

Hybrid green-grey intertidal-flat *plus* wetland restoration as solution for heavily human-intervened coastline management

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ABSTRACT

The world coastlines in the Anthropocene are experiencing a dramatic transition from natural dynamics to predominantly artificial modifications. The latter causes high uncertainties of future evolution, especially in densely populated mega deltas where natural mudflats are damaged by overexploitation, leading to an irreversible retreat. Based on abundant datasets and an integrated hydro-sediment-dynamics model, we *i*) examined decadal-centennial historical coastline change of a densely populated mega delta in the Yangtze Estuary, and *ii*) predicted future morphological developments under variance restoration strategies. We found that human activities, such as intertidal mudflat reclamation and diminished sediment supply from watershed, have disproportionately impacted recent intertidal area change, causing a sixfold greater impact than natural factors of tide, wave, and river runoff combined. Hindcasting using numerical model revealed a unique coastal erosion mechanism post-reclamation and Three Gorges Dam (TGD): a reduced suspended sediment deposition threshold due to sediment fining coupled with increased longshore transport due to wetland loss exacerbates coastal erosion. Various restoration strategies were modelled to identify an approach that could rehabilitate the squeezed tidal flats and degraded wetlands. Our results favor an innovative hybrid “green-grey” structure, combining traditional seawalls (“hard” engineering) with strategically designed long-armed T-groynes (“grey” solution) alongside an integrated saltmarsh (“green” solution) to promote tidal flat growth. This hybrid setup, through a biogeomorphological feedback, captures 30% more sediment than the solely “grey” infrastructure, halving the time needed for tidal flat restoration. Once the intertidal area is recovered, the restored mudflat and habitat could significantly strengthen biodiversity and landscape opportunities, supporting both flood defense and multifunctional ecosystem services.

Key points

- Human influences exhibiting sixfold greater impact than natural forces in recent coastal area changes
- Grey T-groynes with integrated green saltmarshes enhance mudflat restoration efficacy

- The grey-green solution enhances sediment retention by 30% compared to the grey measure

1. Introduction

Globally, as sea level rise (SLR) accelerates and coastal reclamation

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intensifies, less space remains available for natural tidal flats and wetlands, referred to as coastal squeeze (Torio and Chmura, 2013; Temmerman et al., 2013). In addition, the remaining tidal flats and coastal wetlands become increasingly altered by human activities in the catchment area, causing terrestrial sediment deficiency (Darby et al., 2016) that leads global deltas to starve of much-needed sediments (Syvitski et al., 2009). It has been well recognized that natural tidal flats and wetlands beyond being of great ecological value (Kirwan et al., 2016) also strongly contribute to flood safety (Temmerman et al., 2013; Bouma et al., 2014). Their disappearance thus put coastal communities increasingly at risk of severe storm-related flooding (Zhang et al., 2021; Nienhuis et al., 2020). This is particularly true in large deltaic coastlines, where rapid population growth and coastal squeeze intensify (Edmonds et al., 2020), placing natural tidal flats and wetlands at the greatest risk (Murray et al., 2019; Nienhuis et al., 2020).

The resilience of deltaic geomorphology is mainly governed by sediment supply and deposition during quiescent conditions, crucial for stabilizing the coastal foundation (Yang et al., 2020; Guo et al., 2021). Notably, if land reclamation continues, the coastline gets closer to the main channels, leading to over-steepening intertidal systems. This leaves less space for tidal flats and wetlands to develop, because the tidal prism and cross-sectional channel area potentially remain unchanged (Zhang et al., 2023a,b). To preserve these valuable ecosystems, with their critical biodiversity and role in flood safety (Temmerman et al., 2013; Bouma et al., 2014), the development of effective restoration measures for heavily human-intervened coastlines is urgently needed (Torio and Chmura, 2013; Guo et al., 2021). Such restoration measures should be based on fundamental knowledge of the system, including the dominant forcing conditions diagnosis and watershed sediment supply investigation. This understanding provides the knowledge base needed to design low-impact interventions that use natural dynamics for sustainable future development. In this study, we aim to *i)* understand how human-induced changes to the estuary has affected the sediment balance compared to the development in the absence of such changes, and *ii)* use these insights to develop hybrid “green-grey” solutions following the “Building with Nature” concept (Temmerman et al., 2013) to increase the sediment trapping capacity of coastal tidal flat.

To mitigate coastal erosion, nature-based tidal flat restoration measures are increasingly favored for their cost-effectiveness in coastal protection, while also providing important habitats for flora and fauna (Temmerman et al., 2013; Van Coppenolle et al., 2018). These so-called “green” solutions (i.e., saltmarsh and vegetation) are favorable over traditional “hard” coastal protection (i.e., seawalls) or “grey” solutions (i.e., groynes and breakwaters), because they facilitate a self-sustaining coastline that can adjust to SLR (Kirwan et al., 2016). However, the coastal protection service of “green” solutions requires relatively wide areas to be effective due to their large spatial footprint (Zhu et al., 2020; Van Coppenolle et al., 2018). In densely populated mega deltas, the space requirements for these “green” solutions can typically not be met, so that “hard” seawalls and “grey” solutions are commonly used for coastal protection (Zhu et al., 2020). The combination of both measures, so-called hybrid or “green-grey” solutions, can provide storm protection within a relatively narrow area, while at the same time supporting habits that can grow with SLR. Such minimal spatial footprint makes them applicable in densely populated mega deltas facing coastal squeeze (Kirwan et al., 2016; Mi et al., 2022), thereby also enable restoring and preserving degraded but ecologically valuable tidal mudflats and adjacent wetlands.

Approximately 70% of the world’s muddy coastlines and almost all the estuarine deltas are composed of tidal mudflats with adjacent wetlands (Syvitski et al., 2009). We argue that their extent could be improved by developing hybrid “green-grey” solutions, providing sufficient space to increase local resilience (Temmerman et al., 2013; Bouma et al., 2014). In this study, we intend to test a new design that integrates tidal ecosystems with long-armed T-groynes, which extend seaward from existing “hard” seawalls along muddy coasts in densely

populated deltaic cities, to thereby provide both flood defense and enhanced ecological biodiversity. More specifically, we aim to compare the sediment trapping capacity of *i)* existing “hard” seawall, and *ii)* “hard” seawall with purely “grey” T-groynes structure vs. *iii)* optimized “green-grey” coastal protection that includes the biogeomorphic feedbacks of intertidal saltmarsh. We expect that such integrated design consisting of saltmarsh, T-groynes, and hard seawall will be more effective at reducing climate change risks posed by coastal flooding and erosion in densely populated mega deltas, while also enhancing biodiversity.

We selected the north bank of Hangzhou Bay (NHB) in the Yangtze River Delta (YRD) as a typical example of a densely populated mega delta, heavily impacted by urban expansion and reduced river sediment supply (Zhang et al., 2021). Having a unique long-term historical dataset of shoreline and bathymetry changes makes this location an ideal model case. The two key questions that we address are: *i)* can the coastal erosion be reduced by integrating the sediment trapping capacity of the “grey” T-groynes solution and intertidal “green” ecosystems in front of already existing “hard” seawall? and *ii)* how can the deployed hybrid “green-grey” measure be optimized to provide the dual defence and ecosystem services in the face of climate change? We developed and model-tested *a)* short-armed T-groynes (open T-groynes) as a purely “grey” solution vs. *b)* T-groynes with extended arms (closing T-groynes) to stimulate marsh growth as an optimized “green-grey” solution; and *c)* groynes with short (or without) jetties as the traditional “hard” engineering option (e.g., seawalls and breakwater). The difference between “green-grey” and “grey” comes from the length of the T-arms. Based on field measurements and a coupled hydro-sediment-dynamics simulation, we *first* disentangled the relative contributions of natural vs. anthropogenic disturbance on the morphological changes of the tidal flat in YRD, from both watershed and estuary dimensions, based on a series of controlled modelling experiments. *Secondly*, a no seawall projection was modelled to test the influence of traditional hard seawalls on tidal flat evolution. *Thirdly*, we model-tested “grey” measure of long-armed T-groynes attached to the existing “hard” seawalls with the inclusion of saltmarshes, as “green-grey” approach to restore the damaged tidal flats, for comparison with the traditional “hard” (seawall) and “grey” (T-groynes) designs, respectively. *Fourthly* and finally, the uncertainty of human-intervened coastal evolution and the advantages of “green-grey” solution are all discussed in a broader context for the deployment of the newly proposed hybrid approach.

2. Study area

The north bank of Hangzhou Bay (NHB), located at the south fringe of Yangtze River Delta (YRD), is a typical example of a densely populated area in a mega delta in China (Fig. 1). Up to now, more than 50,000 dams have been built upstream of YRD for power generation and irrigation (Yang et al., 2011). The biggest dam is the Three Gorges Dam (TGD) constructed in 2003, with a maximum storage capacity of approximately 22% the annual Yangtze River discharge. Its construction has led to the primary contributor to a 70% reduction of the annual riverine sediment supply to the YRD (Dai et al., 2015). Consequently, sediment arriving at the YRD does not originate from the upper reaches of the Yangtze River, but now predominantly originates from the rivers and lakes downstream of TGD (Dai et al., 2015). As a result, finer cohesive sediment is transported and thus there has been a fining of the suspended sediment delivered to the estuary (Guo et al., 2021). Such changes in water and sediment properties are predicted to impact the long-term deltaic morphological evolution (Guo et al., 2021). Although resilient tidal flats in the YRD like the Nanhui Dongtan (ND, Fig. 1a) are still accreting (Zhang et al., 2018), fragile tidal flats, for instance, located west of ND, i.e., NHB has shown visible signs of erosion (Xie et al., 2017). Moreover, erosion at NHB has been exacerbated by continuous coastal reclamations over the last century (Zhang et al., 2021), leading to the complete loss of the local mudflat and wetland



Fig. 1. The geomorphology and landscape of the study area. (a) Three-dimensional view of the north bank of Hangzhou Bay (NHB) in 2022 showing the distribution of seawalls, reclamation works, tidal flat morphology, and saltmarsh wetland obtained from stereo-pair satellite photogrammetric mapping, the yellow points referring to field sampling locations to collect the SSC, D_{50} , and water depth information performed in 2020, (b) the overall view of Yangtze River Delta, (c) the location of the study area in China, and (d–h) photos taken on-site showing the typical landscape of NHB with the locations shown in (a). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

system (Fig. 1a), hence amplifying storm flooding along the coastline (Zhang et al., 2021). This threatens the safety of NHB and motivates us to design solutions that enable more resilient and sustainable coastal zone.

3. Material and methods

3.1. Data sources and defined estuarine boundary changes

Bathymetric data of navigation charts from 2005, 2007, and 2008 covering the Yangtze Estuary and the mouth bar area at a 1:10,000 scale were obtained from the Shanghai Navigation Bureau (Zhang et al., 2016). The intertidal bathymetry, not shown on navigation charts, was derived from remote sensing interpretation (Wen et al., 2024; Zhang et al., 2018), using waterlines extracted from multi-temporal Landsat 5 MSS, Landsat 8 OLI/TIRS, and Sentinel-2 L2A images, aligned with tidal gauge elevations (see Table S1 for image timings). The seawall positions and intertidal areas for seven periods (1984, 1987, 1994, 2000, 2003, 2013, and 2020) were interpreted from Landsat images during low spring tide (see Table S1 for dates). For earlier years lacking remote sensing data, historical navigation charts from 1840 to 1900 were sourced from HR Wallingford Ltd. to determine seawall positions and water depths with an accuracy exceeding 0.2 m (Fig. 6a). Eighty-three suspended and near-bottom sediment samples were collected from eight cross-sections along NHB near high spring tide between December 13–17, 2020 (Fig. 1a). Suspended sediment samples were obtained using a peristaltic sampler with volumes exceeding 1000 ml, while near-bottom samples were collected using a clam-type dredger from 1 to 5 cm surface sediments. Laboratory analysis included filtration to

determine median grain size (D_{50}) and suspended sediment concentration (SSC) density (Zhang et al., 2018).

Changes of boundary conditions in the YRD through human interventions were mainly coastal reclamations and TGD regulations. When TGD commenced operation, the yearly sediment load measured at Datong station decreased sharply from ~470 Mt to ~132 Mt after 2003 (Fig. S1a). Consequently, the sediment compositions of three major components of clay, silt, and sand changed from 30.58%, 52.65%, and 16.77% in the pre-TGD period to 33.74%, 62.65%, and 3.6% in the post-TGD period, respectively (Figs. S2 and S3, Table S2). Simultaneously, the measured SSC decreased from 0.2 kg/m³ to 0.1 kg/m³, from 0.5 kg/m³ to 0.3 kg/m³, from 0.6 kg/m³ to 0.4 kg/m³, and from 0.2 kg/m³ to 0.1 kg/m³ at Datong station, at the inner estuary, at the turbidity maximum zone, and at the outer estuary, respectively (Fig. S1b). These changes also affected the D_{50} of the suspended sediment, which decreased from ~27 μ m to ~11.7 μ m between 2000 and 2020 (Luo et al., 2012; Guo et al., 2021). Interpretation from navigation charts in 1840 and 1900 and remote sensing images in 1984, 1987, 1994, 2000, 2003, 2013, and 2020 highlighted how the large-scale human land-reclamations had a profound impact on coastline evolution (Fig. 6a–S4).

