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# Morphodynamic response to extreme basin flooding and its mechanism in a tide-dominant estuary

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## ABSTRACT

Extreme basin floods can strongly reshape tide-dominated estuaries, but their effects are often conditioned by antecedent channel geometry and human-induced river-bed incision. Here, we investigated the annual-scale morphodynamic response of the North Branch of the Changjiang (Yangtze) Estuary to the 2020 extreme basin flood using hydrological records, bathymetric surveys, surficial sediment samples, and Delft3D scenario experiments. Despite a peak discharge of  $83,400 \text{ m}^3 \text{ s}^{-1}$  at Datong, the North Branch showed net shoaling rather than reach-wide erosion over the May 2020–May 2021 survey interval, which encompassed both the 2020 flood and approximately nine months of post-flood adjustment. Mean water depth decreased from 3.35 to 2.91 m, with most channel-volume loss concentrated within the 2–5 m and 5–8 m depth intervals. Erosion was restricted to the bend-apex main channel, the straight middle-channel thalweg, and the mouth-bar area, whereas ebb duration remained longer than flood duration and surficial sediments became coarser and better sorted. Scenario results showed that extreme basin flooding increased the ebb-tide and total diversion ratios by 180.4% and 170.0%, respectively, enhanced the peak ebb current by 37.03% and weakened landward sediment transport. Mid-lower Changjiang channel incision slightly enhanced tidal access under mean-runoff conditions, but model comparisons showed that, under coupled flood and incision conditions, incision attenuated the flood-driven increase in total diversion while further strengthening peak ebb currents. Together, the observations and scenario results support a tide-filtered flood-response mechanism in which extreme flooding promotes local scour and seaward transport, whereas persistent lower-branch tidal import, limited exportable sediment, and reclamation-constrained channel geometry favour internal sediment storage. These findings show that extreme floods in engineered, tide-dominated estuaries may reorganize internal sediment storage rather than produce system-wide erosion.

## Highlights

- The 2020 extreme basin flood was associated with net shoaling rather than reach-wide erosion in the North Branch.
- A four-scenario Delft3D design quantifies the effects of riverine bed incision, flood, coupled, and their coupling.
- Mid-lower Changjiang channel incision modulated flood response by weakening diversion (−7.1%) but enhancing peak ebb currents (4.75%).

## ARTICLE HISTORY

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## KEYWORDS

Extreme basin flood; riverine bed incision; Delft3D; sediment partitioning; morphodynamics; North Branch of Changjiang (Yangtze)

## 1. Introduction

Extreme basin floods are increasingly important drivers of estuarine change as climate warming intensifies the hydrological cycle and increases human exposure to flood hazards, as recent disasters demonstrate (Barneveld

et al., 2025; Corringham et al., 2019; Lux, 2020; Merz et al., 2021; Mei et al., 2018; Pall et al., 2011; Tellman et al., 2021). In estuaries, floods can alter water levels, current asymmetry, and sediment transport, leaving persistent geomorphic signatures through channel scour, bar

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migration, wetland deposition, and delta-front adjustment (Eekhout & Hoitink, 2015; van Dijk et al., 2013). These responses depend on discharge, tidal forcing, sediment supply, and channel geometry, all of which may already have been modified by human activities (Barnveld et al., 2025; Borga et al., 2014; Brenna et al., 2025; Grill et al., 2019).

Human-induced hydrogeomorphic adjustment can strongly condition estuarine flood response (Tang et al., 2023). Reservoir trapping reduces downstream sediment supply and promotes channel incision (Mei et al., 2021), while bank stabilization, embankments, and floodplain contraction alter conveyance, storage, and stage response (Heine & Pinter, 2012; Ma et al., 2022; Maxwell et al., 2021; Opperman et al., 2009, 2010). Land reclamation further narrows channels (Zhang et al., 2001; Zhang, Yang, et al., 2025; Zhu et al., 2026), removes intertidal accommodation, and modifies tidal propagation and sediment trapping (Ghoneim et al., 2015; Siemes et al., 2025; Thanh et al., 2020). Similar controls occur in the Mississippi Delta, Mekong Delta, and regulated European rivers, where altered sediment budgets, floodplain disconnection, incision, and engineering works have changed flood-stage sensitivity and sediment routing (Carle et al., 2015; Edmonds et al., 2023; Heine & Pinter, 2012; Heritage & Entwistle, 2020; Thanh et al., 2020; Wyżga et al., 2015). Extreme floods act on inherited boundary conditions rather than natural estuarine templates.

