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A thirteen-year record of bathymetric changes in the North Passage, Changjiang (Yangtze) estuary

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ABSTRACT

The mouths of major rivers in the world have always been important waterways and as a result, subject to significant human intervention. Therefore, it is necessary to understand the coupling of natural processes and human intervention in the sediment movement and deposition to determine long-term morphodynamic evolution in the mouth regions of major rivers. A multivariate technique was used to analyze high-resolution bathymetric data from the North Passage of Changjiang (Yangtze River), which is the vital shipping channel in the mouth region and for the entire Changjiang waterway. Our findings show that there are two modes of bathymetric changes. The first mode represents 85% of the variability, which includes the deposition in the peripheral groin fields along the shipping channel and deepening of the shipping channel, which is primarily due to the channel maintenance. The second mode represents 6% of the variability of the river-mouth shoal (seaward migration and size reduction), attributable to the declining sediment discharge of the Changjiang due to the Three Gorges Dam, and the enhancement of the ebb flow as the result of dredging.

1. Introduction

Estuaries are located at the junctions of rivers and the sea. They are complex systems in which exchanges of fluvial and marine sediments take place (Wright and Coleman, 1974). Estuaries possess valuable natural and human resources such as biodiversity and waterway; they have therefore been the foci of several scientific enquiries. Many estuaries in the world have been subject to human intervention, such as the excavation for aggregates and dredging for waterway (Lafite and Romaña, 2001; Blott et al., 2006; Benedet and List, 2008; Talke et al., 2009; Jiang et al., 2012), and no longer "behave" naturally. The examples can be seen in many estuaries around the world. In the past 200 years, because of the navigational needs, the channel in the Ribble estuary in N. England has been dredged, leading to deposition in the estuary especially in the upper intertidal zone (van der Wal et al., 2002). Due to the construction of retaining walls and dredging of the approaching channels, in the past 150 years the volume of the Mersey Estuary decreased by 0.1% or 1 million m^3 (Lane, 2004). After channel improvements in the Columbia River Estuary, the tidal prism decreased, leading to the loss of river-mouth wetland and habitat (Sherwood, et al., 1990). Dredging and dumping activities in the Ems Estuary altered the estuarine dynamics and sedimentation process, causing the upriver displacement of the Estuarine Turbidity Maximum (ETM) zone (De Jonge, 1983; Talke et al., 2009). Accumulation of a large amount of silt and fine sand occurred in the middle reaches of the Lune Estuary in the last 100 years due to the construction of retaining walls (Spearman et al., 1998).

In the Anthropocene, many estuaries face declining sediment load, river engineering modifications, and the relative sea-level rise (Syvitski et al., 2005). There have been studies on estuarine sediment transport (Wright, 1977), estuarine morphodynamic modeling (Karunarathna et al., 2008; van der Wegen et al., 2010; Rossington et al., 2011), estuarine tidal flat reclamation (van Proosdij et al., 2009), and channel dredging and regulation (Stark, 2006; van Proosdij et al., 2009). Yet, little has been focused on how human interventions affect estuarine changes and evolution. Based on studies of the river catchments, many large rivers in the world have been regulated (Nilsson et al., 2008), but due to the complexity in the estuarine hydrodynamics, even with human regulation, it is still unclear how the regulations affect estuaries.

Changjiang (Yangtze River) is the largest river on the Eurasia continent whose estuary is the largest in China (Fig. 1A). In the lower reaches of the Changjiang, the river channel sequentially bifurcates at four islands, Chongming, Hengsha, Changxing and Jiuduansha Shoal, forming a 3-tiered branching meso-tidal estuary that has 4 openings to the East China Sea (Fig. 1B, C). At the mouth of the Changjiang the average tidal range is 2.67 m and flow rate is 1 m/s. Since June 2003, when the upper reaches of the Changjiang began