The non-human-influenced boundary condition changes were mainly represented by seasonal variations in hydrology and meteorology. The seasonal Yangtze River discharge changes from ~35,000 m³/s in the wet season (April–September) to ~15,000 m³/s in the dry season (October–March) between 2000 and 2020 (Figs. S5a and S5b). Consequently, under river-tide interactions, the Canter-Cremers number changed from ~0.5 in the wet season to ~0.1 in the dry season during a mean spring tide. Hence, the average tidal storage volume of the

Yangtze Estuary reaches $\sim 4.8 \times 10^9 \text{ m}^3$ in the dry season, which is approximately double the volume in the flood season (Fig. S5c) (Zhang et al., 2018). Seasonal variations in atmospheric boundaries affected the generation of seasonal wind waves, which revealed an average wind speed of $\sim 5.5 \text{ m/s}$ and significant wave height of $\sim 0.35 \text{ m}$, with consistent wind and wave directions of 300°SE (from ocean to land) and 180°NW (from land to ocean) in summer and winter, respectively (Fig. S6).

3.2. Hydro-sediment-dynamics model

3.2.1. Model construction

The numerical model of hydro-sediment dynamics process was constructed using the coupled MIKE21FM Hydrodynamics (HD)-Spectral Waves (SW)-Mud Transport (MT) modules in two-dimensions (www.mikepoweredbydhi.com/). Since the hydrodynamics modules of HD and SW (Zhang et al., 2016, 2018; Mi et al., 2022) and the MT sediment dynamics module (Zhang et al., 2023a,b) have been described in previous publications, we provide a simplified description here. A large-scale mesh grid covering the entire Yangtze Estuary, Hangzhou Bay, and nearby continental shelf area was constructed using irregular triangular meshes, denser nearshore (50–200 m) and courser offshore (2000–10,000 m), resulting in $\sim 45\%$ of the meshes (165,000) within the estuary area (Fig. 2a). Specifically, in ND, 16,000 triangular meshes following the edges of seawalls and large-scale reclamation works were

generated (Fig. 2b); in NHB, 20,000 meshes following the edges of seawalls were generated based on the same set of triangular meshes, assuming the inclusion and exclusion of the T-groynes (Fig. 2c). In addition, a mesh grid extending 5 km inland of the current coastline with an elevation set to 1.85 m was constructed so that future coastal erosion could be simulated (Fig. 2d). The water level at the ocean boundary was driven by statistical tidal constituents obtained from TPX09 database, with a spring tide range of $\sim 4 \text{ m}$ and a neap tide range of 1–2 m. The river boundary extending 600 km upstream of the Yangtze River was imposed with daily measured water and sediment discharge values (Zhang et al., 2023a,b). The eroded or deposited sediments were then redistributed within the model domain or discharged through the open ocean boundary. The atmosphere-ocean boundary was forced with typical seasonal wind imposed on each triangular node to generate wind waves, considering winter and summer monsoons within the simulation period. The large-scale model domain ensured sufficient development of wind waves, resulting in an average significant wave height of 0.35 m, a period of 3.2 s, and a mean wave direction of 315° in summer and 0.39 m , 3.5 s, and 175° in winter, respectively. For further details of model construction and model coupling, please refer to the Supplementary Information.

3.2.2. Model configuration

For the hydrodynamics modelling, the HD-SW model used a uniform bottom friction coefficient of $k_N = 0.001 \text{ m}$ ($M = 45 \text{ m}^{1/3}/\text{s}$, $n = 0.022 \text{ s/m}^{1/3}$).

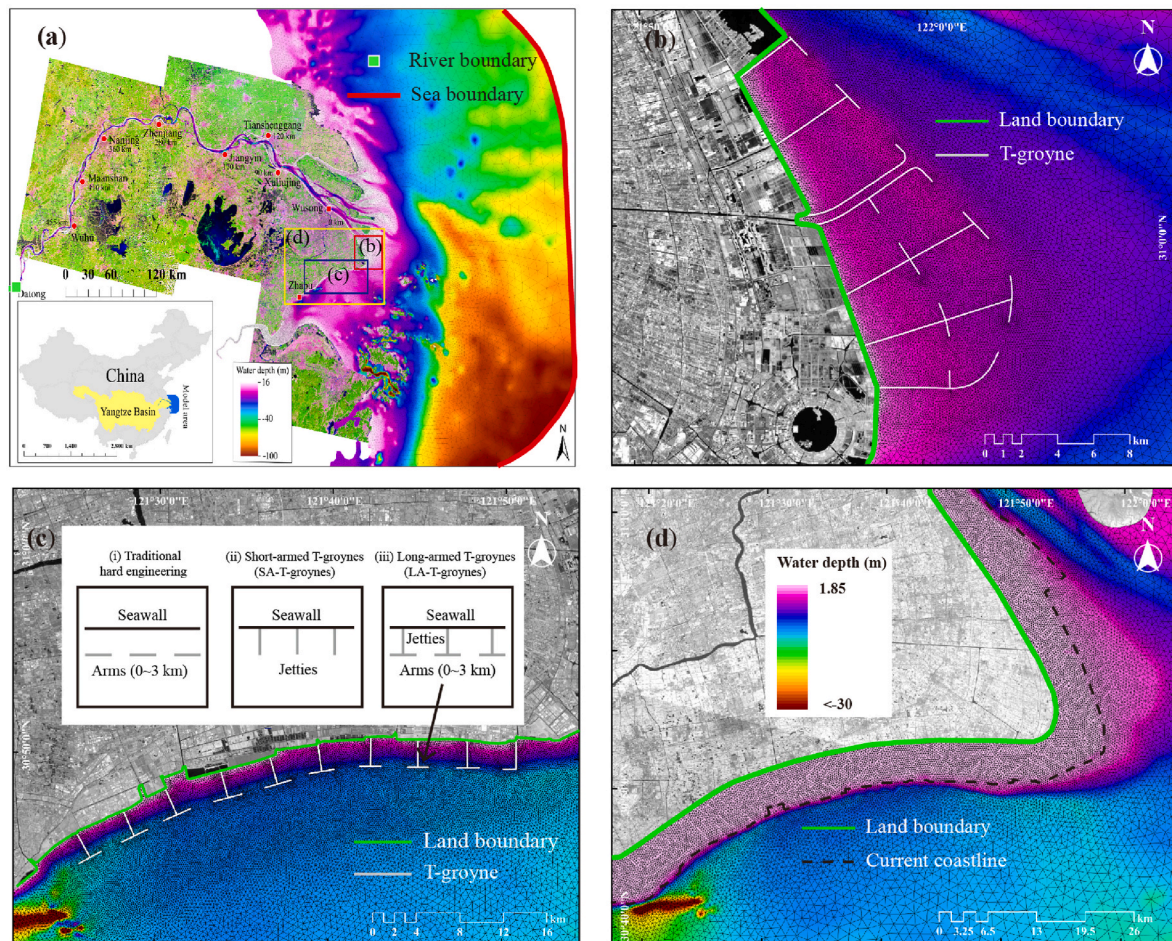


Fig. 2. Triangular meshes and boundary conditions for (a) the large-scale Yangtze Estuary-Hangzhou Bay model, and the enlarged view showing (b) Nanhui Dongtan (ND) model, (c) north bank of Hangzhou Bay (NHB) model, and (d) future YRD morphology prediction model with the land boundary set at 5 km inside of the current coastline. The engineering works in ND model were tested with *i*) traditional hard seawall, *ii*) short-armed T-groynes (SA-T-groynes, or open T-groynes), and *iii*) long-armed T-groynes (LA-T-groynes, closing T-groynes). The difference between “green-grey” and “grey” comes from the length of the T-arms. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

$\text{m}^{1/3}$) for the seabed and $k_N = 0.002 \text{ m}$ ($M = 40 \text{ m}^{1/3}/\text{s}$, $n = 0.025 \text{ s}/\text{m}^{1/3}$) for the bare tidal flat, which had been calibrated multiple times (Zhang et al., 2016, 2021; Mi et al., 2022). When considering saltmarsh, the intertidal zone below 0.3 m (MHWN) was set to be bare flat, and the zone between 0.3 m and seawall was set to be a vegetated area with a friction coefficient linearly transitioning from *S.maritima* ($k_N = 0.014 \text{ m}$, $M = 28 \text{ m}^{1/3}/\text{s}$, $n = 0.035 \text{ s}/\text{m}^{1/3}$) to *S.alterniflora* ($k_N = 0.12 \text{ m}$, $M = 13 \text{ m}^{1/3}/\text{s}$, $n = 0.07 \text{ s}/\text{m}^{1/3}$) (Zhang et al., 2023a,b). For grid cells of hundreds of meters in size, the horizontal eddy viscosity and diffusivity coefficients were set to $0.28 \text{ m}^2/\text{s}$ using the formula proposed by Smagorinsky (1963). In the SW module, the Madsen bottom friction formula was modified (Madsen et al., 1989), and the BJEB formula (Battjes and Janssen, 1978) was used to simulate depth-induced wave breaking. JONSWAP with standard shape parameters of $\gamma = 3.3$, $\sigma_a = 0.07$, $\sigma_b = 0.09$ was used for the spectral wave model at the ocean boundary, and the empirical formula of Mi et al. (2022) was used to calculate the Gamma parameter. The simulation time step was set to 30 s, ensuring that the Courant–Lewy–Friedrichs number (CLF) meets the requirement for stable and non-divergent simulations ($\text{CLF} < 0.8$).

For sediment dynamics modelling, the MT module considers two spatially uniform types of cohesive sediment (clay and silt) and one non-cohesive fine sediment (sand) that are typically presented on tidal flats and saltmarshes in Yangtze Estuary (Luan et al., 2017; Zhang et al., 2018). The suspended sediment density is $2650 \text{ kg}/\text{m}^3$, and the density of the dry bed sediment was set to $640 \text{ kg}/\text{m}^3$ based on the analysis of field samples (Zhang et al., 2023a,b). The settling velocities of the three components (w_s) were set to $0.1 \text{ mm}/\text{s}$ for clay, $0.2 \text{ mm}/\text{s}$ for silt calculated according to Van Rijn (1993) based on observations at the edge of a saltmarsh in the Yangtze Estuary (Luan et al., 2017). The erosion threshold (τ_{ce}) was set to $0.5 \text{ N}/\text{m}^2$ based on an empirical formula (Luan et al., 2017; Zhang et al., 2018). The erosion coefficient (E_0) of the tidal flat bed was set to $5 \times 10^{-5} \text{ kg}/\text{m}^2/\text{s}$ (Luan et al., 2017), which was used to calibrate the sediment critical shear stress (τ_{cd}) with and without vegetation (Table S3). The optimal morphic acceleration factor (MF) was set to 80 after model calibration and validation. The detailed HD-SW-MT model parameter configurations are summarized in Table S3.

3.2.3. Model calibration and validation

The calibration and validation for the hydrodynamic model were based on measured water levels at Zhapu (August 16–20, 1997) and Wusong (August 17–21, 1997) tidal gauge stations, respectively (Fig. 3). Results demonstrate that the observed water level is highly consistent with the simulated water level, with the root mean square error (RMSE), mean normalized deviation (B_{MN}), and skill value are 0.2 m , -0.2 , and 0.99 for Wusong station, and 0.4 m , 0.1 , and 0.99 for Zhapu station, respectively (Fig. 3). To further validate the accuracy of sediment dynamics model, the morphological evolution at ND under artificial reclamation projects was compared with historical remote sensing detections of the same year (Fig. 4b). Results show two phases of reclamation works carried out from 2013 to 2021. The first phase was from 2013 to 2016 when 4–6 km and 3–4 km long vertical groynes were built north and south of Dazhi River, respectively. The second phase was from 2016 to 2021, when the groynes in the south of Dazhi River were further extended seaward by 8–9 km. Starting from the measured coastal DEM in 2013, the tidal flat accretion during 2013–2016 was used for model calibration, and during 2016–2021 was used for model validation (Fig. 4). For detailed descriptions of the validation of flow velocity, readers can refer to our previous publications (Zhang et al., 2016, 2023). These verification data come from observations at both neap tides (22–24 July 2007) and spring tides (29–31 July 2007) and 19–20 July 2005, respectively, covering a total of three time periods including the year 1997.

The modelled and observed tidal flat showed a highly consistent morphological pattern, indicated by numerals I–VI in the compartment between groynes (Fig. 4b, e and 4c, 4f). After installing of the groynes, the tidal flat silts up to the top of groynes during the simulation period and forms a tidal flat front edge in arc-shaped waterlines within each compartment. The shape and position of the contours -1.8 m , 0 m , 0.3 m , and 0.8 m dividing the high, medium, and low tidal flats also showed a highly consistent pattern with the field measurements (Fig. 4). Tidal channels formed in the compartments I–V are similar to the observations, as tidal flow scour and shear stress decrease on tidal flat (Fig. 4c and f). Compartment I, position the most upstream (closer to the Yangtze River) of all compartments, intercepted more riverine sediment and developed a broader middle-high tide flat of approximately 3 km wide

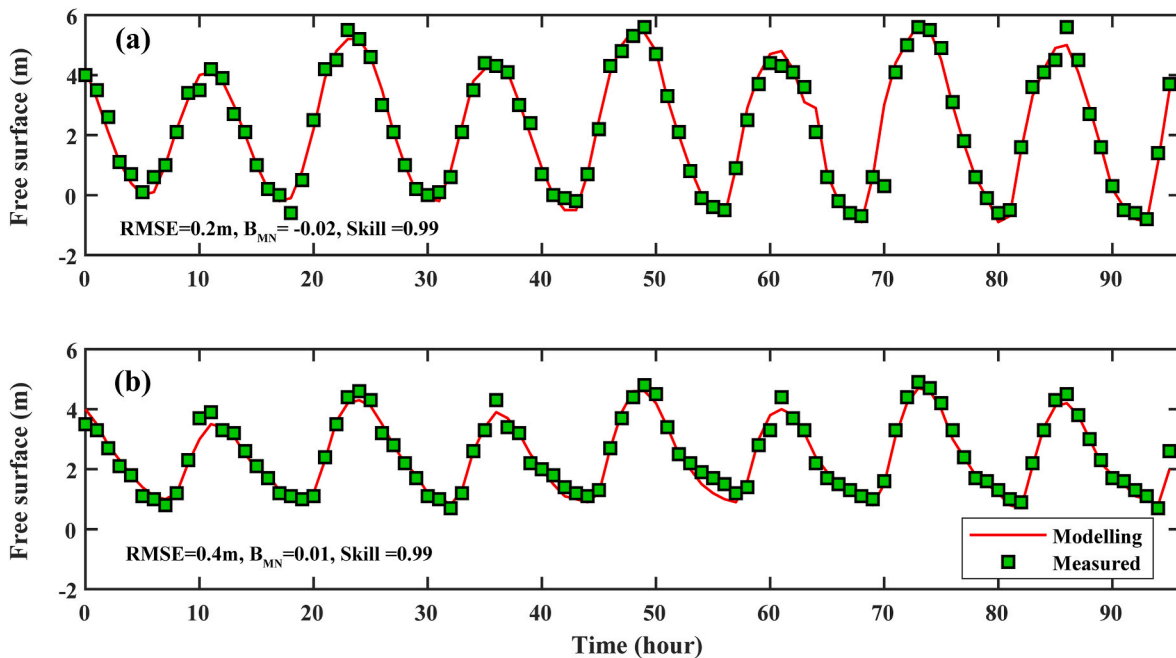


Fig. 3. Validation of free surface at tide gauge stations Zhapu station (a) starting from 0:00 August 16, 1997 and Wusong station (b) starting from 0:00 August 17, 1997.