Research has documented flood-driven morphodynamics in rivers and river-dominated deltas. Large floods often increase flow velocity, bed shear stress, and downstream sediment transport, thereby promoting channel scour, bar erosion, floodplain reworking, and rapid sediment redistribution (Scorpio & Comiti, 2024; Slingerland & Smith, 1998; Thompson & Croke, 2013). Flood pulses may also build mouth bars, nourish wetlands, or redistribute sediment across adjacent shelves, as shown in the Mississippi, Rhone, Red River, and Yellow River systems (Bourrin et al., 2008; Carle et al., 2015; Fisk et al., 1954; Vinh et al., 2014). In tide-influenced systems, however, flood effects may be modified by tidal asymmetry, bidirectional transport, tidal storage, and estuarine circulation (Dronkers, 1986; Geyer & MacCready, 2014). Studies from the Sittoung and Guadiana estuaries show that discharge can modify tidal propagation and sediment convergence in ways that differ fundamentally from river-dominated deltas (Choi et al., 2020; Gareil et al., 2009). Recent models have improved tidal prediction, shallow-water circulation analysis, and engineered sediment-transport simulation in estuaries (Guo et al., 2025; Wei et al., 2026; Zhang, Liu, et al., 2025). However, it remains unclear how extreme floods reshape erosion and

sediment storage in engineered, tide-dominated estuaries where tidal control, reduced sediment supply, and reclamation-constrained geometry coexist.

The North Branch of the Changjiang Estuary is well suited for examining this gap. It was formerly a major distributary but has evolved into a shallow, strongly convergent, tide-dominated channel with weak fluvial input, persistent landward sediment transport, and severe long-term infilling (Dai et al., 2016). Recent models have improved tidal prediction, shallow-water circulation analysis, and engineered sediment-transport simulation in estuaries (Dai et al., 2016, 2018). Previous studies have documented sustained channel-volume loss, enhanced sediment import, and increasing saltwater intrusion risk. Recent Changjiang floods rank among the highest on record under intensifying climate forcing (Guo et al., 2026; Jia et al., 2022; Shankman & Lai, 2022; Tang et al., 2023). Although peak discharges in the upper basin show a declining trend, flood recession stages have lengthened significantly in 61.1% of cases, changing floodwave structure (Zhang et al., 2021). In 2020, basin-wide rainfall generated one of the most severe flood seasons of recent decades, with peak discharge at Datong ranking among historical maxima (Cai et al., 2022; Jia et al., 2022). The flood reached an estuary affected by reduced sediment supply, post-dam incision, reclamation, and persistent adjustment. Observations also show heterogeneous flood responses among Changjiang distributary channels, including changes in sediment transport direction and turbidity maximum position (Fan et al., 2023).

Here, we investigate the annual-scale North Branch's morphodynamic response to the 2020 extreme Changjiang flood. Our objectives are to characterize the flood-associated morphological evolution of the North Branch and to clarify how hydrodynamics, water-sediment partitioning, and sediment-transport behaviour responded to this event. To address these questions, we combine hydrological observations, multi-temporal bathymetric data, surficial sediment measurements, and Delft3D scenario experiments. The added value of this study is to link flood-associated morphology, sediment texture, water-sediment partitioning, and scenario-based modelling within a single process framework. Observations characterize flood-associated hydrodynamic and geomorphic changes, whereas model experiments test plausible mechanisms and isolate the role of channel incision. This design separates observed responses from model-based interpretations and assesses how extreme floods operate in an engineered, tide-dominated estuary.

