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Marine sediment sustains the accretion of a mixed fluvial-tidal delta

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ABSTRACT

There has been a decline in fluvial sediment inputs to the world's deltas but it is still unclear to which extent upstream changes in sediment supply directly relate to variations in wetlands extent. We address this gap by investigating the contribution of marine and fluvial sediment sources to tidal flats in Changjiang Delta. Surprisingly, field measurements show that tidal flats accreted despite a > 50% decline in fluvial suspended sediment discharge due to the Three Gorges Dam. Results show that at a decadal time scale only a minimal portion of fluvial sediments contribute to sediment deposition on tidal flats while the adjacent estuary and ocean zone contributed over 90% of the deposit. We conclude that marine sediments give a substantial contribution to the maintenance of coastal wetlands and that there can be a long-time lag between human interventions and the delta's response to the decline in sediment supply.

1. Introduction

Human interventions have frequently altered the delivery of sediments to coastal areas (Syvitski et al., 2005; Murray et al., 2019; Nienhuis et al., 2020). Reservoir construction has trapped over 50% of the world's sediment flux (Dunn et al., 2019) and most of the world's deltas have now been significantly dammed in their upper and central reaches (Syvitski et al., 2005; Dunn et al., 2019). A large number of deltas are experiencing erosion because the construction of dams has trapped river-borne sediments and prevented the natural development of deltas' plains. Among the others, the Mississippi Delta (Blum and Roberts, 2009), Mekong Delta (Kondolf et al., 2014; Anthony et al., 2015), and the Nile Delta have experienced wetlands loss. The latter shifted from being a naturally prograding delta to a locally receding coastal plain as its fluvial sediment supply decreased to almost zero (Stanley, 1996). However, there are other systems where deltaic growth has occurred despite the low sediment supply such as the Pearl River Delta, Red River Delta as well as the lower Colorado River channel (Zamora et al., 2013; Zhang et al., 2015; Besset et al., 2019). Understanding the influence of upstream changes in sediment supply on deltaic systems is crucial because it could influence the maintenance of coastal wetlands under a scenario of increasing pressure from both climate change and human interventions (Weston, 2014; Fagherazzi et al., 2015; Darby et al., 2016; Leonardi et al., 2018; Donatelli et al., 2020).

In this article, we use one of the largest deltas in the world, the Changjiang Delta, to explore the impact of a large decadal decrease in sediment supply on coastal wetlands. Originating on the Qinghai-Tiber Plateau and stretching 6300 km eastward to the East China Sea, Changjiang River annually discharges 4.8×10^8 t of sediment to the East China Sea and nourishes $\sim 5.2 \times 10^4$ km^2 of wetlands (Milliman and Meade, 1983; Li, 1986; Dai et al., 2018a). Following the establishment of the Three Gorges Dam (TGD; 30.74°N, 111.28°E) in 2003, the annual fluvial suspended sediment supply to the estuary declined by 56.13% compared to the period of 1991–2002 (Mei et al., 2018, Fig. S2). Currently, there are large uncertainties about the impact of the decreased sediment supply on the system. Yang et al. (2011a, 2011b) showed that after the closure of the TGD there was net erosion in the subaqueous delta front and lower salt marsh accretion rates. Lai et al. (2017) revealed that the river bed material downstream of TGD has become coarser, thereby buffering sediment carrying capacity and suggested that the adverse impact of TGD may stop at the middle reach. Dai et al. (2018b) showed that both erosion and deposition have occurred in the Changjiang Estuary following the closure of the TGD. Wei et al. (2019) showed that the largest Changjiang estuarine marginal shoal keeps a fast accretion despite a great decrease in the riverine sediment input driven by the TGD.

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Here, we investigate the decadal morphological evolution of the Eastern Chongming Shoal (ECS, Fig. 1, Chi et al., 2019) which is the most mature wetland in the Changjiang Estuary and the preferential sources of sediments contributing to its maintenance. We use morphological surveys and numerical modelling to focus on erosion and accretion patterns during 1984–2018 (Fig. 1A, red square) and explore the potential for sediment delivery from different portions of the domain to understand the impact of decreasing fluvial supply on the system resilience. These insights are expected to clarify estuarine delta management strategies. The findings also have relevance for new tidal flat development in similarly river systems.