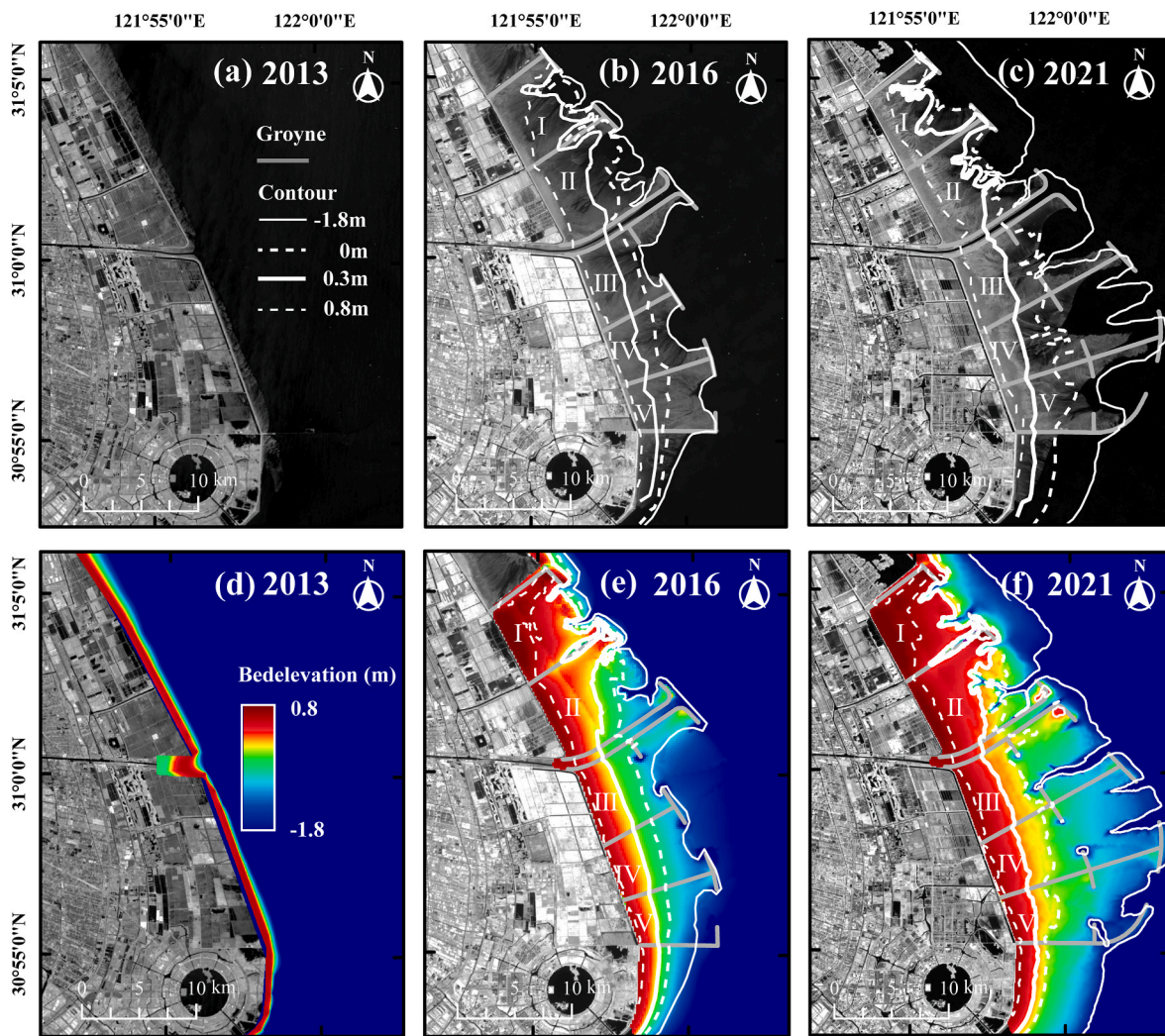


Fig. 4. Comparison between observed (a, b, c) and modelled (d, e, f) tidal flat sedimentation on Nanhui Dongtan (ND) from 2013 to 2021. Sediment-morpho dynamics modelling was started from the 2013 landscape and tidal flat bathymetry (a, d), until the first phase of the reclamation project during 2013–2016 (b, e) for model calibration, and the second phase of reclamation project during 2016–2021 (c, f) for model validation.

compared with the gradual narrowing of the rest tide flat in the downstream from II to VI with an average width of approximately 2 km, a highly consistent pattern as observed in the remote sensing interpretation (Fig. 4c and f). In 2016, the modelled areas were 12.9 km², 38.9 km², 19.7 km², and 35.5 km² in zones of high-medium-low marsh and bare tidal flat, respectively, with an average error of 1.7% compared with the measured data; in 2021, the modelled areas were 14.8 km², 43.2 km², 22.9 km², and 10.5 km², respectively, with an average error of 1.9% compared with the measured data, indicating that the sediment-dynamics model can reproduce the post-groynes development of the tidal mudflat in the Yangtze Estuary.

3.3. Scenario simulations

Three sets of scenarios were simulated to assess tidal flat restoration in heavily human-intervened coastline management depends on 1) natural (tides & waves) vs. anthropogenic (embankment) impact in estuary, 2) changes in sediment supply (amount & grain size) due to disturbance within the basin, and 3) the implementing “green” vs. “grey” solutions. Additionally, as a control group, 4) a theoretical scenario with no seawall protection was also designed for comparison. By systematically modifying the boundary conditions in the model, i.e., coastline, discharge, tide, wave, and sediment load, the typical coastal

morphodynamic patterns can be characterized. The tests undertaken are detailed in Table 1 and explained below.

Test 1 – no seawall projection: a projection of the long-term coastline evolution from 2020 to 2100 with seawall removal under post-TGD hydrology and sediment conditions (See 3.1, Table S2 and Fig. S6). The effects of SLR at a rate of 4.4 mm/year (WMO, 2022) and ground subsidence at a rate of 2 mm/year (Li, 2016) were also considered for future coastline modelling.

Test 2 – natural (tides & waves) vs. anthropogenic (embankment): sensitivity tests to examine how tides, waves, and human disturbance from within the estuary, respectively, effect accretion and erosion of the tidal flat. Test 2a considered the impact of tides on coastline evolution from 1985 to 2020. Test 2b considered the combined impacts of tides and wind-waves on coastline evolution for the same period. The contribution of waves on tidal flat development was obtained by removing the tidal influence, i.e., subtracting Test 2a from 2b.

Test 3 – changes in sediment supply (amount & grain size): sensitivity tests to discern the dominant driving forces from the watershed (See 3.1 and Table S2). Tests 3a and 3b were designed to explore the influence of sediment reduction and fining by TGD. Tests 3c and 3d were designed to explore the influence of seasonal river discharges during flood and dry seasons, respectively. Tests 3e and 3f were designed to explore the influence of seasonal changes in tidal prism. The

Table 1
Scenarios and model boundary conditions.

Test	Short description	Bathymetry	Discharge (m ³ /s)	Tide	Wave	Sediment ^a
1	Projection (2020–2100)	2020	2010 ts	2010 ts	2010 ts	Post-TGD
2a	Tide only (1985–2020)	1985	–	Feb–Jul 2010	–	Table S2
2b	Tide and wave (1985–2020)	1985	–	Feb–Jul 2010	Feb–Jul 2010	Table S2
3a	Sediment Pre-TGD	2020	35,000	Feb–Jul 2010	Feb–Jul 2010	Pre-TGD
3b	Sediment Post-TGD	2020	35,000	Feb–Jul 2010	Feb–Jul 2010	Post-TGD
3c	Wet season discharge	2020	35,000	Feb–Jul 2010	Feb–Jul 2010	Post-TGD
3d	Dry season discharge	2020	10,000	Feb–Jul 2010	Feb–Jul 2010	Post-TGD
3e	Wet season tide	2020	35,000	Mean spring	–	Post-TGD
3f	Dry season tide	2020	10,000	Mean spring	–	Post-TGD
4a	SA-T-groynes	2020	35,000	Feb–Jul 2010	Feb–Jul 2010	Post-TGD
4b	LA-T-groynes	2020	35,000	Feb–Jul 2010	Feb–Jul 2010	Post-TGD
4c	T-groynes and saltmarsh	2020	35,000	Feb–Jul 2010	Feb–Jul 2010	Post-TGD

ts: time series for Jan–Dec 2010.

^a For the sediment properties pre- and post-TGD construction refer to Table S2.

contribution of sediment reduction and fining by TGD on estuary morphology evolution was obtained by subtracting Test 3b from 3a. The contribution of seasonal river discharge change was obtained by subtracting Test 3d from 3c. The contribution of seasonal tidal prism change represented by Canter-Cremers number N (where $N = q_r T / q_t$, q_r is the river discharge, T is the tidal period, q_t is the tidal prism) was obtained by subtracting Test 3f from 3e.

Test 4 – green vs. grey: the efficiency of “green” and “grey” measures was examined for the damaged tidal flat restoration. Tests 4a, 4b, and 4c all include the construction of T-groynes along NHB (Fig. 2c). In Tests 4a and 4b, a T-groynes comprises jetties (set to 0–1.5 km) and arms (set to 0–2 km) in a T-shaped form, perpendicular and parallel to the coastline, respectively. The arms of the T-groynes, installed at a

compartment of 5 km and 2 km gaps between the jetties, was calculated using the Villemonte formula (Villemonte, 1947). The difference between “green-grey” and “grey” comes from the length of the T-arms (Fig. 2c). A long-armed T-groynes (LA-T-groynes, or closing T-groynes) gives more accretion and “green” marsh formation compared with the “grey” short-armed T-groynes (SA-T-groynes, or open T-groynes), while groynes with short (or without) jetties is the traditional “hard” engineering approach (e.g., seawall and breakwater). For Test 4c, the “green” solution of highly salt-tolerant plants, the detailed settings can be found in 3.2.2.

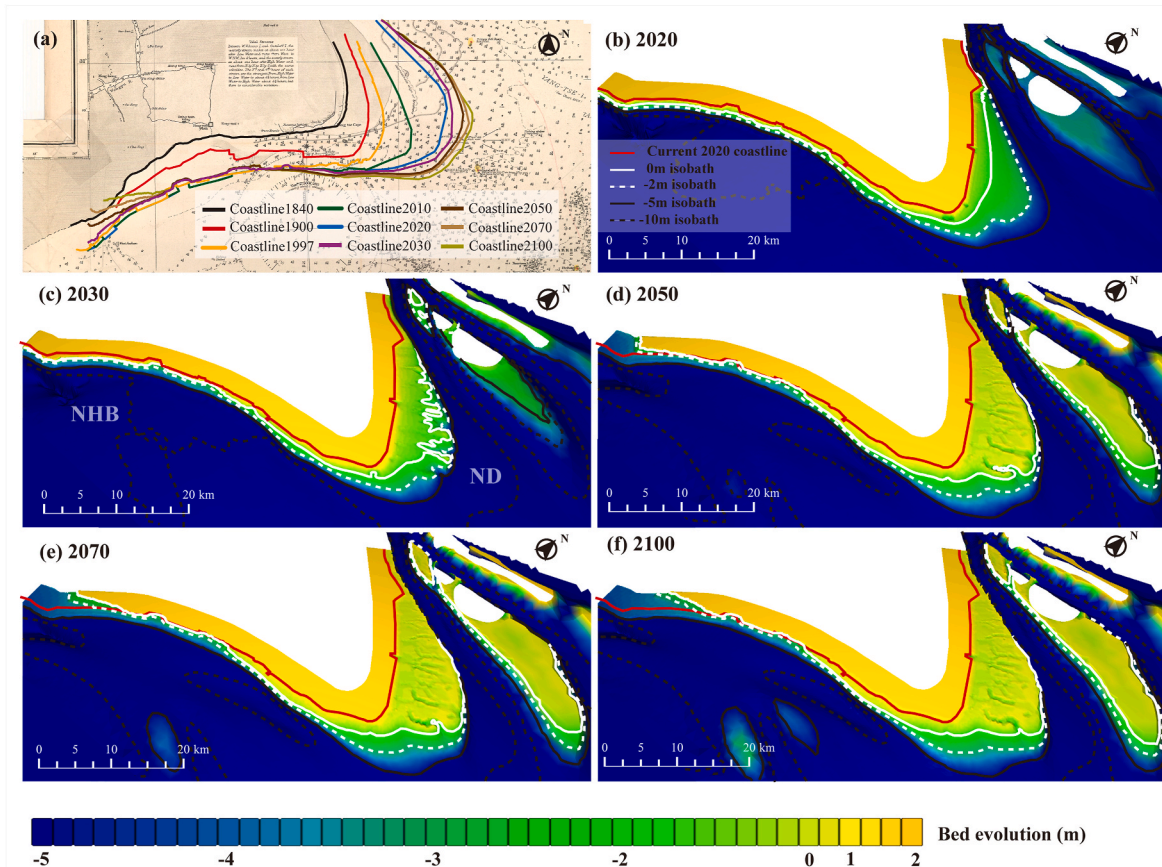


Fig. 5. The distribution of historical (a, b) and projected coastline positions (c, d, e, f) with the future tidal flat morphology modelling starting from 2020 to 2100 without considering seawall protection.