## 2. Materials and methods

### 2.1. Study area

The Changjiang (Yangtze) River constitutes the seaward continuation of Asia's longest river, extending approximately 6,300 km and draining a vast catchment of  $1.80 \times 10^6 \text{ km}^2$  (Figure 1(A)). The landward limit of tidal penetration conventionally defines the upper basin boundary, where the Datong ( $\sim 630 \text{ km}$  upstream) marks the maximum upriver propagation of tides during the dry season, while Xuliujing ( $\sim 120 \text{ km}$ ) denotes the effective limit of saltwater intrusion into the estuarine transition zone (Dai, 2021; Ma et al., 2026). The Changjiang Delta is an archetypal mega fluvial-tidal delta, characterized by a low-lying topography (average elevation 2–4 m) and high population density (Figure 1(A)). At Datong Station, the landward limit of tidal propagation, the long-term mean annual water and suspended sediment discharges are  $8.98 \times 10^{11} \text{ m}^3 \text{ yr}^{-1}$  and  $3.51 \times 10^8 \text{ t yr}^{-1}$ , respectively (Changjiang Water Resources Commission, 2024). Multiple human interventions have driven significant bed erosion in the lower reach between Datong and Xuliujing, as evidenced by an average incision of 2.19 m. (Figure 1(B)). Over the past two millennia, the estuary has evolved into a complex distributive network comprising four bifurcating, highly navigable subaqueous channels and extensive intertidal shoals (Liu et al., 2007). The emergence of Chongming Island partitioned this network, initially separating the river into the North and South Branches (Dai, 2021). Since the Holocene, an estimated  $1.16 \times 10^{12} \text{ t}$  of sediment has accumulated across the delta plain and adjacent subaqueous domains (Liu et al., 2007).

The North Branch is an approximately 80-km-long, shallow and strongly convergent distributary that has evolved into a tide-dominated and generally flood-dominant system (Dai et al., 2016). The branch is mesotidal and predominantly semidiurnal, with a mean tidal range of approximately 3.1 m at STG and typical values of 2–4 m along the channel. Its narrow upper reach between Chongmingzhoutou (CMZT) and Qinglonggang (QLG) forms the fluvial entrance (Figure 1(C)), where the channel is oriented at a large angle to the mainstem and receives only about 3–5% of the Yangtze discharge. The middle reach between Qinglonggang (QLG) and Touxinggang (TXG), along with the adjacent QLG-Lingdiangang (LDG) sub-reach, exhibits pronounced sinuosity. Within these bends, the apex sections serve as tidal-convergence zones that typically host a well-developed estuarine turbidity maximum. Downstream of TXG, the lower reach progressively widens

and straightens towards Santiaogang (STG) and Lianxinggang (LXG), and tidal forcing becomes increasingly dominant.

The mean spring tidal ranges at LXG, STG, and QLG are approximately 3.77, 3.82, and 3.811 m, respectively, with mean and maximum tidal flow velocities at QLG of 1.25 and  $3.12 \text{ m s}^{-1}$  (Dai, 2021). Additionally, the discharge diversion rate of the North Branch remained close to  $-5\%$  from 1959 to 1988, rose modestly to 1–5% between 1987 and 2001, and subsequently dropped to  $-24\%$  in 2011 (Dai et al., 2016). Channel convergence amplifies the tide upstream and produces marked tidal asymmetry, generally characterized by a shorter flood duration and stronger peak flood currents than during ebb (Li et al., 2015). Sediments are generally coarser in the upper reach and become progressively finer downstream, reflecting the transition from fluvial advection and energetic tidal resuspension to tidal pumping and fine-sediment accumulation (Dai, 2021).