2. Methods

We produced a unique dataset combining different morphological surveys of the ECS from 1984, 1990, 1997, 2002, 2004, 2009 and 2013. The 1984–1997 surveys have been conducted by the Maritime Survey Bureau of Shanghai (https://www.sh.msa.gov.cn/) and the surveys from 2002-onward are from the Changjiang Estuary Waterway Administration Bureau (http://www.cjkhd.com/). Surveys for tidal flats above −2 m isobaths during 1984–2018 were collected from the Shanghai Water Authority (http://swj.sh.gov.cn/). Surveys were conducted using dual-frequency echo sounders. The average vertical error of modern fathometers is 2–5 cm for water depths less than 5 m and 1% for depths over 5 m (Chen and Yang, 2010; Wei et al., 2019). Accordingly, the maximum measurement error for the tidal flat area above −2 m and shoal volume is respectively 3% and 2%. Theodolite and GPS devices were used for surveys in 1984–1990 with a positioning error of 50 m and 1997–2013 with a 1 m positioning error. The map scale ranged from 1:50,000 to 1:10,000 with 8 to 20 data-points per km^2. Such data density makes secular bathymetric changes greater than 0.1 m acceptable in this study (Dai et al., 2014). The Changjiang Water Resources Commission provided yearly suspended sediment discharge and suspended sediment concentration at Datong gauge station during 1984–2018 (Fig. 1C) and tidal levels required for model simulation and calibration (www.cjw.gov.cn). The 7 bathymetric charts were transformed into depth points relative to the Beijing 54 coordinates and calibrated into Wusong Datum (referring to the lowest water level) through ArcGIS (van der Wal and Pye, 2003; Blott et al., 2006). A digital elevation model with a resolution of 50 × 50 m and − 2 m isobaths for each survey were generated using the Kriging scheme (Burrough and McDonnell, 1998).

To simulate the hydrodynamics and sediment transport processes in the Changjiang Estuary and to explore the potential delivery of sediments from different portions of the system to deltaic wetlands, we used the process-based model Delft3D. The computational domain covers the entire Changjiang Estuary from Datong gauge station to the East China Sea (Fig. 1C). The model is subdivided into 16 subdomains (Fig. 1C, yellow numbering) whose bottom sediments have the same physical properties but are named differently; this allows tracking the amount of sediments delivered from each subdomain to ECS. The model was set-up and run for two suspended sediment input concentration at Datong i.e., 0.58 kg/m^3 and 0.14 kg/m^3 to represent conditions before and after the construction and operation of the TGD. The model was run for one month with a morphological factor of 100 and calibrated at 15 tidal stations spread across the domain (the locations of these stations are indicated in Fig. 1C). The model was calibrated using OpenDA (http://www.openda.org; Kurniawan et al., 2011; Karri et al., 2013) and by adjusting the bed roughness coefficient. Full details of the model setup and calibration are provided in the Supplementary Information.

3. Results

Spatially varying accretion and erosional patterns characterized ECS from 1984 to 2013. The system was relatively stable during 1984–1990, with an annual deposition of 2.3 × 10^6 m^3 and gradual smoothing of the −2 m isobath (Fig. 2A). During 1990–1997, ECS experienced erosion in the front area, a yearly sediment loss of 14.0 × 10^6 m^3/yr and an average retreat rate of the −2 m isobath of 610 m/yr (Fig. 2B). Thereafter, the