4. Result

4.1. Historical observed (1840–2020) vs. model-predicted NHB evolution without a seawall (2020–2100)

To investigate the effect of human embankment on coastal evolution, we predicted future NHB evolution without human protection (i.e., seawall removal), which showed a complete loss of the historically reclaimed intertidal area (Fig. 5a). The historical coastline expansion in NHB was mainly driven by human reclamation of the available tidal flat (Fig. 5a–S4), primarily implemented for flood defense and land demand purposes. For example, the 1840 coastline (solid black line in Fig. 5a) extended approximately 4100 m in 60 years (averaged 68 m/yr) to Penggong dike (solid red line in Fig. 5a) in 1900, of which NHB extended approximately 3500 m (averaged 58 m/yr), and ND extended 3000–5300 m (averaged 50–88 m/yr). Subsequently, from 1900 to 1984, the coastline extended 5000 m in the seaward direction with the fastest rate of 60 m/yr in NHB, but in ND the coastline only extended 1500 m with a slow rate of 18 m/yr. Recently, from 1984 to 2020, reclamation rates slowed down due to tidal flat erosion occurring in NHB (Fig. 5a). However, the largest reclamations were observed in ND from 1997 to 2020, with coastline movement up to 12,500 m (averaged 550 m/yr). In contrast, with modelled seawall removal, the predicted 2100 coastline would retreat to the 1984 coastline position at NHB, with even larger erosion occurring at the west end, where the coastline retreats to the 1840 coastline position, although ND still showed accretion. Therefore, YRD would move toward the southeast direction without seawall protection, following the spatial evolution pattern of strong deposition–deposition from north to south at ND and erosion–strong erosion from east to west at NHB.

In the absence of a seawalls, the projected coastline development of ND and NHB showed the opposite trends under natural-forcing. Specifically, the ND showed continuous accretion from 2020 to 2100, when the expanding intertidal area extended to the southeast direction under strong ebb current (Fig. 5). First, the 0 m contour of ND moved nearly 10,000 m seaward (averaged 330 m/yr) with jagged tidal front during 2020–2030 (Fig. 5b and c), then the tidal creeks developed from the jagged tidal front from 2050 and infilled during 2070–2100 (Fig. 5). The

accretion speed of ND slowed down to 40 m/yr and only accreted 2000 m during 2050–2100 due to the higher rate of SLR. Notably, the vertical profiles showed continuous deposition in both intertidal and subtidal areas, with faster accretion in the north and constant accretion in the south (Fig. 6a–d). Meanwhile, the flow gradually deposited sediment on the tidal flat to form a gentle slope towards the southeast. In contrast, the NHB showed continuous erosion without protection by the current seawall. Specifically, in the first 10 years (2020–2030), NHB retreated inland by 1000 m (averaged 100 m/yr). Then, the erosion speed slowed to 10 m/yr in the next 20 years (2030–2050), although the erosion was faster (averaged 50–100 m/yr) at the west side of NHB. After 2050, the entire NHB retreated with the largest erosion of 3700 m and 6000 m until 2070 and 2100, respectively (Fig. 5d and e). Unlike the gentle profile formed in ND, the erosional NHB formed a steep cliff profile approximately 2 m high with continuous erosion in the intertidal area and deposition in the subtidal area (Fig. 5e–h). With the loss of tidal flat at NHB, the mudflat faced deeper water directly, inducing an unstable coastline under higher waves. Therefore, NHB benefits most from coastal protection measures.

4.2. Contribution from local dimension: human disturbance vs. hydrodynamics (1985–2020)

The local factors affecting NHB evolution mainly include human disturbance (e.g., reclamation and embankment) and hydrodynamic forces (e.g., tides and waves). To discern the relative importance of human activity vs. natural forces on the recent NHB evolution, the relative contribution of tides, waves, and human reclamation on the NHB coastal area change was quantified based on morphodynamics modelling from 1985 to 2020. For human disturbance, remote sensing interpretation identified over 200 km² of tidal flat reclamation in NHB over the past 35 years, almost triple the remaining the tidal flat area in 2020 (Fig. 7a and b, and S4).

Modelling using the tidal effect showed a dramatic intertidal area increase in ND from 4.1 km² in 1985 to 58 km² in 2020 (Fig. 7a red line), while the wave effect was almost negligible on ND, accounting for only 1/50 of the contribution by the tide (Fig. 7a green line). In contrast, the relative contribution of tidal (accretion effect) and wave (erosion effect)

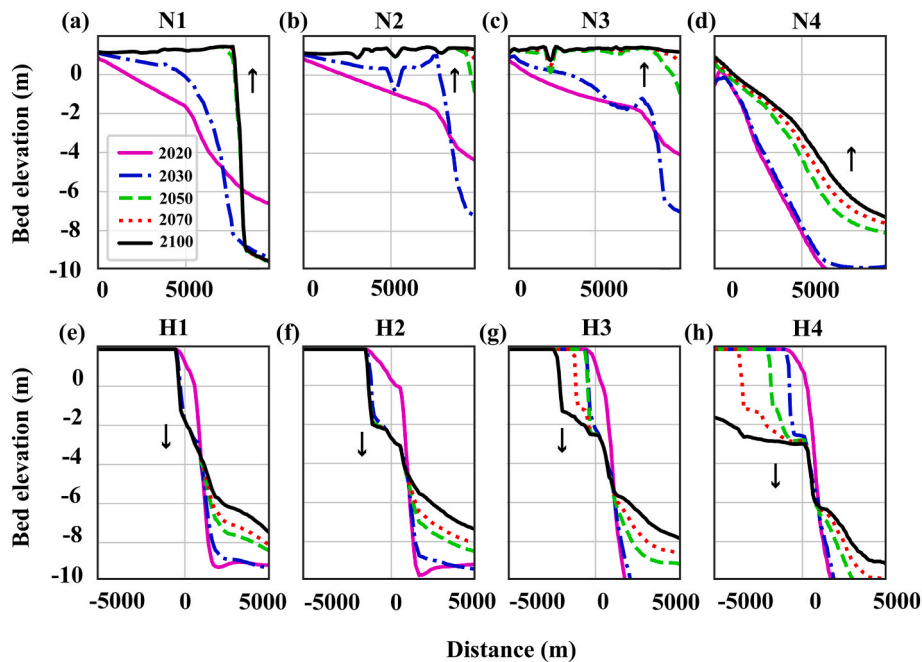


Fig. 6. The evolution of coastal geomorphology profile over time during 2020–2100 in ND (first row) and NHB (second row) along cross-sections shown in Fig. 1b. The X-axis starts from the current seawall in 2020.

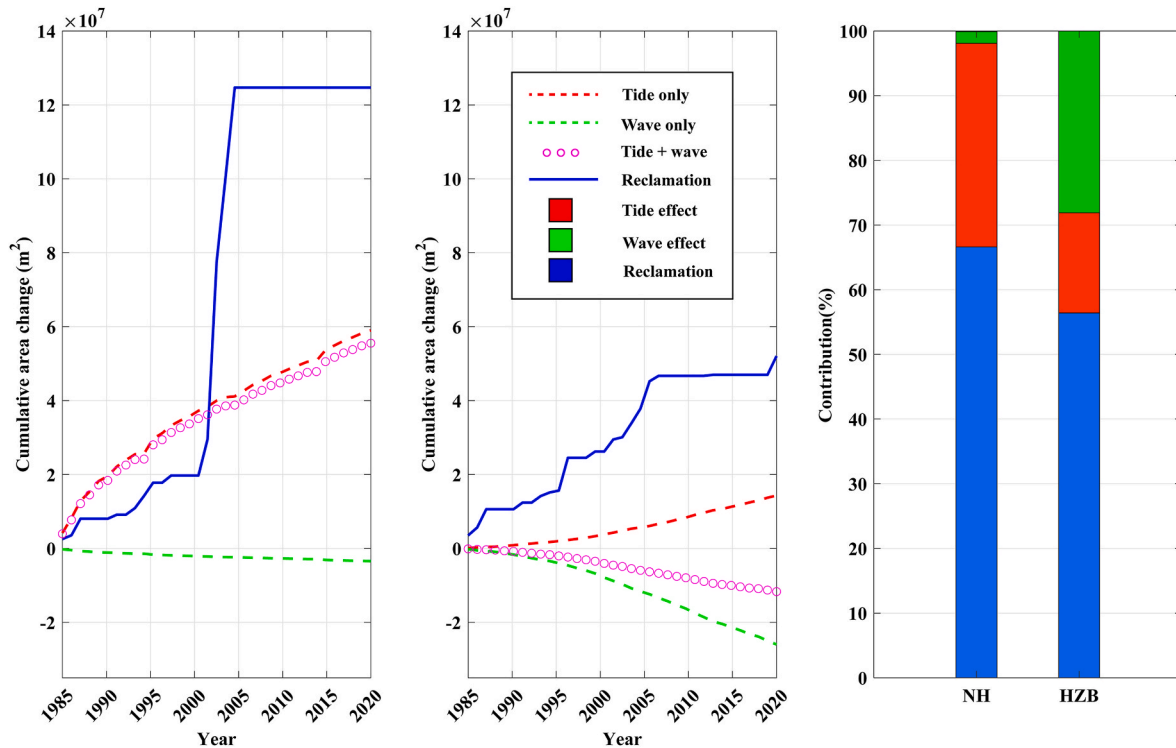


Fig. 7. Relative contributions of coastal morphology change in (a) ND and (b) NHB from local contributory factors of tide, wave, and reclamation, and (c) their combined relative contributions. Note that tidal effects causing tidal flat deposition are represented as positive values and wave effects causing erosion as negative values.

on tidal flat area change along NHB was almost equal, with the contribution from wave erosion slightly greater than that of tide accretion. Therefore, NHB was a slightly erosive landform under ocean driving forces of tide and wave (Fig. 7b pink dotted line). In addition to ocean forces, human reclamation greatly impacted the recent tidal flat area change. After three phases of tidal flat embankment in ND between 1985

and 1987, 1993–1998, and 2001–2004, 140 km² of the intertidal area was lost, twofold larger than natural tidal flat accretion. Similarly, 50 km² of the tidal flat was reclaimed by human embankment in NHB during 1985–2020, almost fourfold the magnitude of natural erosion (Fig. 7c). In principle, human reclamation, tide, and wave contributed approximately 66.7%, 31.5%, and 1.8% of the tidal flat area change in

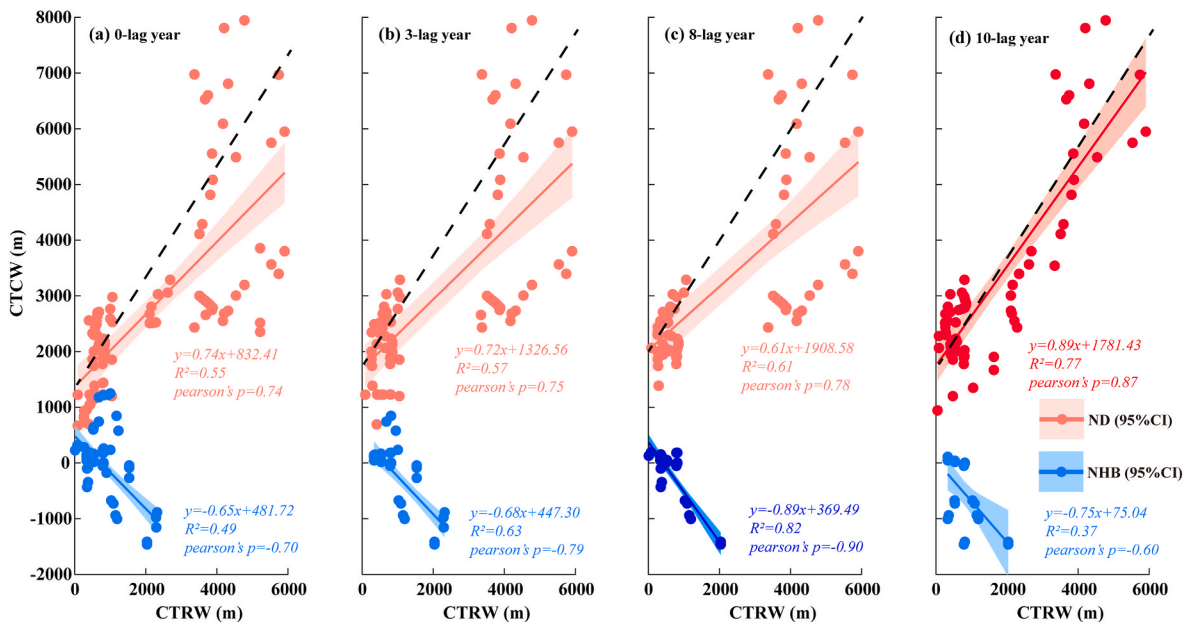


Fig. 8. Lag-correlation analysis between the cumulative tidal flat reclamation width (CTRW) and cumulative tidal flat change width (CTCW) with a testing lag-period of 0, 3, 8, and 10 years. The points show the sampling profiles every 1 km along the coastline of ND (red dots) and NHB (blue dots), with the colored shading indicating the 95% confidence interval. The dashed lines are the 1:1 relationship for ND. The determination coefficient R^2 and pearson's p value indicate the significance of correlation. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

ND and 54.4%, 15.5%, and 28.1% of the tidal flat area change in NHB, respectively (Fig. 7c).