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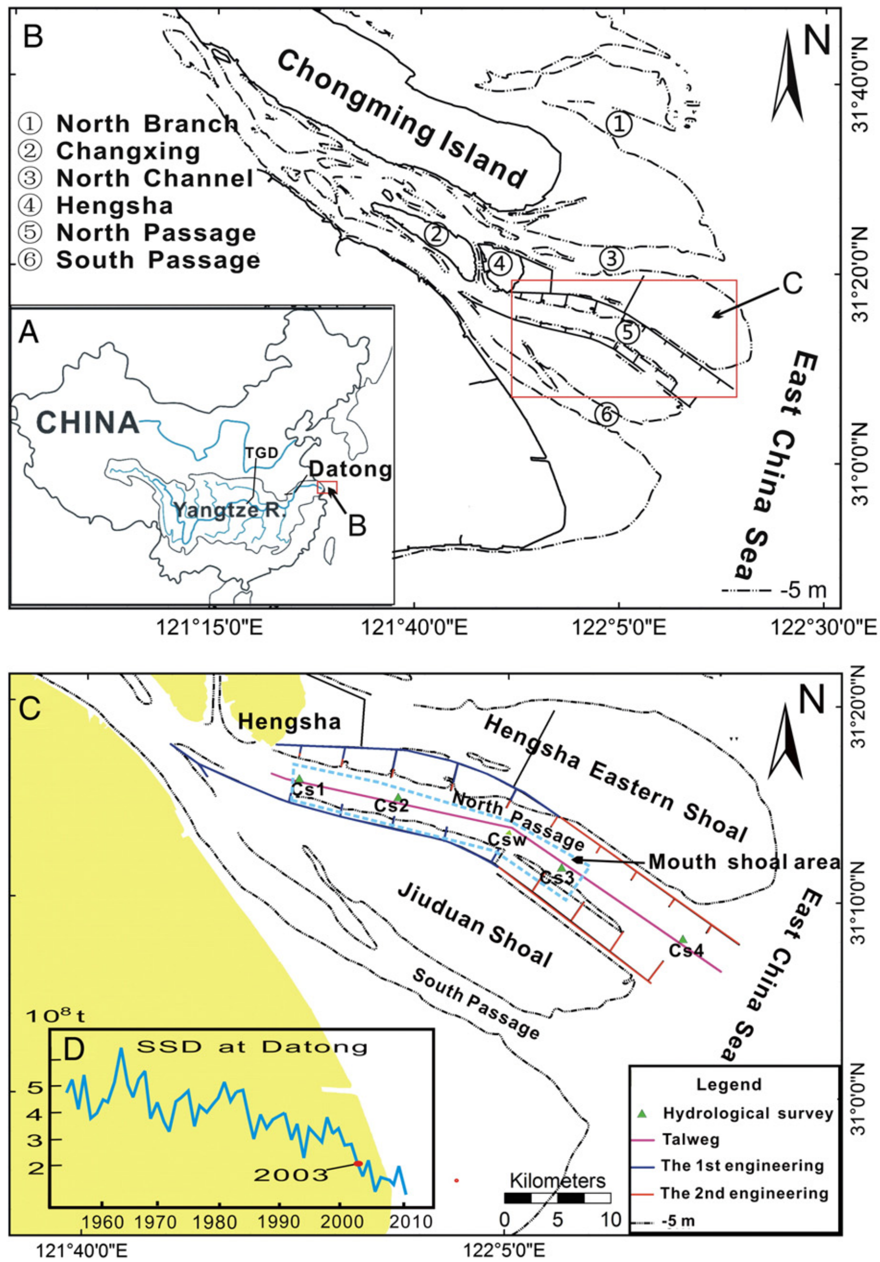

Fig. 1. Geographic information of the study area including (A) the map of China, which shows the Changjiang river basin, the locations of the Three Gorges Dam (TGD) and the Datong gauging station; (B) three-tiered branching Changjiang Estuary and the four bifurcated channels; (C) enlarged map of the North Passage showing the locations of the T-shaped groins and the 5 hydrographic stations where river flow was measured; and (D) the suspended sediment discharge (SSD) recorded at Datong over the past 50 years.

to be impounded by the world's largest Three Gorges Dam (TGD), the sediment load rapidly decreased (Fig. 1D), leading to localized erosions in the mouth area (Yang et al., 2007; Dai et al., 2008a, 2011).

Since 1998 the North Passage (N. Passage), where the main shipping channel of the Changjiang waterway is located, has been continually dredged from the average depth less than 7 m to the present day 12.5 m using trailing-suction hopper dredgers. For the maintenance of the dredged shipping channel, nineteen T-shaped groins were constructed off two dikes on both flanks along the shipping channel (Fig. 1C). On each side the dikes were 49. 2 and 48 km long, respectively. They were designed to maintain the outer perimeter of the N. Passage. The dikes and groins are emerged at low tide and submerged at high tide. Their first intended function was to stabilize the shipping channel. Their second intended function was to prevent sediment entrained by waves on the tidal flats on both sides of the N. Passage entering the channel. The third intended function was to redirect the peripheral ebb flows into the main channel to strengthen the ebb flow in the channel and also to ensure the ebb flow dominance in the channel so that the flow field in the channel maintains the trough-shaped cross-sectional geometry. The average length of the groins is 2 km. There were ten groins on the north side and 9 on the south side. The total length of all the groins was about 30 km.

This channel maintenance project is by far the largest estuarine hydraulic engineering endeavor in China whose scale and regional influence is comparable to that of the Dutch Delta Works, which is located near the confluence of the Rhine, Maas and Schelde. Although the N. Passage Improvement Project and the Delta Works are located in different regions and in river systems with contrasting hydrodynamic regimes, they share similarities in the scale of engineering work, the impact on the immediate estuarine environment, and their far-reaching influence on the socio-economical well-being of the population.