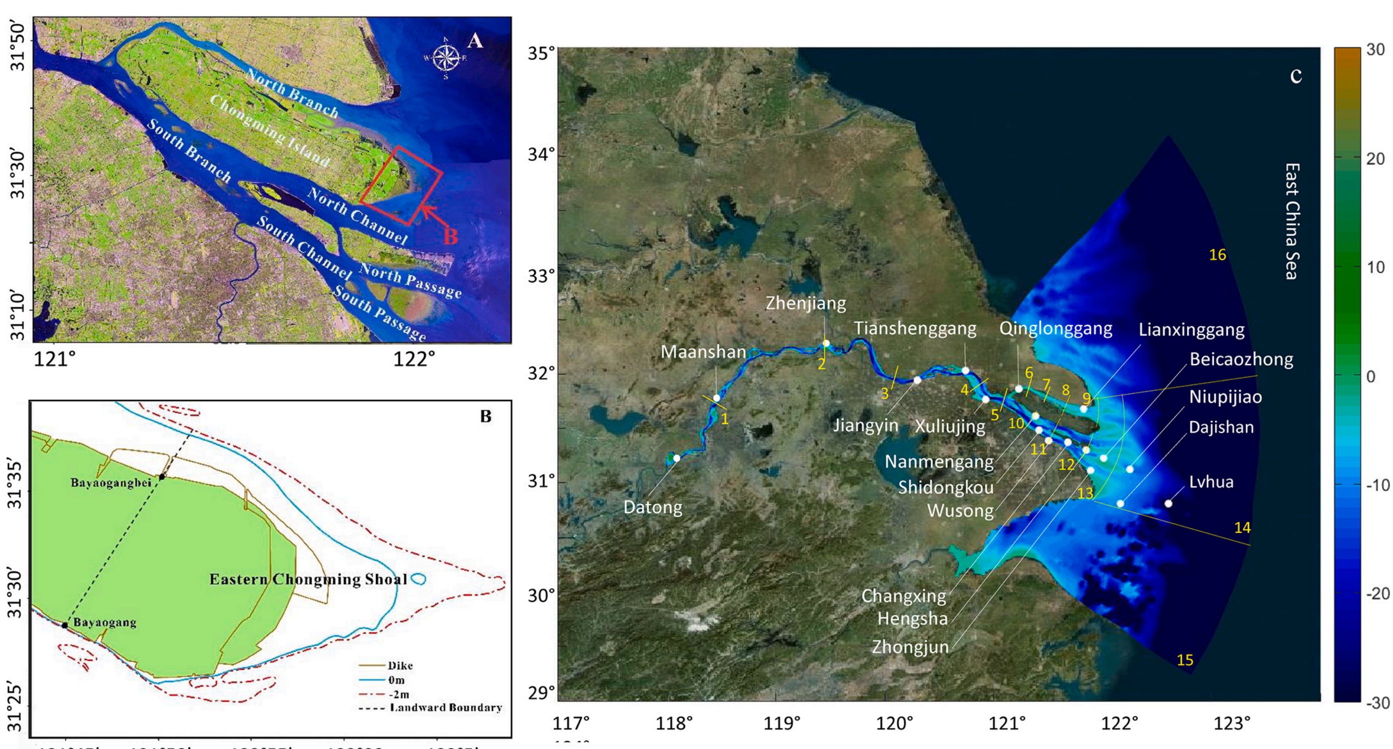

Fig. 1. Map of the study area. A) Location of Eastern Chongming Shoal in the Changjiang Estuary (red square); B) zoom view of Eastern Chongming Shoal and isobaths locations (red square in panel A); C) Computational domain of the Changjiang Estuary model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