As indicated above, most tidal flat loss during the past 35 years was due to human reclamation (Fig. S4). Lag correlation analysis between the cumulative tidal flat reclamation width (CTRW) and cumulative tidal flat change width (CTCW), using the 35 years satellite image interpretation results, showed the most significant correlations for 10-lag years for ND and 8-lag years for NHB, respectively (Fig. 8). In ND, the most significant correlation with the biggest determination coefficient (R^2) has a value of 0.77 and p -value of 0.87 (Fig. 8d), when the slope of CTRW to CTCW is close to 1:1, indicating the dynamic equilibrium between artificial tidal flat reclamation reduction and natural tidal flat accretion has a 10-year lag effect. Therefore, ND is defined as a resilient accretional coastline. In contrast, the foreshore of NHB showed constant erosion with reclamation, and the most significant correlation has 8-lag years with a determination coefficient (R^2) of 0.82 and p -value of -0.9 , indicating dynamic equilibrium reached 8 years after reclamation (Fig. 8c). Therefore, the accretional trend of ND and erosional trend of NHB becomes more evident under human reclamation, and there is a lag of 8–10 years between human influence and tidal stabilization. Such a lag effect reflects the difference in tide and wave activities on the role of local tidal flat morphology evolution after human reclamation.

4.3. Contribution from watershed disturbance by dam-building: pre-vs. post-TGD

The TGD and the >50,000 dams upstream have had far-reaching and long-term impacts on deltaic tidal flat evolution. The impact was driven by watershed factors such as the decrease in sediment supply and sediment fining by TGD interception (Figs. S1 and S2), flattening of the seasonal river discharge variance by TGD regulation (Figs. S5a and S5b), as well as the induced tidal changes (Fig. S5c). The numerical model showed that river sediment reduction and fining in the post-TGD period reduced tidal flat accretion in ND, which developed a steep slope and erosional subtidal compared to the pre-TGD period (Fig. 10a and b). Specifically, the reduction and fining of supplied sediment by TGD

reduced the sediment deposition volume by 26.3% ($1.3 \times 10^7 \text{ m}^3$) and increased the sediment erosion volume by 49.6% ($3.8 \times 10^7 \text{ m}^3$) above -5m contour in ND under the wet season discharge and spring tide scenario (Fig. 9a and b). Moreover, the erosional trend worsened in NHB, and the seabed morphodynamics changed from equilibrium to strong erosion in the subtidal area (Fig. 9a and b). Specifically, the deposition volume decreased by 1.1% ($3.7 \times 10^4 \text{ m}^3$), and the erosion volume increased by 8.6% ($3.8 \times 10^6 \text{ m}^3$) within the -5 m contour of NHB compared to the pre-TGD period; the erosion volume deeper than -5 m contour increased by $2.7 \times 10^8 \text{ m}^3$, which is 7.6 times of pre-TGD period (Fig. 9a and b).

Sediment transport modelling under the influence of seasonal river discharge and tidal variance showed a greater impact on ND than on NHB. Specifically, in ND, the sediment deposition volume reduced by 4.6% ($2.3 \times 10^6 \text{ m}^3$), and the sediment erosion volume decreased by 14.3% ($9.7 \times 10^6 \text{ m}^3$) above -5 m contour, while in NHB, the sediment deposition volume only reduced by 0.3% ($9.5 \times 10^3 \text{ m}^3$), and the sediment erosion volume only decreased by 0.5% ($2.3 \times 10^5 \text{ m}^3$) above -5 m contour (Fig. 9a and c). Although the seasonal river discharge altered the tidal prism dramatically, with Canter-Cremers number changing from ~ 0.5 in the wet season to ~ 0.1 in the dry season during a mean spring tide, the change in river-induced tidal force is minor and only accounts for 4% of the mean value (Fig. 9d). Consequently, the relative contributions to the geomorphic evolution from seasonal hydrodynamic changes in river and tide account for approximately 60% and 40%, respectively (Fig. 10). Comparatively, the sediment interception by the TGD and sediment fining in the estuary resulted in a much more significant effect on NHB erosion, accounting for 67.5%–99.3% of the total geomorphic change (Fig. 10). In comparison, the impacts from seasonal river discharge and the induced tide change are minor, only accounting for 19.5%–0.4% and 13.0%–0.3%, respectively (Fig. 10). Similarly, in ND, the sediment reduction and fining by TGD induced over 90% of the total geomorphic change, compared with river-tide-induced geomorphic change, although there showed some patches of accretion in ND and erosion in NHB (Figs. 9 and 10).

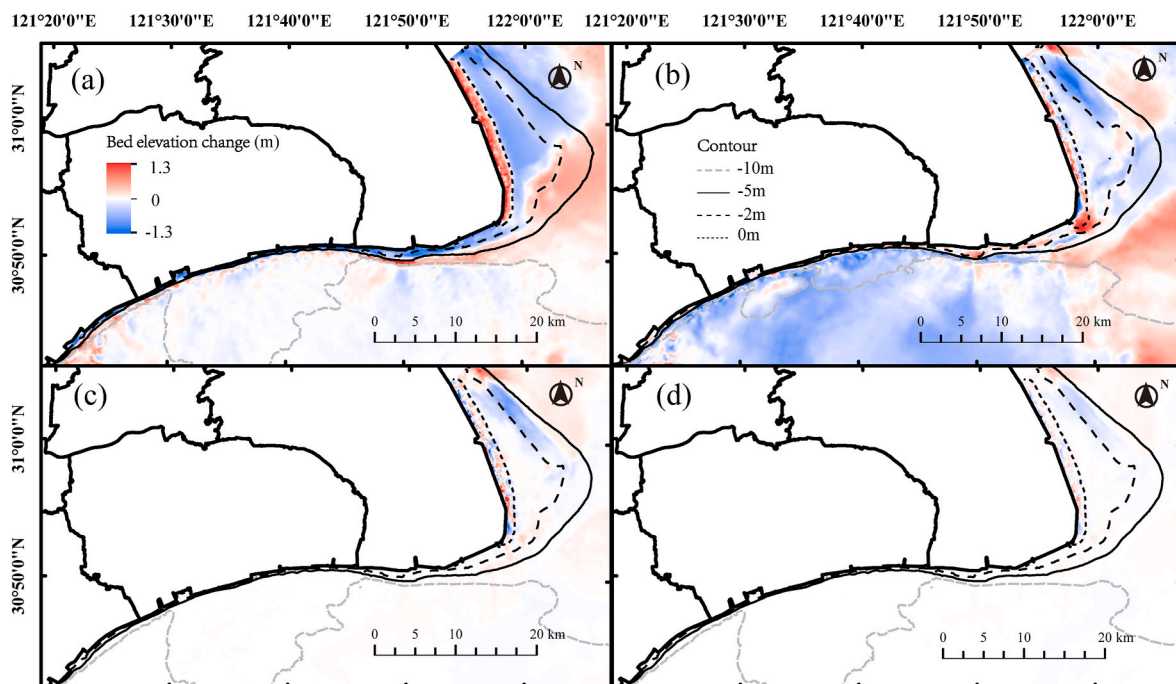


Fig. 9. Spatial changes in bed elevation for (a) a reference case during spring tide in the wet season and (b, c, d) the impacts from watershed cases with sediment change by TGD interception (b), seasonal river discharge change (c), river-induced tide force change (d).

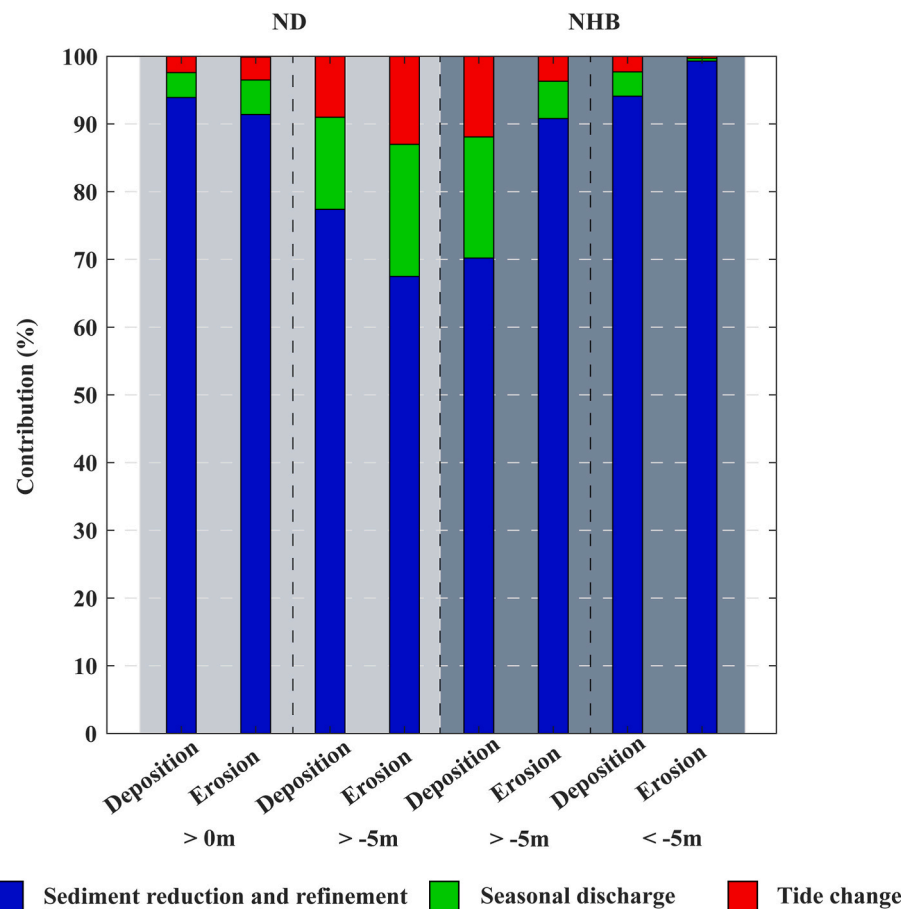


Fig. 10. Relative contribution of coastal morphology changes in ND and NHB from the watershed disturbance.

4.4. Sensitivity test of seawall and T-groynes on intertidal restoration

To restore the damaged tidal flat in NHB, various solutions were tested (See 3.3 Test 4) that have contrasting effects on eroded tidal flats. Field measurement and numerical modelling showed that a hard seawall effectively prevents coastal erosion meanwhile developing a squeezed intertidal area (Figs. 5 and 8). Following two phases of historical coastal reclamation, the tidal flat area in NHB decreased from $\sim 80 \text{ km}^2$ in 1990 to $\sim 20 \text{ km}^2$ in 2010 and further decreased to around 0 in 2020 (Fig. 11a). The future predicted tidal flat area would be maintained around 0, under current seawall defense and hydrodynamic conditions. However, with the seawall removal, the coastal zone would further erode by $\sim 40 \text{ km}^2$ by 2030 (Fig. 11a).

In contrast, the LA-T-groynes structure attached to existing seawall proved very effective in tidal flat recovery, even along the strongly erosive sections of NHB (Fig. 11a and 11f–11h). As demonstrated by the hydro-sediment-dynamics modelling, the eroded tidal flat recovers rapidly with the increase of arm length and the intertidal area extends seaward, mainly because the jetties reduce the longshore current and the arms attenuate the nearshore wind-waves (Fig. 11). The gaps between arms allow seawater-carrying sediment to flow in during flood tide and trap sediment during ebb tide. As shown by the flow fields, the horizontal longshore current during flood tide was reduced from above 0.45 m/s to $< 0.1 \text{ m/s}$ with the increase of arms-length (Fig. 11c–f), thus changing the shear stress gradient for sediment transport and increasing the local sedimentation. Moreover, the onshore current and waves were further reduced by arms, helping to capture the suspended sediment, and flow velocity along the wall of the T-groynes was reduced due to friction, forming arc-edged tidal flat reflecting the flow circulation (Fig. 11d–h). The flow current was further reduced by the combined bio-

hydrodynamics effect of saltmarsh in the “green-grey” solution (Fig. 11h), further reducing the shear stress gradient for sediment transport and increasing sedimentation.