Theoretically, the TGD in the distal upper reaches of the Changjiang and the proximal shipping channel engineering activities in the estuary would affect the estuarine hydrodynamics and produce pronounced effects. Furthermore, the effects of the proximal channel dredging and the groin fields on the morphodynamics in the N. Passage are not well studied. We hypothesize that these two major factors, the distal TGD and the proximal channel maintenance engineering will affect the sedimentation the North Passage. Therefore, this study used quarterly high-resolution bathymetric survey data since 1998 to examine the spatial and temporal variability of the bathymetry along the N. Passage. The goal is to determine the combined influence of hydrodynamics and human intervention on the N. Passage and further distinguish the relative significance of the proximal and distal influence. This is an interesting aspect that is of wider international significance.

2. Materials and methods

The scarcity of high-resolution bathymetric survey data that cover a long time span makes it difficult to quantify long-term sediment morphodynamics in estuaries. Since January 1998 when the channel deepening and maintenance engineering project began, the N. Passage was surveyed on a semi-quarterly basis every year by the Changjiang Estuary Waterway Administration Bureau (CJWAB), Ministry of Transportation (data available at www.cjkhd.com) using dual-frequency echo sounders and GPS positioning. The vertical error in the depth surveys was 0.1 m. The surveyed raw data were made into 1:10,000 and 1:25.000 bathymetric charts suing AutoCad software (Table 1). The water depths on channel cross-sections were spaced 1 km apart, having 50 m intervals along each cross-section on the 1:10,000-scale chart, and the cross-sectional spacing was the same but the depth-intervals along each cross-section was 250 m on the 1:25,000-scale chart. Every square kilometer on each chart should contain 8–40 surveyed data points. This study collected 45 bathymetric charts between August 1998 and August 2011 in February, May, August, and November each year. Subsequently on the ArcGis9.3 platform using Kriging interpolation method each data set was gridded into charts of 200×200 m resolution. Each chart contained 11,255 interpolated data points so that cross-comparisons could be made between charts of different times.

This study also acquired measured flow data (source: CJWAB) in a 25-hour tidal cycle at 5 locations in the N. Passage in the months of June 1999, and August 2002, 2005, 2007, 2008 and 2011, respectively (Fig. 1C, Table 2). The measured tidal cycles all coincided with the spring tide. In addition, monthly records of suspended sediment data since 1955 monitored at Datong station, which is located beyond the tidal limit of the Changjiang (Fig. 1A), were also acquired (data available at www.cjw.com.cn).

Table 1
Surveyed water depth data in the North Passage, Changjiang Estuary.[a]

Year	February	May	August	November	Scale
1998			∨		1:25,000
1999	∨		∨	∨	1:25,000
2000	∨	∨	∨	∨	1:25,000
2001	∨	∨	∨	∨	1:25,000
2002	∨	∨	∨	∨	1:25,000
2003	∨	∨	∨	∨	1:25,000
2004	∨	∨	∨	∨	1:25,000
2005	∨	∨ (1:25,000)	∨	∨	1:10,000
2006	∨	∨	∨	∨	1:10,000
2007	∨		∨		1:10,000
2008		∨		∨	1:10,000
2009		∨		∨	1:10,000
2010	∨	∨	∨	∨	1:10,000
2011	∨	∨	∨		1:10,000

[a] The symbol "∨" represents collected data.

At each hydrographic station, the coefficient of flow dominance (defined as tidal excursion during the ebb divided by the sum of tidal excursions of the ebb and flood) was calculated (Simmons, 1955) as follows:

$$A = \frac{Q_e}{Q_e + Q_f} \times 100\% \tag{1}$$

where A is the dominance coefficient, Q_e is the unit width ebb volume, and Q_f is the unit width flood volume. When the ebb flow is dominant, $A > 50\%$, and vice versa.

To quantify the volume change of the N. Passage so that the sediment change could be deduced, ArcGIS was used as the platform for data assimilations. Generally in the deltaic region of the Changjiang, the estimate of the volume of the river channel is estimated from the bathymetry below the 0 m elevation. The area of the tidal flat is considered within elevation range between 0 and −2 m. To comprehensively represent the average channel depth and dredged navigational depth, −8 m elevation was used. Therefore, for each dataset the volumes of the river channel below −0 m, −8 m and above −2 m, and the volume of the river-mouth shoal were estimated. The depth values along the thalweg location were extracted and their anomalies (deviations from the mean) were subsequently calculated at each location for each data set.