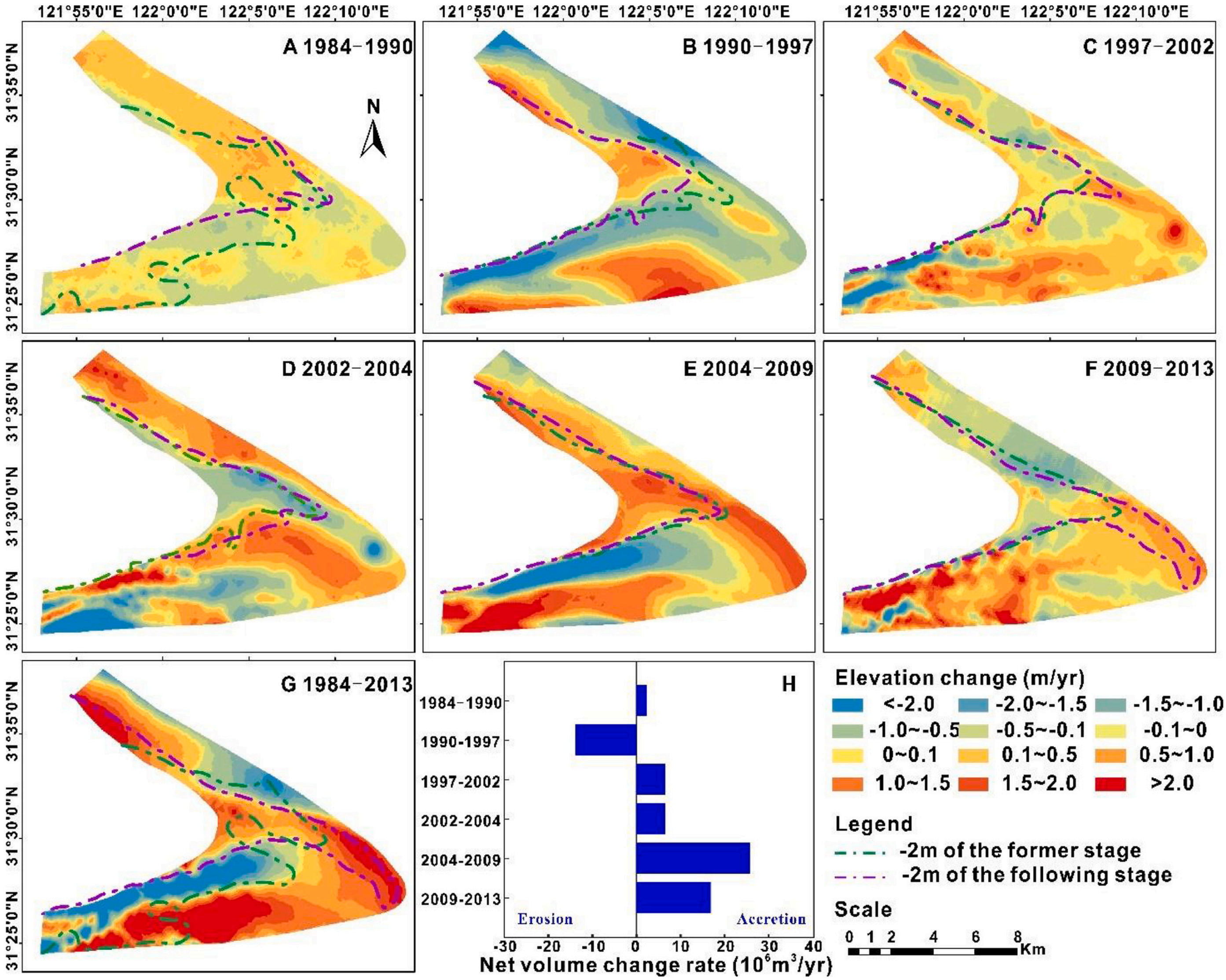

Fig. 2. Yearly erosion/deposition patterns of the Chongming Eastern Shoal from 1984 to 2013.

majority of ECS started to accrete. The ECS yearly sediment gain during 1997–2002 and 2002–2004 was 6.5×10^6 m^3 and 6.6×10^6 m^3 (Fig. 2C-D). The gain of sediments then increased to 25.7×10^6 m^3/yr in 2004–2009 where the whole northern ECS showed substantial sediment accumulation (Fig. 2E). From 2009 to 2013, ECS continually gained sediments at an annual rate of 16.8×10^6 m^3/yr and exhibited the most

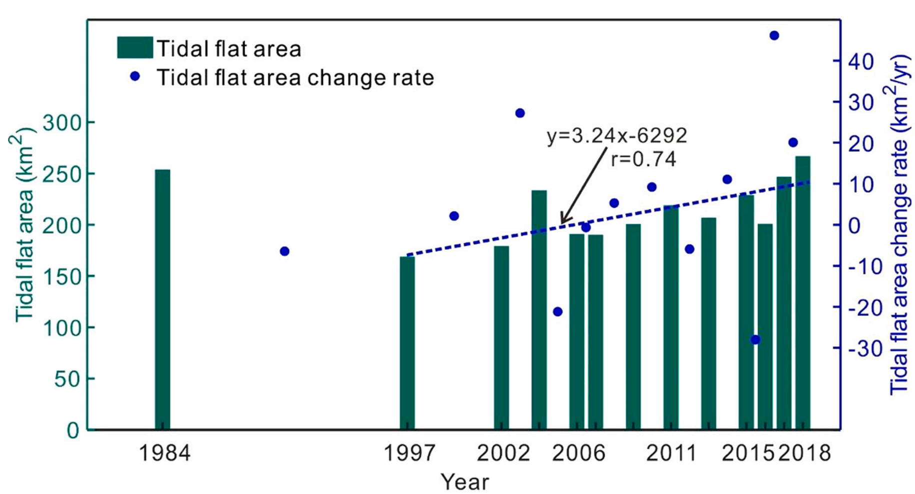

Fig. 3. Changes in the tidal flat area of the East Chongming Shoal during 1984–2018.

observable variation in the −2 m isobath (Fig. 2F). Overall from 1984 to 2013, there was a yearly volume increase of 5.4×10^7 m^3/yr and the −2 m isobath extended seaward at an average rate of 260 m/yr (Fig. 2G).

From 1984 to 1997, the tidal flat area (Fig. 3) decreased by 32% from 250 km^2 to 170 km^2. However, from 1997 to 2018 tidal flats followed a statistically significant trend in areal increase rate (Fig. 3). Tidal flats extent reached the historic high of 270 km^2 in 2018. Biggest variations occurred when it dropped to −28.08 km^2/yr in 2015–2016 and rose again to 48.08 km^2/yr in 2016–2017 (Fig. 3). Therefore, a decrease in sediment supply due to the TGD did not correspond to a contemporaneous decline in tidal flat areas, neither it corresponded to a decline in the volume of the ECS (see also Fig. 3 in supplementary information for scatter plots between suspended sediment concentration and volume/ tidal flat changes).