4.5. Hybrid “green-grey” vs. “grey” intertidal mudflat restoration

In addition to the hard structure of T-groynes for tidal flat restoration, the biogeomorphic effect of the attached saltmarsh on sediment trapping process was tested (Fig. 11b and 12). The hybrid “green-grey” measures with saltmarsh (solid green line in Fig. 11b) accelerate the artificial intertidal restoration by 1–2 times compared with “grey” measure of LA-T-groynes and seawall (green dashed line in Fig. 11b). Without vegetation sediment trapping, the tidal flat for the low-medium-high tidal flat (above 0.3 m) area showed a relatively gentle accretion speed with an average linear increase rate of $4.1 \text{ km}^2/\text{yr}$; when vegetation was included the accretion speed of tidal flat above 0.3 m was 1.5 times faster than the pure “grey” measure after seven years of restoration (Fig. 11b green dotted line). However, considering the vegetation sediment trapping effect, the initial fast accretion of bare tidal flat (-1.8 – 0.3 m) reduced after five years due to the rapid expansion of vegetation, which encroached the bare tidal flat area (solid blue line in Fig. 11b). With the bare tidal flat converted to saltmarsh, the area of vegetation zone (above 0.3 m) and bare tidal flat zone (-1.8 – 0.3 m) showed a trade-off from the 7-th year. Overall, modelling showed an additional 30% tidal flat area increase was contributed by the attached saltmarsh due to the positive feedback of vegetation colonization and sediment trapping, and the time required for tidal flat restoration was reduced by 50%. Finally, the total recovered intertidal area maintained $\sim 50 \text{ km}^2$ after seven years of implementing the damaged tidal flat restorations with the proportion of vegetation area to the bare tidal flat

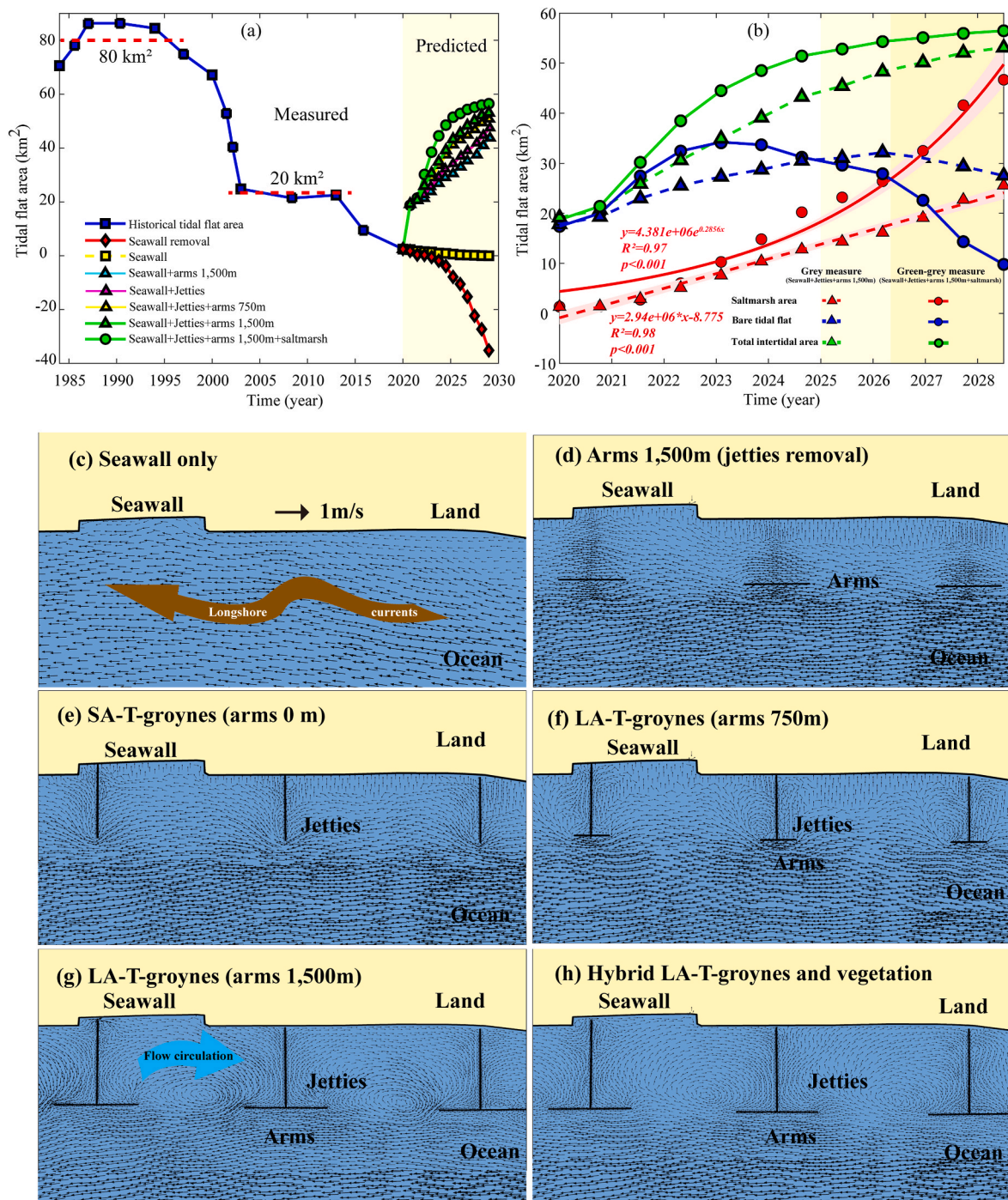


Fig. 11. Sensitivity test of seawall and T-groyne structure on tidal flat accretion for (a) the observed historical tidal flat area change and future prediction with solutions for T-groynes (arms ranging from 0 m to 1500 m), jetties removal (arms 1500 m), T-groynes removal (seawall only), and seawall removal, (b) comparison of tidal flat accretion speed between grey (1500 m LA-T-groynes) and hybrid (1500 m LA-T-groynes and saltmarsh) solutions for bare tidal flat (−1.8–0.3 m) and saltmarsh area (above 0.3 m), (c–h) comparisons of longshore current field during flood tide for solutions of T-groynes removal (seawall only), jetties removal (1500 m arms only), SA-T-groynes (arms 0 m), LA-T-groynes (arms 750 m), LA-T-groynes (arm = 1500 m), and hybrid LA-T-groynes and vegetation.

area at around 80% and 20% for “green-grey” solution compared to 50% and 50% for pure “grey” solution.

Applying the designed “grey” and “green-grey” solutions to the erosive coastline of NHB suggested effective tidal flat recovery. The average tidal flat width along NHB was only 50–100 m before the artificial restoration at the start of the model run (Fig. 12a). After sediment trapping by LA-T-groynes, the artificial tidal flat accreted rapidly from the toe of the seawall toward the edge of arms and formed an arc-shaped intertidal area within the compartment between jetties, similar to the

zeta bays observed in nature. Then, the elevation of intertidal area gradually increased and developed into a zoning intertidal landform of bare tidal flat (−1.8–0.3 m), low (0.3–0.8 m), medium (0.8–1.3 m), and high (1.3–1.8 m) tide flats, respectively (Fig. 12). Generally, the “green-grey” solution is more effective than the “grey” solution for tidal flat recovery. Moreover, the tidal flat recovery speed with the T-groynes requires further consideration of the surrounding flow field, i.e., the large-scale flow field within Hangzhou Bay. In this case, the average velocity on the east side of NHB was reduced to ~0.05 m/s, while the

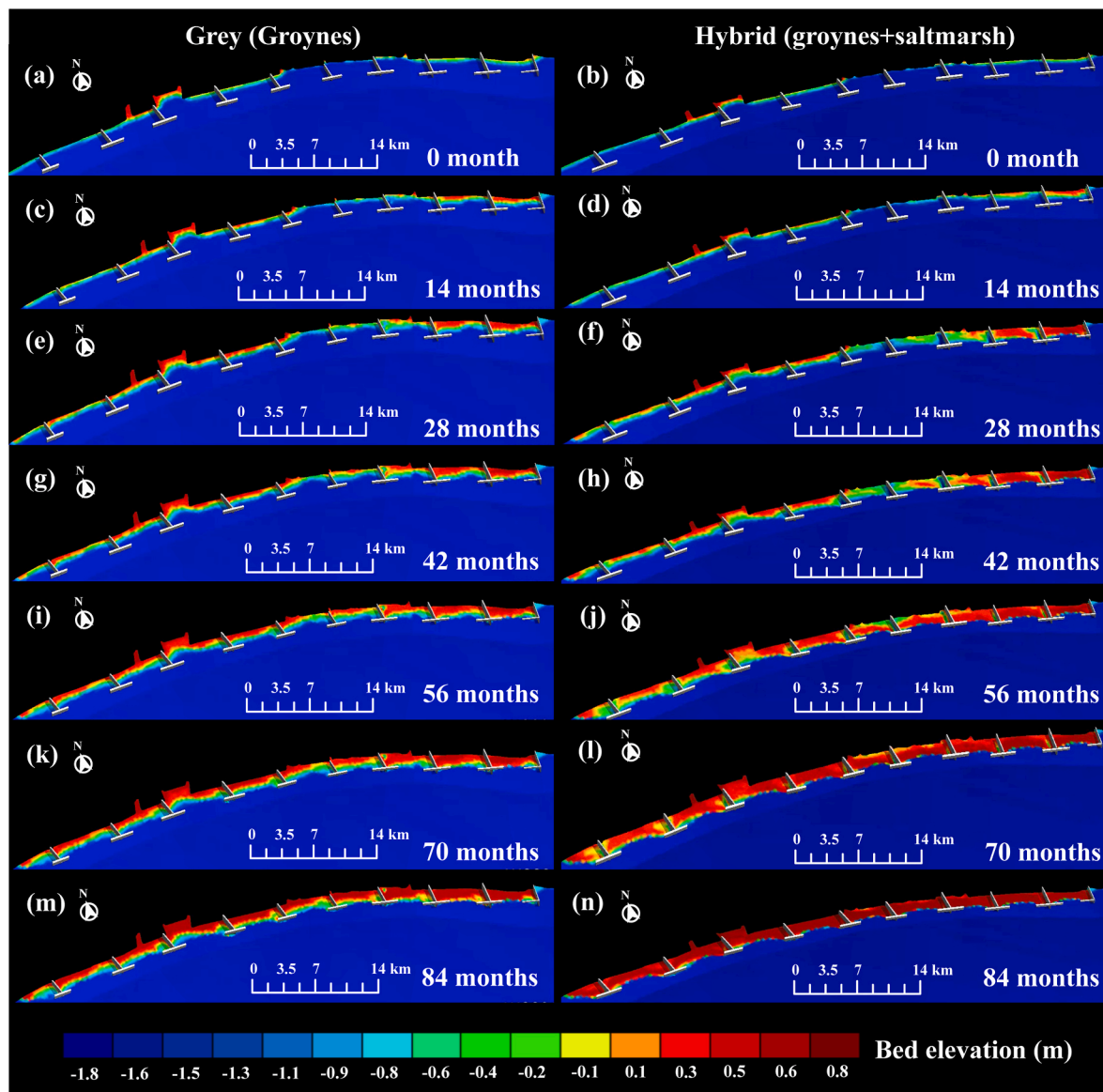


Fig. 12. Time series display of tidal flat morphology evolution in NHB every 14 months with restoration works for (a, c, e, g, i, k, m) the grey LA-T-groynes (arms 1500 m) solution, (b, d, f, h, j, l, n) the hybrid LA-T-groynes and attached saltmarsh solution.

average velocity on the west side was still above 0.13 m/s. The difference in the regional flow fields determined the difference in the bottom shear stress and the sediment carrying capacity. Consequently, the tidal flat recovery efficiency in the east of NHB was 1/2 to 1/3 faster than that in the west NHB, hence the tidal flat recovery speed in the west NHB was 4–5 years slower than that in the east NHB (Fig. 12h–l).

5. Discussion

To mitigate the negative impact of human-induced overexploitation on damaged mudflats, we investigated the “Building with Nature” concept by assessing the effectiveness of hybrid “green-grey” solutions in guiding where and how to develop sustainable tidal flats. The problem is exemplified in Shanghai, where there is a desire to achieve both flood defense and environmental benefits. Traditional “Building Seawall with Nature” approaches, such as the double dike system and living shorelines, recommend flooding the polder land with seawater (Temmerman et al., 2013; Zhu et al., 2020). However, this proposal provokes controversy due to flooding valuable land, particularly in constricted, deltaic cities like Shanghai, home to crucial infrastructure,

including Pudong International Airport, Shanghai International Free-Trade Port, Petrochemical Industry, and Qinshan Nuclear Power Plant, among others (Fig. 1b). As an alternative, we suggest creating the required buffer space of wetlands to seaward through sediment trapping using T-groynes structure. Hydro-sediment-dynamic modelling demonstrated that a hybrid long-armed T-groynes with attached saltmarsh on the mudflat above mean sea level proved more efficient in restoring tidal flats, due to their biogeomorphological feedback effect. Once the tidal flat is restored, the new wetland can provide additional benefits, including flood defense, and other multi-functional ecological advantages.

5.1. The uncertainties of human-intervened coastline evolution

The periodic forces of rivers, tides, and waves have dominated the natural geomorphic evolution of YRD for thousands of years (Yang et al., 2020). However, human interferences of estuary reclamation and dam construction have escalated over the past half-century, disrupting this predictable nature evolutionary process and amplifying system uncertainties (Guo et al., 2021). The uncertainty derived from the

entangled forcing of human and natural factors, an unstable sediment supply from upstream and the open sea (Darby et al., 2016; Luan et al., 2017; Zhang et al., 2018; Murray et al., 2019), the future SLR and intensifying storms under global warming (Kirwan et al., 2016), as well as their intertwined effects in hydro-geomorphological processes (Schwarz et al., 2018; Leuven et al., 2019), make any predictions of the future coastline development deeply uncertain (Guo et al., 2021). Therefore, it is necessary to disentangle the impact of human and natural factors on the deltaic evolution before attempting to design effective tidal flat restoration measures.