EOF (Empirical Orthogonal/Eigen Function) is eigentechniques that can permit us to extract information from large datasets. The advantage of EOF analysis is that a set of intercorrelated variables can be decomposed into a set of statistically independent variables. Eigenanalysis separates the temporal and spatial dependence of the data, considering data as a linear combination of products of corresponding functions of time and space (Dai et al., 2008b, 2010). Obviously, the aim of EOF is to find a relatively small number of independent variables that describe as much of the original information as possible. This technique has been widely used in the study of estuarine morphodynamics and sediment dynamics (Zarillo and Liu, 1988; Emery and Thomson, 2001; Lane, 2004; Liu and Lin, 2004; Dai et al., 2008b; Liu et al., 2009; Dai et al., 2010). Here, all the bathymetric data sets were standardized to form a single matrix X

$$X = (X_1 \ldots X_N)$$

where each X_N represents a single grouped observation of the M variables and X is an $M \times N$ data matrix. M is a spatial point, and N is the observed time.

By definition, the EOFs are the eigenfunctions of the standardized covariance matrix S, which is given by $S = XX'$. Based on singular value decomposition of the matrix S, the eigenvalues $\lambda(\lambda_1, \lambda_2, \ldots, \lambda_M)$ of S and spatial patterns (V) can be obtained. Thereafter, the time series describing the loadings (T) is calculated by $T = V'X$.

Subsequently, eigenvalues $\lambda(\lambda_1, \lambda_2, \ldots, \lambda_M)$ can be rearranged from largest to smallest in order, the variance contribution of each

Table 2
Data collected at the different hydrological stations.

Stations	Position	Observed periods
Cs1	121.86° E, 31.26° N	6.1999, 8.2002, 8.2005, 8.2007, 8.2008, 8.2011
Cs2	121.96° E, 31.25° N	6.1999, 8.2002, 8.2005, 8.2007, 8.2008, 8.2011
Csw	122.10° E, 31.23° N	8.2002, 8.2005, 8.2008, 8.2011
Cs3	122.12° E, 31.18° N	6.1999, 8.2002, 8.2005, 8.2007, 8.2011
Cs4	122.25° E, 31.13° N	6.1999, 8.2002, 8.2005, 8.2007, 8.2011

eigenvalue R_k, and the cumulative contribution for the first pth eigenvalues G can be considered as:

$$R_k = \lambda_k / \sum_{i=1}^{M} \lambda_i \quad [k = 1, 2, \ldots p(p<M)]$$
$$G = \sum_{i=1}^{p} \lambda_i / \sum_{i=1}^{M} \lambda_i \quad (p<M)$$

If the cumulative contribution for the first pth is over 85%, the corresponding temporal and spatial functions that were represented by the first pth eigenvalues could reflect main information of the original data (Emery and Thomson, 2001; Lane, 2004).

3. Results

3.1. Bathymetric changes in the N. Passage

The engineering project in the N. Passage progressed in 3 stages. In the first stage (August 1988–May 2001) the depth of the shipping channel was deepened to 8.5 m. The first stage only affected the upper part of the N. Passage where the dikes and groin fields were put in place and the navigational channel was deepened (Fig. 2A). However, there was erosion of over 1 m in the channel in the lower part, and minor erosion of less than 0.5 m appeared in the middle part of the N. Passage. There was deposition over 2 m in the groins on the north side of the channel (Fig. 2A). The capacity (volume between 0 m and the channel floor) of the channel was enlarged by about 214.8×10^6 m^3 (Table 3). In the interim period between the 1st and 2nd stages, there was minor deposition. The formerly dredged channel was back-filled by about 145.7×10^6 m^3 (Fig. 2B, Table 3).

During the 2nd stage (May 2002–February 2005), the channel depth reached 10 m and the dikes and groin fields were extended for the entire shipping channel and the groins in the 1st stage on the north side were lengthened (Fig. 2C). During this stage, the channel continued to be deepened and simultaneously deposition occurred in between groins, in which the average vertical accumulations exceeded 1 m (Table 3). Consequently, the channel capacity actually decreased by 125.6×10^6 m^3. In the interim period between the 2nd and 3rd stages, channel deepening took place in the lower part of the N. Passage and deposition occurred in the upper part (Fig. 2D).

During the 3rd stage (August 2006–March 2010), the water depth reached 12.5 m and the deposition rate of about 4.5 cm/year in the groin fields was similar to that during the previous stage, but the main channel was deepened further (Fig. 2E, Table 3). The channel capacity remained unchanged (Table 3). After the completion of the 3rd stage, between February 2010 and August 2011, the N. Passage was back-filled by 80.9×10^6 m^3. The channel capacity below 0 m was decreased by about 15% in comparison with that before the dredged engineering in August 1998. In the meantime, deposition continued to occur in the groin fields. The patterns in bathymetric change showed patchy deposition (Fig. 2F) similar to the interim period between the 1st and 2nd stages (Fig. 2B). During each stage, immediately after dredging, dredgers maintained the shipping channel. In general, the engineering efforts deepened the navigational channel and the groin fields trapped sediment as expected. After the completion of the engineering project, the sediment continued to infill the groin fields but the dredged channel began to be back-filled, starting in the middle section and, then extended down-river (Fig. 2F).

Table 3
Sediment budget for the North Passage, Changjiang Estuary.