The potential contribution of different locations to the delivery of sediments to ECS has been evaluated by simulating the hydrodynamic and sediment transport of the system using Delft3D. Simulations were run for a sediment input concentration at Datong of 0.58 kg/m^3 (suspended sediment concentration in 1984) as well as for a condition of no sediment input at the boundary (Fig. 4A). Simulations were run for 30 days and with a morphological factor of 100 representing thus a time frame of around 8 years. According to numerical model results, at the simulated time scale, sediments on the ECS were derived from four main sources (Fig. 4B): reworking of sediments on the surrounding tidal flat zones (53%), seafloor in front of the system (18%), the South Channel and the North Channel (15%), and the South Branch (8%). Within a yearly time scale, the contribution of the sediment input from Datong to the ECS was minimal (<1%).

4. Discussions

From 1984 to 2018, both the suspended sediment discharge and suspended sediment concentration from the Changjiang River to the estuary have decreased significantly (Fig. S1); after 2003, they exhibited a decrease of 61.94% and 60.74% compared with pre-TGD stage. Such tendency, is not reflected in the morphological changes across wetlands

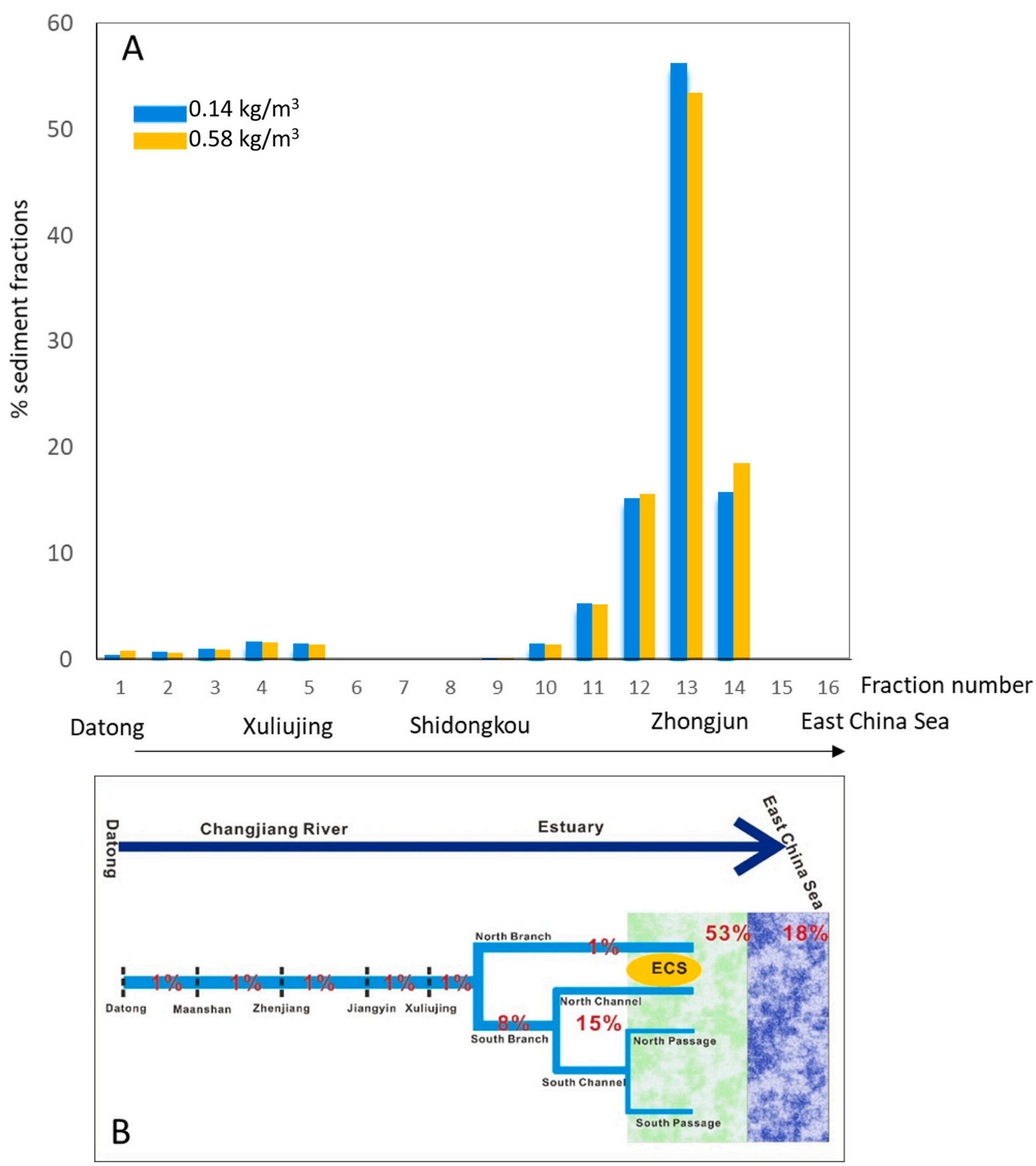

Fig. 4. A) Percentage contribution of different locations to the composition of the ECS for an input concentration at Datong of 0.58 kg/m^3 (suspended sediment concentration in 1984) and reduced input concentration of 0.14 kg/m^3 (suspended sediment concentration in 2014). Zone numbers are indicated in Fig. 1C; B) Summary sketch of the contribution of different estuarine areas to the ECS for 0.58 kg/m^3 input concentration.

and tidal flats in the ECS which have instead shown accretion following the operation of TGD (Figs. 2-3). There was no decline in wetlands volume and tidal flat areas in response to the reduction in fluvial sediment supply (Fig. S2A-B). Similarly, the decrease in sediment input downstream of the TGD has a minor influence in the evolution of Nanhui Shoal, the largest Changjiang estuarine marginal shoal, where substantial siltation promotion projects lead to significant sedimentation on the shoal (Wei et al., 2017; Wei et al., 2019).

Using numerical simulations we found that the contribution of different sediment sources to the composition of the ECS for two suspended sediment concentration scenarios, a pre-TGD input representing sufficient terrestrial sediment supply and a post-TGD reduced sediment input concentration is comparable and the contribution of the upstream portion of the estuary to ECS is almost negligible with respect to the contribution of estuarine and ocean derived sediments. Therefore, the sedimentary material filling up the ECS cannot be derived from upstream source. Changjiang Estuary is dominated by meso-macro tides and is exposed to the vast East China Sea. The monsoon-driven longshore current off the river