is featured by
176 meandering channels and sand bars. The entire estuary becomes narrower and deeper
177 owing to deposition over the shoals and tidal flats and erosion along the channels.

178

179 **3.2 Erosion and deposition patterns**

180 The study area as a whole (including regions A, B, and C) had experienced
181 deposition from 1958 to 2016. The total net deposition amount of the study area
182 reached 8.3×10^8 m³ over 59 years, which equals a net deposition rate of 14.3×10^6
183 m³/year.

184 Temporally, the estuary did not exhibit directional persistent deposition or
185 erosion over 59 years (Table 1, Fig. 4). The entire study area first experienced fast
186 deposition in 1958-1973 (98.2×10^6 m³/year), followed by slight erosion in 1973-1986
187 (9.2×10^6 m³/year), deposition in 1986-1997 (56.3×10^6 m³/year), erosion in 1997-2002
188 again (40×10^6 m³/year), slight deposition in 2002-2010 (13.9×10^6 m³/year), and
189 recently fast erosion in 2010-2016 (175.7×10^6 m³/year).

190 Spatially, the net erosion volume was $9.7 \times 10^8 \text{ m}^3$ in the pan-South Branch
191 between 1958 and 2016. Approximately 52% of that occurred in region A and 48% in
192 region B. To the contrast, the MBZ was deposited by $18 \times 10^8 \text{ m}^3$ in the interval,
193 indicating that the MBZ is a major sediment sink. The erosion and deposition patterns
194 are different in different regions (Table 1). Region A had changed from deposition
195 (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
196 variation behavior was also observed in region B by slight deposition (1958-1973,
197 $5.5 \times 10^6 \text{ m}^3/\text{year}$) and moderate erosion (2010-2016, $31.7 \times 10^6 \text{ m}^3/\text{year}$). However,
198 region C showed a strong deposition trend from 1958 to 2010 and the deposition rates
199 reached up to $75 \times 10^6 \text{ m}^3/\text{year}$ most of the time, followed by significant erosion of
200 $1.15 \times 10^8 \text{ m}^3/\text{year}$ since 2010.

201

202 **3.3 Changes of hypsometry**

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

212 In the vertical direction, the erosion and deposition patterns of the sand bars and
213 shoals and the deep channels were quite different from each other during the past 59
214 years. By comparing the water volumes and areas of the channels under different
215 isobaths in both 1958 and 2016 (Fig. 5D), we see that the entire study area was
216 confined by -8 m isobaths. The water volume of the region above -8 m (-8~+2 m)
217 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
218 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
219 and shoals, which includes intertidal zone (0~+2 m). The water volume of the region
220 below -8 m isobaths (-8~ -20 m) increased by about $1.49 \times 10^9 \text{ m}^3$ and the area
221 increased by $0.1 \times 10^9 \text{ m}^2$. In the deep part of the channels below -12 m isobaths, the
222 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.
223 Thus the channels, especially the deep parts of them, were continuously eroded from
224 1958 to 2016.

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

234

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

256 changes (Fig. 6B and 6C).

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

264

265 **4. Discussion**

266 **4.1 Spatially varying hydrodynamics and sediment characteristics**

267 The Changjiang Estuary covers so large area that hydrodynamics and sediment
268 transport dynamics present strong spatial variations from upstream to downstream due
269 to the combined effect of river and tides (Liu et al., 2010; He et al., 2015). Most of the
270 main channels in the Changjiang Estuary are ebb-dominated with stronger ebb
271 currents than flood currents (Fig. 3A). The ratios of river discharge to tidally mean
272 discharge (Q_r/Q_t) present an obvious decreasing tendency in the seaward direction.
273 For instance, the Q_r/Q_t ratios are 0.44 and 0.12 in regions A and C, respectively (Fig.
274 3B). From the South Branch to the MBZ, the Q_r/Q_t ratio reduces by 73%. It indicates
275 that the South Branch is more river-influenced while the MBZ is much more tidal-
276 influenced than the South Branch.

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

278 upstream (region A) to downstream (region C). For example, the mean SSC was only
279 0.43 kg/m³ between 2003 and 2007 in the South Branch (region A), while the mean
280 SSC increased to 0.99 kg/m³ in the South Passage (region C), which is twice more
281 than that in the South Branch (Fig. 3C; Liu et al., 2010; He et al., 2015).