	8.1998–1.2001	1.2001–5.2002	5.2002.5–2.2005	2.2005–8.2006	8.2006–2.2010	2.2010–8.2011
Ah (m)[a]	+0.89	+0.75	+1.43	+0.90	+1.13	+0.73
Eh (m)[b]	−0.94	−0.56	−0.96	−0.88	−1.10	−0.60
Nh (m)[c]	−0.10	+0.15	+0.59	+0.17	+0.16	+0.10
Nv (10^6 m^3)[d]	−214.8	+145.7	+125.6	+82.1	+3.34	+80.9

[a] Ah is mean accumulation thickness in N. Passage.
[b] Eh is mean removal thickness in N. Passage.
[c] Nh is net change between accumulation and removal in N. Passage.
[d] Nv is channel capacity below 0 m in N. Passage.

In the past 13 years, the capacity of the N. Passage has been on a decreasing trend, punctuated by seasonal fluctuations (Fig. 3A). On average, the mean yearly capacity decreased by 17.2×10^6 m^3. However, in the main shipping channel where the depth was greater than −8 m, the capacity increased (especially in the 3rd engineering stage) by 14.8×10^6 m^3 (Fig. 3B). It is notable that although the alternate phenomena of deposition in the flood season and erosion in the dry season were not as pronounced as observed previously (Yun, 2004), seasonal fluctuations were still presented in our data. Moreover, based the different digital navigational charts, patterns of sediment exchange between the tidal flat and channel can be found (Yun, 2004). Here, the opposing accumulation/removal trend between the groin fields and the channel (deeper than −8 m) suggests some sediment exchange between the two still existed.

During the 13-year period that spanned the engineering project, the depth anomaly along the channel thalweg reveals that the first

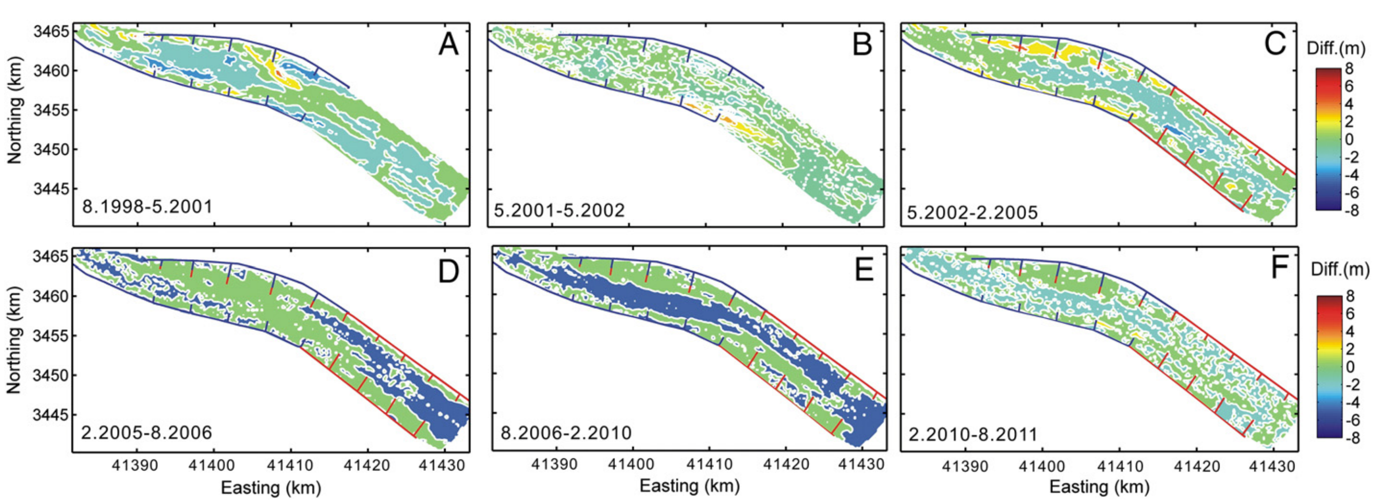

Fig. 2. Bathymetric changes (depth of later time minus that of the previous time) in the follow periods: (A) Aug. 1998–May 2001, (B) May 2001–May 2002, (C) May 2002–Feb. 2005, (D) Feb. 2005–Aug. 2006, (E) Aug. 2006–Feb. 2010, and (F) Feb. 2010–Aug. 2011.