mouth are relatively strong, with a residual flow velocity which can reach approximately 30 cm/s and these can thus contribute to landward sediment transport. Other systems have experienced a similar situation e.g., accretion in spite of a declining sediment supply. Sediment accumulation also occurred in the lower Colorado River channel due to stronger flood flows during spring tides and a net import of sand in spite of the lack of fluvial sediment supply (Zamora et al., 2013). The Pearl River Delta also extended seaward in spite of decreasing sediment supply (Zhang et al., 2015). On the other hand, other mega-deltas such as Mississippi and Nile deltas which have a micro-tidal regime exhibited almost instantaneous land loss following the reduction of riverine sediment (Törnqvist et al., 2006; Hereher, 2011). The evolution trends of the world's mega-deltas can thus differ greatly as their dominant forces are different. For macrotidal deltas where the tide is the dominant component, tidal currents may contribute to the delivery of marine sediments to the estuary and contribute to wetlands maintenance under diminishing fluvial sediment supply as in the Changjiang estuary. This marine derived sediment supporting deltaic wetlands has been sourced by fluvial inputs in the past (Dai et al., 2014). However, the construction of TGD induced dramatic declines in river-borne sediment, thus marine sediment is in turn responsible for the shoal maintenance through estuarine regime adjustment (Wei et al., 2019). Furtherly, the shoals' accretion can dissipate tides and reduce tidal prism lowering the flushing capacity of the system and possibly promoting deposition (Zhang et al., 2018).

Even though sediments from the marine zone might be able to initially mitigate the impact of a decreasing sediment supply, a continuous decline in fluvial sediments could prevent the replenishment of marine sediments and cause sediment starvation. Such imbalance will eventually cause seabed erosion and the degradation of deltaic system, in particular under conditions of increasing pressure from sea-level rise (Tessler et al., 2018; Dunn et al., 2019). Our numerical model did not consider the existing sediment spatial distribution (constant sediment properties are assumed across the entire domain) and it therefore represents the potential for sediment delivery to the area, rather than the actual delivery. The availability of different sediment fractions will, then, serve as a regulating factor for the amount of sediments reaching the surrounding wetlands. Our simplified study also neglected the impact of wind waves which could further increase the delivery of sediments from the deeper portion of the seabed to shallower area due to increased bed shear stress (Liu et al., 2007). This, however, does not affect our main conclusions since the current contribution of ocean-derived sediment on sediment deposition in the ECS is already significantly higher than that of fluvial sediment (Fig. 4).