We found that anthropogenic disturbance far exceeded natural forces, as evidenced by the recent geomorphic evolution modelling of the YRD (Fig. 7c and 10). At the local scale, anthropogenic reclamation contributed over 60% of the tidal flat area change compared with the changes caused by natural forces of tides and waves. Specifically, NHB lost 80 km² of tidal flat during the past 40 years, leading to unstable and uncertain intertidal development. Conversely, ND evidenced an opposite evolutionary trend, gaining 140 km² of tidal flat with the assistance of engineering works (Fig. 7). The modelling highlighted the extent to which the seawall protects the NHB coastline from erosion (Fig. 7a). Similarly, in a larger watershed scale, anthropogenic disturbance of sediment reduction and fining caused by the TGD project contributed 70–90% of tidal flat change in NHB, far beyond the impacts due to seasonal changes in river runoff and tidal prism (Fig. 10). Consequently, the NHB transitioned from relative equilibrium to a strong erosion (Fig. 8e–h). In contrast, ND evolved into a depositional intertidal area with a steep subtidal slope (Fig. 8a–d). In general, the intertwined forcing of human disturbance and changing natural factors, at both local and basin dimensions, coupled with seasonal extremes (Temmerman et al., 2013), SLR (Leuven et al., 2019), and intensifying storms (Temmerman et al., 2013), are projected to exacerbate the uncertainty of future geomorphic evolution in the YRD. For instance, the study by Wang et al. (2020) demonstrated that tropical cyclones significantly alleviate mega-deltaic erosion induced by high riverine flow, reducing sediment loss caused by riverine flow by more than 50%. Similarly, Yang et al. (2011) and Wei et al. (2020) also suggested that storm surges can bring additional sediment, helping to alleviate sediment shortages.

5.2. Building robust coastline with green and grey solutions

To mitigate the uncertainty in future coastline change, both biotic and abiotic measures have been developed to help repair damaged tidal flats (Temmerman et al., 2013; Zhu et al., 2020). Moreover, the threats posed along NHB of YRD suggest that changes to the current coastal protection will be needed in the forthcoming future. We examined the option of using T-groynes along NHB to restore the damaged tidal flat, evaluating their sediment trapping ability, which proved to be effective in countering the positive erosion feedback loop (Fig. 11). As demonstrated by the hydro-sediment-dynamic modelling, the LA-T-groynes enable tidal flat recovery along NHB (Figs. 11 and 12). Nevertheless, it must be acknowledged that the construction of T-groynes results in increased flow velocity in front of the arms compared to conventional structures such as seawalls and jetties, as illustrated in Fig. 11. Simulations from hydro-sediment-dynamics models (Fig. 12) and large-scale estuary studies (Yang et al., 2020) indicates that this increased flow velocity may exacerbate erosion of the foreshore bathymetry. Consequently, it is essential to incorporate stability enhancement designing for T-groynes structures to ensure their long-term safety. Notably, the intensified seabed erosion only occurs in offshore areas, approximately three to five kms from the coastline. Numerical models confirm that this erosion does not extend to the tidal flats within the compartments of T-groynes, where accretion remains continuous (Fig. 12). Additionally, the deeper waters formed by T-groynes are advantageous for the development of deep-water harbors, for instance, enabling the construction of hydrophilic yacht marinas near the arms. Therefore, the strategic utilization and maintenance of T-groynes can yield significant

environmental, economic, and social benefits.

In addition to installing the T-groynes, incorporating saltmarsh as green solution enhances nearshore sediment trapping efficiency. Saltmarshes could not survive in erosional coastal areas due to frequent tidal inundation and strong wave activity (D'Alpaos et al., 2013). The presence of LA-T-groynes dissipated incoming wave energy, thereby fostering tidal flats and thus, providing opportunities for vegetation seedlings on the elevated intertidal area. Given their high salinity tolerance, saltmarshes, specifically *S.maritima* and *S.alterniflora* as eco-engineering species, can effectively colonize in relatively quiescent conditions that are above the mean sea level (Bouma et al., 2014). Modelling showed that the interaction between the hydrodynamics and saltmarsh captured an additional 30% sediment compared to the sole use of LA-T-groynes (Fig. 13). Moreover, saltmarshes support the formation of tidal creeks, which more effectively enables sediment transporting to the inner wetlands (Schwarz et al., 2018). Recent studies using saltmarsh have proved effective for sediment trapping, such as mimicking the role of plant monomer in capturing sediment under strong waves (Willemsen et al., 2022) and using saltmarsh communities as an eco-engineering systems, to rehabilitate degraded tidal flats (Temmink et al., 2020), as well as the employment of semi-permeable T-groynes, or brushwood dams, in the Dutch-German Wadden Sea (Vuik et al., 2016). We examined the idea of “Building with Nature” based on hybrid “green-grey” solutions by modelling the interactions among hydro-sediment dynamics, saltmarsh, and engineering structures of LA-T-groynes for NHB restoration. The results indicate that the synergistic application of eco-friendly LA-T-groynes and saltmarsh can efficiently establish expansive wetlands, thereby enhancing resilience against climate change and SLR.

5.3. Implications for damaged coastline restoration

Many important deltas worldwide are experiencing transitions from natural evolution to human-driven alterations (Guo et al., 2021). Repairing damaged coastlines is a global management challenge, requiring appropriate planning and long-term strategic adaptation (Edmonds et al., 2020). Many previous coastal restorations have explored saltmarsh functionality and their social-ecological values (Kirwan et al., 2016; Willemsen et al., 2022). Here, we propose a flood defense system utilizing the eco-engineering capacity of saltmarshes in the absence of tidal flats (Fig. 13). We designed the LA-T-groynes structures to extend the tidal flat seaward, establishing a habitat for wetlands that enables high-efficiency sediment accretion despite the increase in fine suspended sediments due to activities such as dam construction in the YRD. Vertical jetties in the T-groynes structures interrupt the strong longshore currents, horizontal long arms mitigate the onshore waves, and the opening between T-groynes allows sediment exchange and interception by colonizing vegetation, capturing and stabilizing sediment during flood-ebb tides, once the tidal flat elevation has accrued above mean sea level (D'Alpaos et al., 2013; Hu et al., 2015). This efficient sediment trapping process enables the restoration of new ecological space along the coastline, restoring parts of the lost transition between sea and shore. Notably, such hybrid flood defense measures not only provide coastal protection but have additional benefits combining ecology-recreation-flood defense functions.

Global coastal degradation has been noted as a consequence of diverse factors including storms, rising sea levels, subsidence, heavy precipitation, and flash floods (Temmerman et al., 2013; Murray et al., 2019; Edmonds et al., 2020). Hybrid seawalls, combining green (i.e., saltmarsh and tidal flat) and grey (i.e., conventional seawall) structures, provide ecological benefits in addition to coastal defense (Sutton-Grier et al., 2015; Zhu et al., 2020). In fact, European and American regions have adopted incentive policies aimed at fostering environmental, economic, and societal amelioration (USACE, 2002; CIRIA, 2013). However, restoration activities should address the needs and perspectives of all stakeholders in a sustainable and equitable manner. While “double

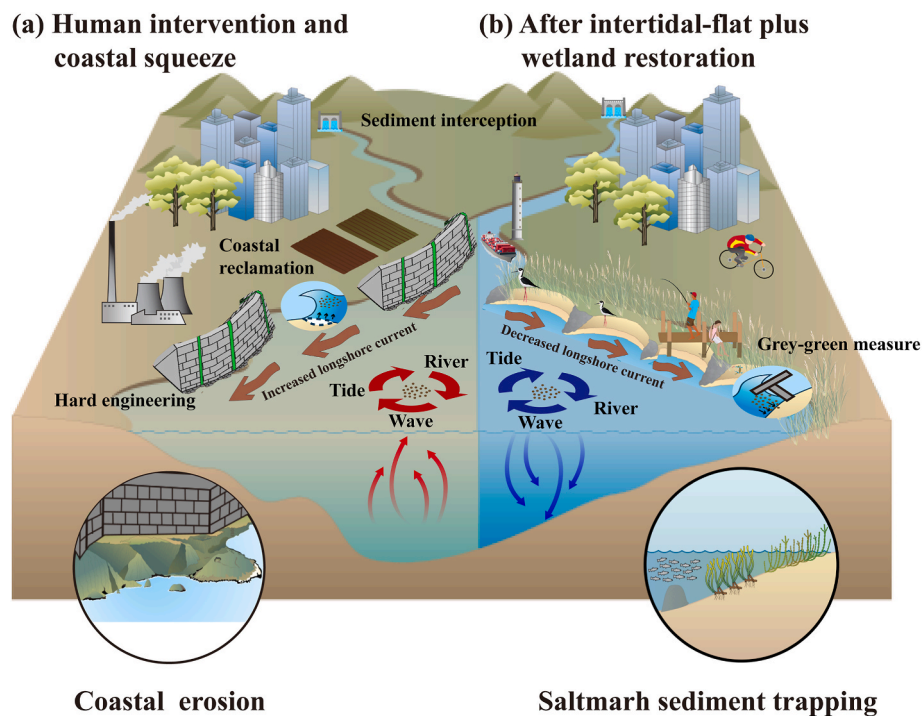


Fig. 13. Conceptual illustration of comprehensive coastal restoration comparing hard engineering with hybrid green-grey solutions for erosion control and sediment trapping. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

dikes" have proven advantageous along Dutch and Belgian territories (Temmerman et al., 2013; Zhu et al., 2020; Vuik et al., 2016), wetland restoration through polder flooding evokes contention, particularly in spatially restricted deltaic metropolises such as Shanghai and Guangzhou (Murray et al., 2019) amidst land scarcity and surging demand (Temmerman et al., 2013; Murray et al., 2019). Moreover, many low-lying deltas rely on hard seawall protections against bank erosion, as exemplified in the Pearl River, Rhine, Mekong, Irrawaddy, and Nile estuaries (Edmonds et al., 2020). In contrast, New York's Howard Beach area demonstrated the efficacy of constructing tidal flats with a seawall for flood mitigation (Sutton-Grier et al., 2015). Therefore, combining the advantages of conventional hard seawalls and environment-friendly saltmarsh offers a viable hybrid "green-grey" solution that provides meaningful insights for broad application, as evidenced by the ND sediment accelerating works (Fig. 5) and exemplified by our NHB intertidal-flatplus wetland restoration analysis (Fig. 13).

6. Conclusion

To effectively restore damaged tidal flats and build a more natural ecological transition between land and sea, it is necessary to have a robust understanding of the dominant driving forces influencing delta evolution at both local and regional scales. Our research, based on coupled hydro-sediment-dynamics models, examined the intertwined forces of natural and human disturbance and discerned their relative contributions to the tidal flat dynamics. The results show that human disturbance has far exceeded the natural forces on the NHB coastline over the past half-century. The sediment reduction and sediment fining caused by river damming in the watershed and the coastal embankments in the estuary were estimated to have had between 3 and 7 times greater impact on the tidal flat area than the impacts from natural driving forces of tide, wave, and river discharge changes combined. Despite intense anthropogenic stress, ND remained relatively unscathed, although substantial erosion occurred along the NHB coastline. This was mainly due to differences in the regional hydrodynamic environment, wherein the accretional ND is predominantly influenced by tides and the erosional

NHB is governed by the synergistic influence of both tides and waves.

Restoration measures combining current seawall and hard coastal infrastructure of LA-T-groynes, characterized as a "grey" solution, was simulated to reverse erosive mechanisms by enhancing the sediment trapping capacity within the coastal zone. Guided by the principle of reducing environmental and social impact while maximizing ecological service benefits, we tested the design of a hybrid LA-T-groynes/saltmarsh or "green-grey" solution for tidal flat restoration. This approach proved to be effective in sediment trapping, wetland restoration, and creating substantial areas for hydrophilic urban design. Numerical modelling reveals enhanced mudflat accretion as the "green-grey" solution with saltmarshes disturbed the longshore current and wave actions, thereby intercepting suspended sediment, which facilitates a negative feedback process of coastal accretion. We demonstrated a mechanism of tidal flat morphological evolution under constraints that prevailing forcing conditions, system resilience, and imposed engineering works collectively determine the formation of an optimal tidal flat, one in dynamic equilibrium. Such a new integrated coastal restoration system, encompasses both ecosystem restoration and carbon storage co-benefits as well as including landscape planning and tourism promotion functions, has theoretical and practical value for future coastal management.

CRedit authorship contribution statement

Jie Mi: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Min Zhang:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Ian Townend:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Christian Schwarz:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Pim W.J.M. Willemsen:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Stefanie Nolte:** Writing – review & editing. **Wenting Wu:** Writing – review & editing. **Tjeerd J. Bouma:** Writing – review & editing, Supervision,

Methodology, Investigation, Conceptualization.

Open research

The navigation charts covering Yangtze Estuary and the surrounding area were collected from the Maritime Survey Bureau of Shanghai, Ministry of Communications of China (Zhang et al., 2019), available at the website www.cccc-sdc.com. Water and sediment discharges in the upper Yangtze River were sourced from archived daily measurements by the Changjiang Water Resources Committee (<http://www.cjw.gov.cn/>). Tidal amplitude and velocity at the ocean boundary were derived from the latest TPX09 model (<http://volkov.oce.orst.edu/tides>). Wind data at the ocean-atmosphere interface, including hourly 10 m height wind velocity and direction, were provided by the ERA5 reanalysis database (<https://www.ecmwf.int>) and validated prior to delivery (Mi et al., 2022). ArcGIS10.6 was used to identify the coastline movement, calculate the reclamation area, and produce spatial-temporal maps. The mud transport process was generated by MIKE21FM of MIKE software 2016 (DHI, 2016), under the license provided by Shanghai Normal University. Figures were made with Matlab version 2020 under the license provided by East China Normal University. Field measurement of flow direction, flow velocity, and SSC was detected with an acoustic doppler current profiler (SonTek-500), direct-read current meters (SLC9-2), and OBS-3A (5 MHz) provided by State Key Laboratory of Estuarine and Coastal Research, East China Normal University.

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.ocecoaman.2025.107595>.

Data availability

Data will be made available on request.