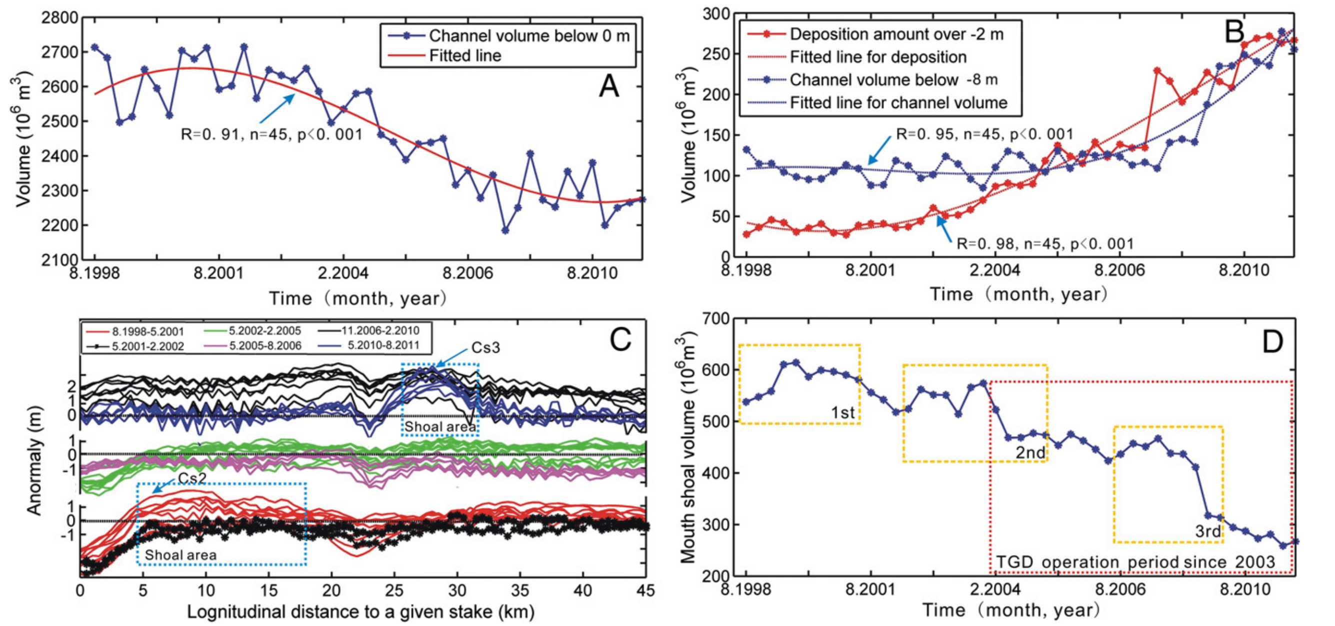

Fig. 3. Secular changes showing (A) the channel capacity (volume below 0 m) of the N. Passage, (B) volume changes of the N. Passage above −2 m depth (asterisk line) and below −8 m depth (asterisk dashed curve), (C) depth anomaly from the thalweg in each of 6 time periods, and (D) the volume of the mouth shoal.

and third engineering stages were more effective in deepening the channel. However, although there were continued dredging efforts, the channel always became back-filled after the completion of each stage (Fig. 3C).

The river-mouth shoal in the N. Passage is a characteristic depositional feature common in estuaries, whose changes are well reflected in the depth anomaly (Fig. 3C). In the beginning of the first engineering period (September 1998–May 2001), the shoal appeared to be symmetrical in the axial direction, having a height as much as 2 m above the channel floor and a wide (about 20 km) base (red curves, Fig. 3C). During the 13-year period, the volume of the shoal decreased by more than twofold (Fig. 3D). It is notable that in the course of the declining trend, the shoal always grew larger during each engineering stage, probably fed by the sediment plume during dredging. In the post-engineering period (May 2010–August 2011), the shoal was located 18 km down river from the pre-engineering position, having a greater height about 3 m and narrower (about 5 km) base in the axial direction (blue curves, Fig. 3C). The morphology of the shoal was changed from having gentle slopes during the pre-engineering period to having steeper slopes during the third engineering period (Fig. 3C).

3.2. Empirical orthogonal function/eigenanalysis of the bathymetric changes

The major morphology of the Changjiang Estuary has remained the same since the 1954 deluge (Yun, 2004). Therefore, our analysis is only on the small-scale depth changes in the N. Passage using the EOF technique.

The EOF results show that the dataset was highly correlated and that the first two eigenmodes explain 91% of the correlations (standardized covariance) of the time-and-space correlated bathymetric changes. Therefore, we present only the first two modes; the remainder is considered as being insignificant (Zarillo and Liu, 1988; Emery and Thomson, 2001).