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

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

291

292 **4.2 Spatially varying morphodynamic behavior of the Changjiang Estuary**

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

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

306 It is widely known that river discharge acting on the Changjiang Estuary did not
307 show significant decreasing or increasing trend from 1958 to 2016, but the sediment
308 load at Datong had significantly reduced since the mid-1980s, mainly attributed to
309 dam constructions in the drainage basin. The annual river discharge at Datong
310 remained about 890×10^9 m³/year in the total six periods while the annual sediment
311 load had continuously reduced from 4.82×10^8 t/year (1958-1973) to 1.28×10^8 t/year
312 (2010-2016), a 2/3 reduction (Fig. 2A; Chen et al., 2008; He et al., 2015). However,
313 there was no directional deposition or erosion trend of the entire study area in the
314 estuary (Table 1), suggesting that estuarine morphological changes are not linearly or
315 simply correlated with riverine sediment supply changes as widely documented in
316 previous studies. We will discuss potential factors acting on the inconsistent change
317 behavior, including spatially varying estuarine morphological response behavior, time
318 lag effect, etc.

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

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

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

344 which is shorter than that in region B. The annual mean erosion or deposition rates of
345 region C (the MBZ) has little ($R^2=0.19$) relationship with the annual mean sediment
346 load at Datong. The correlation also improves ($R^2=0.53$) considering a time lag of
347 5 years (Table 2). Though limited data about sediment load at Datong before 1953 is
348 available, we believe that the time lag of morphological changes in the MBZ can
349 be >10 years considering its large scale and tidal influence.

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

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

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

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

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

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

402

403 **4.3 Spatially varying morphological changes under ~~catastrophic~~big river floods**

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

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

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

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

432 1-2 months in ~~both~~ 1998 and 1999, and ~~also the~~ post-flood discharges maintained at a
433 relatively high level ($>45,000 \text{ m}^3/\text{s}$) for 2-3 months in these two years, ~~which~~The
434 river discharge hydrographs were quite different from ~~the~~-normal yearsconditions. It
435 provided a continuous strong river force ~~to-in~~ flushing sediment seaward ~~and may~~
436 ~~cause erosion in the estuary~~. Moreover, based on the historical data from 1951 to
437 1984, Yin et al. (2009) found significant sediment deficiency for river
438 discharges $>60,000 \text{ m}^3/\text{s}$ at Datong. ~~The h~~High river flow has a larger sediment
439 transport ~~carrying~~ capacity but ~~there is not enough sediment to be transported (the~~
440 ~~sediment source-limited limited~~ condition in the river upstream Datong restricts
441 sediment availability to the estuary), thus triggering erosion in the estuary considering
442 further by enhanced sediment transport capacity thru river-tide interactions (Guo,
443 2014). The net deposition in region A in 1997-2002 reflects the imbalance between
444 channel erosion and shoal accretion which is very much related to channel migration
445 and shoal movement caused by big river floods as well. ~~Overall w~~We ~~also~~ think that
446 it is not only the magnitude of the flood peak discharges, but also its duration and
447 associated sediment deficiency, matter in causing strong estuarine morphological
448 changes ~~during large river floods~~.

449

450 **4.4 The influence of human activities**

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

454 (Fig. 8A).

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

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

476 owing to the navigational works and dredging. The cross-section of the North Passage
477 also became narrower and deeper. Taking cross-section 5 as an example, a 53%
478 reduction in width and a 35% growth in average-depth were observed from 1958 to
479 2016 and a dramatic change mainly occurred since 2002 because of the navigational
480 works and dredging. Other changes such as local erosion in the middle reach of the
481 North Channel and the upper section of the South Passage and reduced horizontal
482 growth and enhanced vertical accretion of the Jiudian Shoal from 2002 to 2010 were
483 also attributed to the navigational works (Jiang et al., 2010).

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

491

492 **5. Conclusions**

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

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

500 Spatially both regions A and B, the inner part of the estuary, turned from
501 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,
502 over 59 years. However, there was $18 \times 10^8 \text{ m}^3$ of deposition in region C, i.e., the
503 mouth bar zone, from 1958 to 2016. Erosion had been also detected since 2010 in the
504 MBZ. The strong spatial variability can be explained by the differences in their
505 hydrodynamic forcing and morphological features owing to along river distribution of
506 river and tide energy. In the vertical direction, the hypsometric curves showed that
507 deposition happened over the sand bars and shoals, whereas erosion mainly occurred
508 in the deep channels since 1958. As a result, the channels of the estuary became much
509 narrower and deeper.

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

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

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

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

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

536

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