5. Conclusions

Deltaic wetlands are important coastal ecosystems that are threatened by human interferences. Here we explore the morphological evolution of Chongming East Shoal (ECS), the most mature deltaic wetland system in the Changjiang Estuary, and the contribution of different portions of the Changjiang river-estuary system to the sediment delivery to the ECS. Results suggest that in spite of the large sediment decline after the construction and regulation of the Three Gorges Dam (TGD), ECS exhibited observable deposition and accretion. At a nearly decadal time scale and even considering pre-TGD adequate suspended sediment concentrations, the contribution of the upstream areas to the composition of bottom sediments in ECS was negligible compared to sediment redistributed from surrounding tidal flats and seabed and sediments coming from the deeper ocean in front of the wetlands. South Branch, South channel and North Channel also contribute a significant amount of sediments to the area. Our results highlight the need for long term monitoring of coastal wetlands, and the fact that the impact of upstream changes in the system might take several years before being felt in downstream areas. Results are relevant for the management and protection of deltaic wetland systems around the Changjiang Estuary and other world's mega deltas.

Author contributions

N.L. and Z.D. conceived the study. N.L. and I.C. carried out the model establishment and calibration. X.M. and Z.D. performed the topographic data collection and analysis. N.L. and X.F. wrote the paper. I.C. and Z.D. contributed to the discussion. All authors discussed the results and commented on the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.margeo.2021.106520.

References

Anthony, E.J., Brunier, G., Besset, M., et al., 2015. Linking rapid erosion of the Mekong River delta to human activities. Sci. Rep. 5, 14745.
Besset, M., Anthony, E.J., Bouchette, F., 2019. Multi-decadal variations in delta shorelines and their relationship to river sediment supply: an assessment and review. Earth Sci. Rev. 193, 199–219.