The eigenvectors of the 1st mode, which explains 85% of the correlations, were contoured with the groin fields superimposed (Fig. 4A). It reflects the dichotomy in the bathymetric changes along the N. Passage due to the engineering project. On one hand, along the thalweg (below −8 m depth) the water became deeper (negative values) due to dredging (Fig. 2). On the other hand, along the flanks of the channel in the groin fields and on the tidal flats (above −2 m depth), the depths became shallower (positive values) due to deposition (Fig. 2). The contoured patterns also indicate that major accumulation occurred in the northern groin field during the 1st stage and in the southern groin field since the 2nd stage (Fig. 4A). The temporal pattern of this mode is represented by the eigenweighting curve (Fig. 4B). The periods of the 3 stages of the engineering project are indicated by three dashed rectangles, and the time frame when the TGD became operational is indicated by dotted rectangle. In essence, this curve is a mirror reflection (opposite) of the channel capacity decrease (Fig. 3A) such that a weak yet significant negative correlation exists between the 1st mode eigenweightings and the capacity below − 0 m ($n=45$, $r=-0.25$, $p<0.1$). Therefore, the first eigenmode primarily describes the decrease in channel capacity over the 13-year period in which the main channel was deepened by human efforts in three incremental stages while sediment accumulated between the groins and on the tidal flats along the channel.

The second eigenmode explains 6% of the correlations. The contoured eigenvectors show positive values are along the thalweg (Fig. 4C). The temporal characteristics of this mode are represented by the eigenweighting curve that shows secular decline (Fig. 4D). The same trends of volume decrease of the river-mouth shoal (Fig. 3D) and the decline of the suspended sediment discharge of Changjiang recorded at Datong (Fig. 1B) suggests that this mode is probably attributed to both. In fact, linear regression analysis shows that a highly significant correlation ($r=0.91$, $p<0.001$) exists between the 2nd mode eigenweightings and the mean yearly-suspended load at Datong. Concurrently significant linear correlation also exists between the 2nd mode eigenweightings and the volume of the river-mouth shoal ($r=0.86$, $p<0.001$). It is also noted that the zero-crossing of the 2nd eigenweighting curve corresponds to the time when the TGD began operation (Figs. 1D, 4D).

3.3. Variations of flow dominance coefficient along the N. Passage

The flow dominance coefficient at the 5 hydrographic stations along the N. Passage (Fig. 1) over one semi-diurnal tidal cycle during

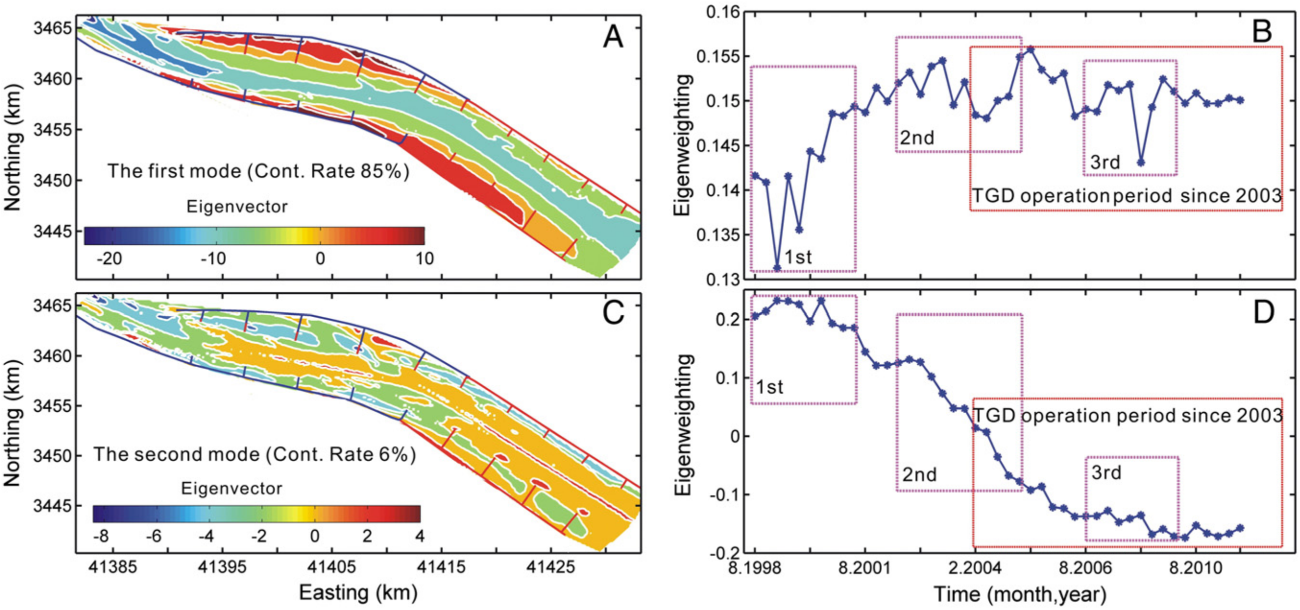

Fig. 4. Results of the EOF analysis showing (A) contoured eigenvectors of the first mode, (B) the first mode eigenweightings, (C) contoured eigenvectors of second mode, and (D) the second mode eigenweightings. The yellow dashed boxes indicate the time periods of the three engineering stages. The red dotted box show the time frame of the TGD impact.

the spring tide in June 1966, August 2022, August 2005, August 2007, August 2008, and August 2011 were computed, respectively (Fig. 5). For each time point, not all stations are available (Table 2). Data from the time points that coincided with the engineering stages are plotted with dashed lines. When comparing the values in June 1999 (pre-engineering) and in August 2011 (post-engineering), one can see that the overall ebb-flow dominance has dropped by 5% along the N. Passage. It is also worth noting that the ebb-flow dominance increased at Cs3, and exceeded that at Cs1. This could explain why the river-mouth shoal was pushed down river from Cs1 to Cs3 during the 13-year period. The relatively weak ebb-flow dominance in the landward bottom estuarine circulation is probably located at Csw after the engineering project.