References

- Battjes, J.A., Janssen, J.P.F.M., 1978. Energy loss and set-up due to breaking of random waves. *Coastal Engineering Proceedings. Proceedings of the 16th International Conference on Coastal Engineering* 1 (16), 32. <https://doi.org/10.9753/icce.v16.32>.
- Bouma, T.J., van Belzen, J., Balke, T., Zhu, Z., Airolidi, L., Blight, A.J., Davies, A.J., Galvan, C., Hawkins, S.J., Hoggart, S.P.G., Lara, J.L., Losada, I.J., Maza, M., Ondiviela, B., Skov, M.W., Strain, E.M., Thompson, R.C., Yang, S., Zanuttigh, B., Zhang, L., Herman, P.M.J., 2014. Identifying knowledge gaps hampering application of intertidal habitats in coastal protection: opportunities & steps to take. *Coast. Eng.* 87, 147–157. <https://doi.org/10.1016/j.coastaleng.2013.11.014>.
- CIRIA, 2013. *The International Levee Handbook*. CIRIA, London (CIRIA, C731).
- Dai, Z., Liu, J.T., Wei, W., Chen, J., 2015. Detection of the three Gorges dam influence on the Changjiang (Yangtze River) submerged delta. *Sci. Rep.* 4 (1). <https://doi.org/10.1038/srep06600>.
- D'Alpaos, A., Carniello, L., Rinaldo, A., 2013. Statistical mechanics of wind wave-induced erosion in shallow tidal basins: inferences from the Venice Lagoon. *Geophys. Res. Lett.* 40 (13), 3402–3407. <https://doi.org/10.1002/grl.50666>.
- Darby, S.E., Hackney, C.R., Leyland, J., Kumm, M., Lauri, H., Parsons, D.R., Best, J.L., Nicholas, A.P., Aalto, R., 2016. Fluvial sediment supply to a mega-delta reduced by shifting tropical-cyclone activity. *Nature* 539 (7628), 276–279. <https://doi.org/10.1038/nature19809>.
- DHI, 2016. *User Guide and Reference Manual of MIKE21 (Coastal Hydraulics and Oceanography)*.
- Edmonds, D.A., Caldwell, R.L., Brondizio, E.S., Siani, S.M.O., 2020. Coastal flooding will disproportionately impact people on river deltas. *Nat. Commun.* 11 (1), 4741. <https://doi.org/10.1038/s41467-020-18531-4>.
- Guo, L., et al., 2021. Changjiang delta in the Anthropocene: multi-scale hydro-morphodynamics and management challenges. *Earth Sci. Rev.* 223, 103850. <https://doi.org/10.1016/j.earscirev.2021.103850>.
- Hu, Z., van Belzen, J., van der Wal, D., Balke, T., Wang, Z.B., Stive, M., Bouma, T.J., 2015. Windows of opportunity for salt marsh vegetation establishment on bare tidal flats: the importance of temporal and spatial variability in hydrodynamic forcing. *Journal of Geophysical Research-Biogeosciences* 120 (7), 1450–1469. <https://doi.org/10.1002/2014JG002870>.
- Kirwan, M.L., Temmerman, S., Skeehan, E.E., Guntenspergen, G.R., Fagherazzi, S., 2016. Overestimation of marsh vulnerability to sea level rise. *Nat. Clim. Change* 6 (3), 253–260. <https://doi.org/10.1038/nclimate2909>.
- Leuven, J.R.F.W., Pierik, H.J., Vegt, M.V.D., Bouma, T.J., Kleinans, M.G., 2019. Sea-level-rise-induced threats depend on the size of tide-influenced estuaries worldwide. *Nat. Clim. Change* 9 (12), 986–992. <https://doi.org/10.1038/s41558-019-0608-4>.
- Li, B., 2016. A preliminary study on the influence of sea level rise and ground subsidence to Taihu Lake Basin and its countermeasures. *Pearl River* 37 (01), 38–41.
- Luan, H.L., Ding, P.X., Wang, Z.B., Ge, J.Z., 2017. Process-based morphodynamic modeling of the Yangtze Estuary at a decadal timescale: controls on estuarine evolution and future trends. *Geomorphology* 290, 347–364. <https://doi.org/10.1016/j.geomorph.2017.04.016>.
- Luo, X.X., Yang, S.L., Zhang, J., 2012. The impact of the Three Gorges Dam on the downstream distribution and texture of sediments along the middle and lower Yangtze River (Changjiang) and its estuary, and subsequent sediment dispersal in the East China Sea. *Geomorphology* 179, 126–140. <https://doi.org/10.1016/j.geomorph.2012.05.034>.
- Madsen, O.S., Poon, Y., Graber, H.C., 1989. Spectral wave attenuation by bottom friction: theory. *Coast. Eng.* 1988, 492–504.
- Mi, J., Zhang, M., Zhu, Z., Vuik, V., Wen, J., Gao, H., Bouma, T.J., 2022. Morphological wave attenuation of the nature-based flood defense: a case study from Chongming Dongtan Shoal, China. *Sci. Total Environ.* 154813 <https://doi.org/10.1016/j.scitotenv.2022.154813>.
- Murray, N.J., Phinn, S.R., Dewitt, M., Ferrari, R., Johnston, R., Lyons, M.B., Clinton, N., Thau, D., Fuller, R.A., 2019. The global distribution and trajectory of tidal flats. *Nature* 565 (7738), 222–225. <https://doi.org/10.1038/s41586-018-0805-8>.
- Nienhuis, J.H., Ashton, A.D., Edmonds, D.A., Houtink, 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. <https://doi.org/10.1038/s41586-019-1905-9>.
- Schwarz, C., Gourgue, O., van Belzen, J., Zhu, Z., Bouma, T.J., van de Koppel, J., Ruessink, G., Claude, N., Temmerman, S., 2018. Self-organization of a biogeomorphic landscape controlled by plant life-history traits. *Nat. Geosci.* 11 (9), 672. <https://doi.org/10.1038/s41561-018-0180-y>.
- Ministry of Natural Resources of the People's Republic of China, 2022.
- Smagorinsky, J., 1963. General circulation experiments with the primitive equations: I. The basic experiment. *Mon. Weather Rev.* 91 (3), 99–164. [https://doi.org/10.1175/1520-0493\(1963\)091<0099:GCEWTP>2.3.CO;2](https://doi.org/10.1175/1520-0493(1963)091<0099:GCEWTP>2.3.CO;2).
- Sutton-Grier, A.E., Wolk, K., Bamford, H., 2015. Future of our coasts: the potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environ. Sci. Pol.* 51, 137–148. <https://doi.org/10.1016/j.envsci.2015.04.006>.
- Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls, R.J., 2009. Sinking deltas due to human activities. *Nat. Geosci.* 2 (10), 681–686. <https://doi.org/10.1038/ngeo629>.
- Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M.J., Ysebaert, T., De Vriend, H.J., 2013. Ecosystem-based coastal defence in the face of global change. *Nature* 504 (7478), 79–83. <https://doi.org/10.1038/nature12859>.
- Temmink, R.J.M., Christianen, M.J.A., Fivash, G.S., Angelini, C., Boström, C., Dideren, K., Engel, S.M., Esteban, N., Gaeckle, J.L., Gagnon, K., Govers, L.L., Infantes, E., van Katwijk, M.M., Kipson, S., Lamers, L.P.M., Lengkeek, W., Silliman, B.R., van Tussenbroek, B.I., Unsworth, R.K.F., Yaakub, S.M., Bouma, T.J., van der Heide, T., 2020. Mimicry of emergent traits amplifies coastal restoration success. *Nat. Commun.* 11 (1). <https://doi.org/10.1038/s41467-020-17438-4>.
- Torio, D.D., Chmura, G.L., 2013. Assessing coastal squeeze of tidal wetlands. *J. Coast Res.* 29 (5), 1049–1061. <https://doi.org/10.2112/JCOASTRES-D-12-00162.1>.
- U.S. Army Corps of Engineers (USACE), 2002. *Coastal Engineering Manual*, 1110th-2nd-110th edn. U.S. Army Corps of Engineers, Washington, D.C.
- Van Coppenolle, R., Schwarz, C., Temmerman, S., 2018. Contribution of mangroves and salt marshes to Nature-Based mitigation of coastal flood risks in major deltas of the

- world. *Estuaries Coasts* 41 (6), 1699–1711. <https://doi.org/10.1007/s12237-018-0394-7>.
- Van Rijn, L., 1993. *Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas*. Aqua Publications, The Netherlands.
- Villemonte, J.R., 1947. Submerged weir discharge studies. *Eng. News Rec.* 866, 54–57.
- Vuik, V., Jonkman, S.N., Borsje, B.W., Suzuki, T., 2016. Nature-based flood protection: the efficiency of vegetated foreshores for reducing wave loads on coastal dikes. *Coast. Eng.* 116, 42–56. <https://doi.org/10.1016/j.coastaleng.2016.06.001>.
- Wang, J., Dai, Z., Mei, X., Fagherazzi, S., 2020. Tropical cyclones significantly alleviate mega-deltaic erosion induced by high riverine flow. *Geophys. Res. Lett.* 47, e2020GL089065. <https://doi.org/10.1029/2020GL089065>.
- Wei, W., Dai, Z., Pang, W., Wang, J., Gao, S., 2020. Sedimentary zonation shift of tidal flats in a meso-tidal estuary. *Sediment. Geol.* 407, 105749. <https://doi.org/10.1016/j.sedgeo.2020.105749>.
- Wen, Qiwei, Yang, Zhenhua, Zhao, Tongtiengang, et al., 2024. A monitoring study on tidal-flat structures in the Inner Lingding Sea for Pearl River Estuary during 1988–2021. *Water Resour. Hydropow. Eng.* 55 (7), 82–92.
- Willemssen, P.W.J.M., Smits, B.P., Borsje, B.W., Herman, P.M.J., Dijkstra, J.T., Bouma, T. J., Hulscher, S.J.M.H., 2022. Modeling decadal salt marsh development: variability of the salt marsh edge under influence of waves and sediment availability. *Water Resour. Res.* 58 (1), e28962W. <https://doi.org/10.1029/2020WR028962>.
- World Meteorological Organization, 2022. WMO provisional state of the global climate. <https://public.wmo.int/en>.
- Xie, D., Pan, C., Wu, X., Gao, S., Wang, Z.B., 2017. Local human activities overwhelm decreased sediment supply from the Changjiang River: continued rapid accumulation in the Hangzhou Bay-Qiantang Estuary system. *Mar. Geol.* 392, 66–77. <https://doi.org/10.1016/j.margeo.2017.08.013>.
- Yang, S.L., Luo, X., Temmerman, S., Kirwan, M., Bouma, T., Xu, K., Zhang, S., Fan, J., Shi, B., Yang, H., Wang, Y.P., Shi, X., Gao, S., 2020. Role of delta-front erosion in sustaining salt marshes under sea-level rise and fluvial sediment decline. *Limnol. Oceanogr.* 65 (9), 1990–2009. <https://doi.org/10.1002/lno.11432>.
- Yang, S.L., Milliman, J.D., Li, P., Xu, K., 2011. 50,000 dams later: erosion of the Yangtze River and its delta. *Global Planet. Change* 75 (1), 14–20. <https://doi.org/10.1016/j.gloplacha.2010.09.006>.
- Zhang, M., Dai, Z., Bouma, T.J., Bricker, J., Townend, I., Wen, J., Zhao, T., Cai, H., 2021. Tidal-flat reclamation aggravates potential risk from storm impacts. *Coast. Eng.* 166, 103868. <https://doi.org/10.1016/j.coastaleng.2021.103868>.
- Zhang, M., Schwarz, C., Lin, W., Naing, H., Cai, H., Zhu, Z., 2023a. A new perspective on the impacts of spartina alterniflora invasion on Chinese wetlands in the context of climate change: a case study of the Jiuduansha shoals, yangtze estuary. *Sci. Total Environ.* 868, 161477.
- Zhang, M., Townend, I., Cai, H., He, J., Mei, X., 2018. The influence of seasonal climate on the morphology of the mouth-bar in the Yangtze Estuary, China. *Cont. Shelf Res.* 153, 30–49. <https://doi.org/10.1016/j.csr.2017.12.004>.
- Zhang, M., Townend, I., Zhou, Y., Cai, H., 2016. Seasonal variation of river and tide energy in the Yangtze estuary, China. *Earth Surf. Process. Landf.* 41 (1), 98–116. <https://doi.org/10.1002/esp.3790>.
- Zhang, M., Townend, I., Zhou, Y., Wang, L., Dai, Z., 2019. An examination of estuary stability in response to human interventions in the South Branch of the Yangtze (Changjiang) estuary, China. *Estuarine. Coastal and Shelf Science* 228, 106383. <https://doi.org/10.1016/j.ecss.2019.106383>.
- Zhang, M., Wu, H., Dai, Z., Mi, J., Cai, H., 2023b. Morphodynamic resilience of the Tide-Dominated estuary with interference from tidal flat reclamations. *J. Geophys. Res.: Oceans* 128 (4), e19321J. <https://doi.org/10.1029/2022JC019321>.
- Zhang, X., Zhang, Y., Zhu, L., Chi, W., Yang, Z., Wang, B., Lv, K., Wang, H., Lu, Z., 2018. Spatial-temporal evolution of the eastern Nanhui mudflat in the Changjiang (Yangtze River) Estuary under intensified human activities. *Geomorphology* 309, 38–50. <https://doi.org/10.1016/j.geomorph.2018.02.023>.
- Zhu, Z., Vuik, V., Visser, P.J., Soens, T., van Wesenbeeck, B., van de Koppel, J., Jonkman, S.N., Temmerman, S., Bouma, T.J., 2020. Historic storms and the hidden value of coastal wetlands for nature-based flood defence. *Nat. Sustain.* 3 (10), 853–862. <https://doi.org/10.1038/s41893-020-0556-z>.