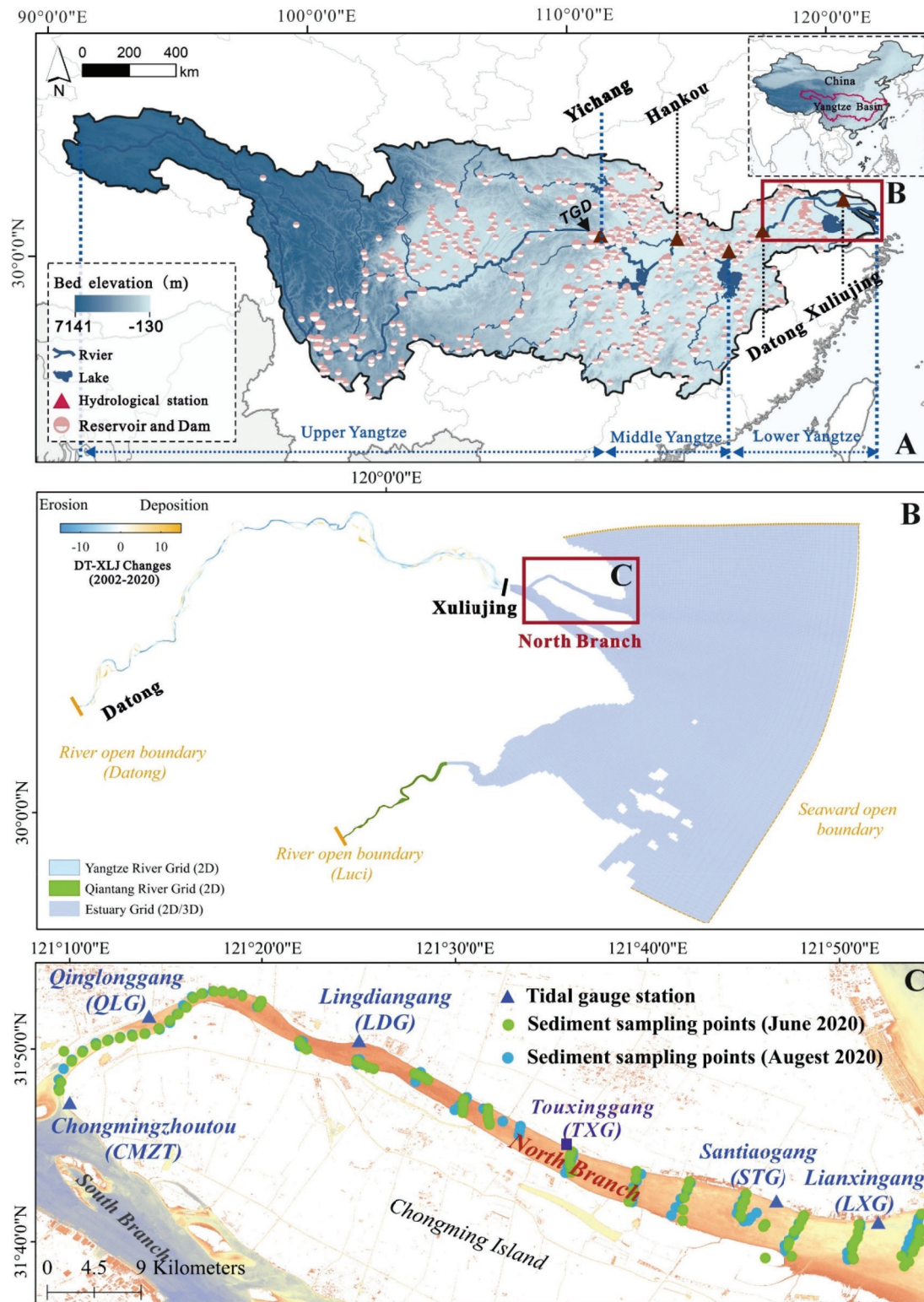
### 2.2. Data and methods

#### 2.2.1. Data acquisition

Hydrological data for the middle and lower Changjiang River were compiled for three key control stations, including Yichang, Hankou and Datong (Figure 1(A)). The dataset includes water level, discharge, suspended sediment concentration, surveyed cross-sections and sediment grain-size composition since the 1950s. Daily discharge and water-level data from June to September 2020 were used to identify flood peaks, rising and falling stages, and stage-discharge hysteresis. These records were obtained from the *Hydrological Data of the Changjiang River Basin* published by the Bureau of Hydrology, Ministry of Water Resources of China, together with related statistical datasets.