Blott, S.J., Pye, K., van der Wal, D., Neal, A., 2006. Long-term morphological change and its causes in the Mersey Estuary, NW England. Geomorphology 81 (1–2), 185–206.
Blum, M.D., Roberts, H.H., 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. Nat. Geosci. 2 (7), 488–491.
Burrough, P.A., McDonnell, R.A., 1998. Principles of Geographical Information Systems. Oxford University Press, Oxford.
Chen, J.T., Yang, F.D., 2010. Observation experiment and analysis between fathometer and sounding pole. Yellow River 32 (10), 57–59 (In Chinese).
Chi, Y., Zhang, Z., Gao, J., et al., 2019. Evaluating landscape ecological sensitivity of an estuarine island based on landscape pattern across temporal and spatial scales. Ecol. Indic. 101, 221–237.
Dai, Z., Liu, J.T., Wei, W., Chen, J., 2014. Detection of the three Gorges Dam influence on the Changjiang (Yangtze River) submerged delta. Sci. Rep. 4, 1–7.
Dai, Z., Mei, X., Darby, S.E., Lou, Y., Li, W., 2018a. Fluvial sediment transfer in the Changjiang (Yangtze) river-estuary depositional system. J. Hydrol. 566, 719–734.
Dai, Z., Fagherazzi, S., Gao, S., Mei, X., Ge, Z., Wei, W., 2018b. Scaling properties of estuarine beaches. Mar. Geol. 404, 130–136.
Darby, S.E., Hackney, C.R., Leyland, J., et al., 2016. Fluvial sediment supply to a mega-delta reduced by shifting tropical-cyclone activity. Nature 539 (7628), 276–279.
Donatelli, C., Zhang, X., Ganju, N.K., Aretxabaleta, A.L., Fagherazzi, S., Leonardi, N., 2020. A nonlinear relationship between marsh size and sediment trapping capacity compromises salt marshes' stability. Geology 48 (10), 966–970.
Dunn, F., Darby, S., Nicholls, R., Cohen, S., Zarfl, C., Fekete, B., 2019. Projections of declining fluvial sediment delivery to major deltas worldwide in response to climate change and anthropogenic stress. Environ. Res. Lett. 14 (8), 1–11.
Fagherazzi, S., Edmonds, D.A., Nardin, W., et al., 2015. Dynamics of river mouth deposits. Rev. Geophys. 53 (3), 642–672.
Hereher, M.E., 2011. Mapping coastal erosion at the Nile Delta western promontory using Landsat imagery. Environ. Earth Sci. 64 (4), 1117–1125.
Karri, R.R., Badwe, A., Wang, X., El Serafy, G.Y.H., Sumihar, J., Babovic, V., Gerritsen, H., 2013. Application of data assimilation for improving forecast of water levels and residual currents in Singapore regional waters. Ocean Dyn. 63, 43–61.
Kondolf, G.M., Rubin, Z.K., Minear, J.T., 2014. Dams on the Mekong: Cumulative sediment starvation. Water Resour. Res. 50, 5158–5169.
Kurniawan, A., Ooi, S.K., Hummel, S., Gerritsen, H., 2011. Sensitivity analysis of the tidal representation in Singapore regional waters in a data assimilation environment. Ocean Dyn. 61, 1121–1136.
Lai, X., Yin, D., Finlayson, B.L., Wei, T., Li, M., Yuan, W., et al., 2017. Will river erosion below the three Gorges Dam stop in the middle Yangtze? J. Hydrol. 554, 24–31.
Leonardi, N., Carnacina, I., Donatelli, C., Ganju, N.K., Plater, A.J., Schuerch, M., Temmerman, S., 2018. Dynamic interactions between coastal storms and salt marshes: a review. Geomorphology 301, 92–107.
Li, C., 1986. Deltaic sedimentation. In: Ren, M. (Ed.), Modern Sedimentation in Coastal and Nearshore Zone of China. China Ocean Press, Beijing, pp. 253–378 (in Chinese).
Liu, P.L.F., Park, Y.S., Cowen, E.A., 2007. Boundary layer flow and bed shear stress under a solitary wave. J. Fluid Mech. 574, 449–463.
Mei, X.F., Dai, Z.J., Wei, W., Li, W.H., Wang, J., Sheng, H., 2018. Secular bathymetric variations of the North Channel in the Changjiang (Yangtze) Estuary, China, 1880-2013: causes and effects. Geomorphology 303, 30–40.
Milliman, J.D., Meade, R.H., 1983. World-wide delivery of river sediment to the oceans. J. Geol. 91, 1–21.
Murray, N.J., Phinn, S.R., DeWitt, M., et al., 2019. The global distribution and trajectory of tidal flats. Nature 565, 222–225.
Nienhuis, J.H., Ashton, A.D., Edmonds, D.A., Hoitink, A.J.F., Kettner, A.J., Rowland, J. C., Törnqvist, T.E., 2020. Global-scale human impact on delta morphology has led to net land area gain. Nature 577 (7791), 514–518.
Stanley, D.J., 1996. Nile Delta: extreme case of sediment entrapment on a delta plain and consequent coastal land loss. Mar. Geol. 129, 189–195.
Syvitski, J.P.M., Vörösmarty, C.J., Kettner, A.J., Green, P., 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308, 376–380.
Tessler, Z.D., Vörösmarty, C.J., Overeem, I., Syvitski, J.P.M., 2018. A model of water and sediment balance as determinants of relative sea level rise in contemporary and future deltas. Geomorphology 305, 209–220.
Törnqvist, T.E., Bick, S.J., van der Borg, K., de Jong, A.F., 2006. How stable is the Mississippi Delta? Geology 34, 697–700.
van der Wal, D., Pye, K., 2003. The use of historical bathymetric chartsin a GIS to assess morphological change in estuaries. Geogr. J. 169 (1), 21–31.
Wei, W., Dai, Z., Mei, X., Liu, J.P., Gao, S., Li, S., 2017. Shoal morphodynamics of the Changjiang (Yangtze) estuary: Influences from river damming, estuarine hydraulic engineering and reclamation projects. Mar. Geol. 386, 32–43.
Wei, W., Dai, Z., Mei, X., Gao, S., Liu, J.P., 2019. Multi-decadal morpho-sedimentary dynamics of the largest Changjiang estuarine marginal shoal: Causes and implications. Land Degrad. Dev. 30 (17), 2048–2063.
Weston, N.B., 2014. Declining sediments and rising seas: an unfortunate convergence for tidal wetlands. Estuar. Coasts 37 (1), 1–23.
Yang, S.L., Milliman, J.D., Li, P., Xu, K., 2011a. 50,000 dams later: erosion of the Yangtze River and its delta. Glob. Planet. Chang. 75, 14–20.
Yang, S.L., Milliman, J.D., Li, P., Xu, K.H., 2011b. 50,000 dams later: Erosion of the Yangtze River and its delta. Glob. Planet. Chang. 75, 14–20.
Zamora, H.A., Nelson, S.M., Flessa, K.W., Nomura, R., 2013. Post-dam sediment dynamics and processes in the Colorado River estuary: implications for habitat restoration. Ecol. Eng. 59, 134–143.
Zhang, W., Xu, Y., Hoitink, A.J.F., et al., 2015. Morphological change in the Pearl River Delta, China. Mar. Geol. 363, 202–219.
Zhang, X., Fagherazzi, S., Leonardi, N., Li, J., 2018. A positive feedback between sediment deposition and tidal prism may affect the morphodynamic evolution of tidal deltas. J. Geophys. Res. Earth Surf. 123 (11), 2767–2783.