4. Discussion and conclusion

Our findings show that the engineering project to deepen the thalweg and the construction of the T-shaped groin fields along the N. Passage to improve and maintain the navigation channel is the main cause for the predominant form (85%) of bathymetric changes in N. Passage. Throughout the course of the engineering project, the bathymetric changes appeared in two opposite and yet related patterns. Within the navigational channel (water depth deeper than −8 m) during the engineering stages, the depth increased due to dredging. The combined effect of the groins and the dyke prevented sediment from entering the N. Passage and also reinforced the ebb flow (Fig. 1B). However, in the interim periods between two engineering stages, the dredged channel got back-filled and the depth became shallower. Eventually, the continual dredging did increase the capacity of the North Passage below the depth of −8 m. The groins on the other hand, trapped sediment and caused deposition in the groin fields and on the tidal flats outside the channel in areas shallower than −2 m depth.

Two factors contributed to the second most important form of bathymetric changes (6% of the data variability) that occurred in the thalweg of the N. Passage. The first one is the declining sediment supply to the estuary that is directly linked to the operation of the TGD. Since its operation in 2003, the amount of sediment trapped by TGD was 124×10^6 t in 2003, 102×10^6 t in 2004, 151×10^6 t in 2005, and 196×10^6 t in 2010 (data available at www.cjh.com.cn). This induced an obvious decrease in sediment discharge into the Changjiang Estuary from 420×10^6 t/y during the last 50 years to 150×10^6 t/y in recent years (Fig. 1D). Meanwhile, suspended sediment concentration around the shoal area in the Changjiang Estuary decreased from 0.34 kg/m^3 in 1999 to 0.28 kg/m^3 in 2009 (Dai et al., 2012). The other factor is the down-river migration and volume reduction

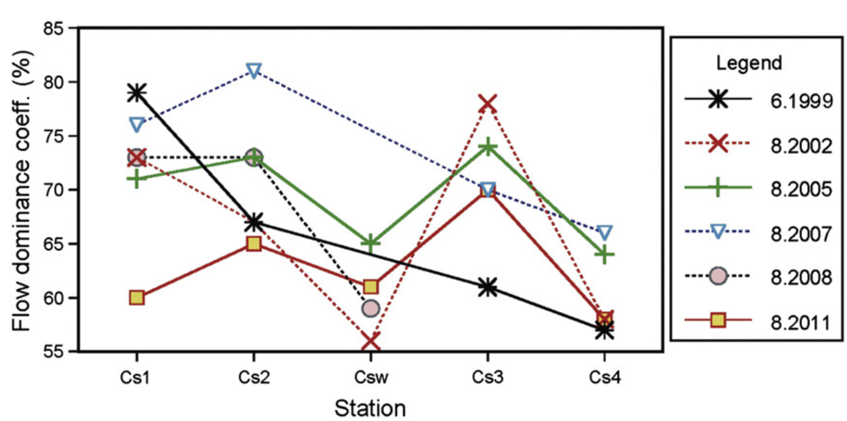

Fig. 5. Measured flow dominance coefficients at each hydrographic station at different times.

of the river mouth shoal in the N. Passage, the latter of which is indirectly related to the TGD. The capacity increased by dredging strengthened the river discharge and thus caused the ebb dominance to be extended down river over the 13 years of the engineering project. Consequently, the river-mouth shoal was pushed down river by 18 km. However, because of the reduced sediment supply from Changjiang, the volume of the shoal became smaller.

To summarize, in the case of the Changjiang Estuary, both proximal (dredging) and distal (TGD) human intervention were the primary cause for the morphological changes of the N. Passage. The engineering project achieved most of its objectives to deepen the channel by dredging and to trap lateral sediment movements by the emplacement of groins. However, it did not eradicate the river-mouth shoal in the N. Passage, which is still a potential navigational hazard for the Changjiang waterway. To keep the river-mouth shoal in check, the dredging needs to be kept up to maintain and even to increase the channel capacity.

Lastly, our study shows the feasibility of using the EOF technique to examine the spatially and temporally correlated bathymetric changes in the N. Passage. This method successfully resolved the two major factors that caused the morphological changes in the study area. It could therefore be applied to other areas in the world in which morphological changes are due to a complex interaction of anthropogenic and natural causes.

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