To quantify monthly discharge anomalies of the extreme flood in the Changjiang River, the standardized streamflow index (SSI), which was calculated by transforming the cumulative probability of streamflow into a standard normal variate,  $\text{SSI} = \Phi^{-1}[F_Q(q)]$ , where  $F_Q(q)$  is the cumulative distribution function of streamflow  $Q$  evaluated at the observed value ( $q$ ) (Shukla & Wood, 2008), was employed at individual hydrological stations. For each station, a probability distribution was fitted to the historical monthly discharge series, and the cumulative probability of a target discharge was then transformed into a standard normal variable with a mean of 0 and a variance of 1.

Published bankfull-channel erosion and deposition data for the middle and lower Changjiang River were compiled from the Changjiang Water Resources Commission. These estimates were derived from surveyed



**Figure 1.** Geographic location of the Changjiang River Basin with longitudinal bed elevation profile (A), the North Branch (C), and the Delft 3D model grid (B), combined Delft3D model of the Changjiang and Qiantang River estuaries. Note that panel A is modified from Tang et al. (2023).

riverbed topography using the cross-section method. Fixed cross-sections were spaced at approximately 1000 m, with spacing reduced to about 500 m in morphologically complex reaches. Cross-sectional points were generally extracted at 35–40 m intervals from 1:5000 topographic data and locally densified to about 20 m. Channel-volume changes between adjacent cross-sections were calculated using the frustum method, and reach-scale erosion or deposition was obtained from differences in channel storage between survey periods.

Bathymetric data for the North Branch were obtained from digitized navigation charts and field-surveyed water-depth datasets for 2020 and 2021. The May 2020–May 2021 comparison captures integrated post-event adjustment rather than instantaneous flood-induced bed change. These data were surveyed mainly during the dry season, published by the Changjiang Waterway Bureau, and referenced to the theoretical lowest tidal datum using the China Geodetic Coordinate System 2000 and Gauss–Krüger projection. Five tidal gauging stations, Lianxinggang (LXG), Santiaogang (STG), Lingdiangang (LDG), Qinglonggang (QLG), and Chongmingzhoutou (CMZT; Figure 1(C)), recorded daily high and low water levels throughout June–August 2020, as presented in Figure S1 in the Supplementary material. Propagation speed between adjacent stations was estimated from station spacing and the time lag of paired high- or low-water.

Surficial bed sediments in the North Branch were sampled before and after the 2020 flood, in June and August 2020, to examine flood-induced changes in sediment texture. Samples were collected along the main channel using a grab sampler, with the upper 1–2 cm of the approximately 20 cm surface layer retained for grain-size analysis. Sampling intervals were 1 km from CMZT to LDG, about 5 km from LDG to STG with 5 samples per section, and about 5 km from STG to LXG with 8–10 samples per section due to channel widening. A total of 109 sediment samples were collected in each survey month (Figure 1(C)). Mean grain size in phi units, sorting, skewness and kurtosis were calculated using the Folk–Ward method (Folk & Ward, 1957).

### 2.2.2. Delft3D model configuration and scenario design

A process-based Delft3D model was used to quantify the 2020 flood impacts on North Branch hydrodynamics and sediment transport, adapting the Changjiang Estuary framework of Chu (2019). The domain extends from Datong, the wet-season tidal limit, to the East China Sea, including the estuary, Hangzhou Bay and major distributaries, with discharge and suspended-sediment concentration (SSC) prescribed at Datong and Qiantang

River input prescribed at Lucipu (Figure 1(B)). Datong was selected because it is free from tidal influence and has long-term measured discharge and SSC records. The decomposed grid includes a riverine section from Datong to Xuliujing ( $\sim 500$  km,  $1056 \times 30$  points, 100 m–1.5 km resolution), an estuarine section from Xuliujing to the open sea ( $\sim 300 \times 300$  km,  $200 \times 200$  curvilinear points, 200 m–6 km resolution), and a Hangzhou Bay–Qiantang subdomain from Lucipu to Haining. All domains use boundary-fitted orthogonal curvilinear grids.

Three-dimensional simulations employed 12 sigma layers, accounting for 3, 5, 8, 10, 12, 12, 12, 10, 8, 5 and 3% of the total water depth from surface to bed, with  $k$ - $\epsilon$  turbulence closure. Initial hydrodynamic, salinity and sediment fields were taken from restart files generated by the calibrated model configuration, and the model ran for a 15-day warm-up period before diagnostic outputs were analysed. Bathymetry from navigation charts and surveys was interpolated to the model grid, smoothed to reduce small-scale artefacts, and unified with water-level data to the HH85 vertical datum.

Hydrodynamics were forced by discharge boundaries at Datong and Lucipu and by seven principal tidal constituents ( $M_2$ ,  $S_2$ ,  $N_2$ ,  $K_2$ ,  $K_1$ ,  $O_1$  and  $P_1$ ) along eight open-sea boundary sections. Datong discharge was imposed across 23 transverse boundary points, whereas Lucipu discharge was imposed across four boundary points. The computational time step was 1.5 min, and wetting and drying were controlled using a threshold depth of 0.1 m. The initial open-sea tidal constants were derived from the China Sea Model and calibrated against observed tidal constituents. Open-sea salinity was prescribed from long-term mean values, river inflows were treated as freshwater, and transport-boundary concentrations were prescribed uniformly at both ends of each boundary section.

Sediment transport included three fractions, fine cohesive sediment, coarse silt and fine sand. Fine cohesive SSC was prescribed as  $0.5 \text{ kg m}^{-3}$  at Datong,  $0.225 \text{ kg m}^{-3}$  at Lucipu and  $0.02 \text{ kg m}^{-3}$  at the open-sea boundary, while coarse silt and fine sand boundary concentrations were set to zero or treated using equilibrium boundary conditions. Following the calibrated configuration of Chu (2019), Manning's roughness coefficient was set to  $0.011 \text{ s m}^{-1/3}$  in the estuarine domain and  $0.019 \text{ s m}^{-1/3}$  in the riverine domain. The horizontal eddy viscosity and diffusivity were set to 2 and  $1 \text{ m}^2 \text{ s}^{-1}$ , respectively (Chu, 2019; Zhao et al., 2023). For cohesive sediment, the flocculation-related settling velocity was set to  $0.25 \text{ mm s}^{-1}$ , and the specific and dry-bed densities were set to 2650 and  $800 \text{ kg m}^{-3}$ , respectively (Chu, 2019; Luan et al., 2017; Zhang et al., 2018).

**Table 1.** Factorial Delft3D scenario design.

| Scenario | River forcing                   | Bathymetry in DXR     | Interpretation                     |
|----------|---------------------------------|-----------------------|------------------------------------|
| S1       | Multi-year mean runoff          | 2002 pre-incision bed | Baseline condition                 |
| S2       | Multi-year mean runoff          | 2020 incised bed      | Bathymetry-related response        |
| S3       | 2020 extreme basin flood runoff | 2002 pre-incision bed | Flood response                     |
| S4       | 2020 extreme basin flood runoff | 2020 incised bed      | Coupled flood-bathymetry responses |

Model performance was evaluated against available hydrodynamic and sediment-related observations in the Changjiang Estuary and the North Branch, including water levels, tidal ranges, current velocities and water-sediment partitioning patterns (Figures S2–S6). Across six water-level stations, the model achieved an overall RMSE of 0.386 m, MAE of 0.299 m,  $r$  of 0.932 and Skill Score of 0.962 (Figures S2 and S3). Tidal-constituent validation at four North Branch stations also showed good agreement, with an amplitude RMSE of 0.015 m, MAE of 0.011 m, and phase MAE and RMSE of 2.99° and 3.68°, respectively (Figures S4 and S5). Because synchronous SSC-profile observations were unavailable within the North Branch during the 2020 flood, sediment reliability was assessed using estuary-scale water-sediment partitioning and SSC-related validation evidence (Figure S6), together with previously validated Changjiang Estuary sediment-transport settings. Although these SSC validation stations are outside the North Branch, they cover the main outlet channels and mouth-bar region, where salinity gradients, tidal pumping and fine-sediment trapping are strongest, and therefore provide a relevant test of the sediment module's ability to reproduce regional SSC structure and sediment-transport tendency. These results support the model's use for diagnosing mechanism-level responses and relative scenario differences, rather than exact point-by-point SSC reconstruction in the North Branch.

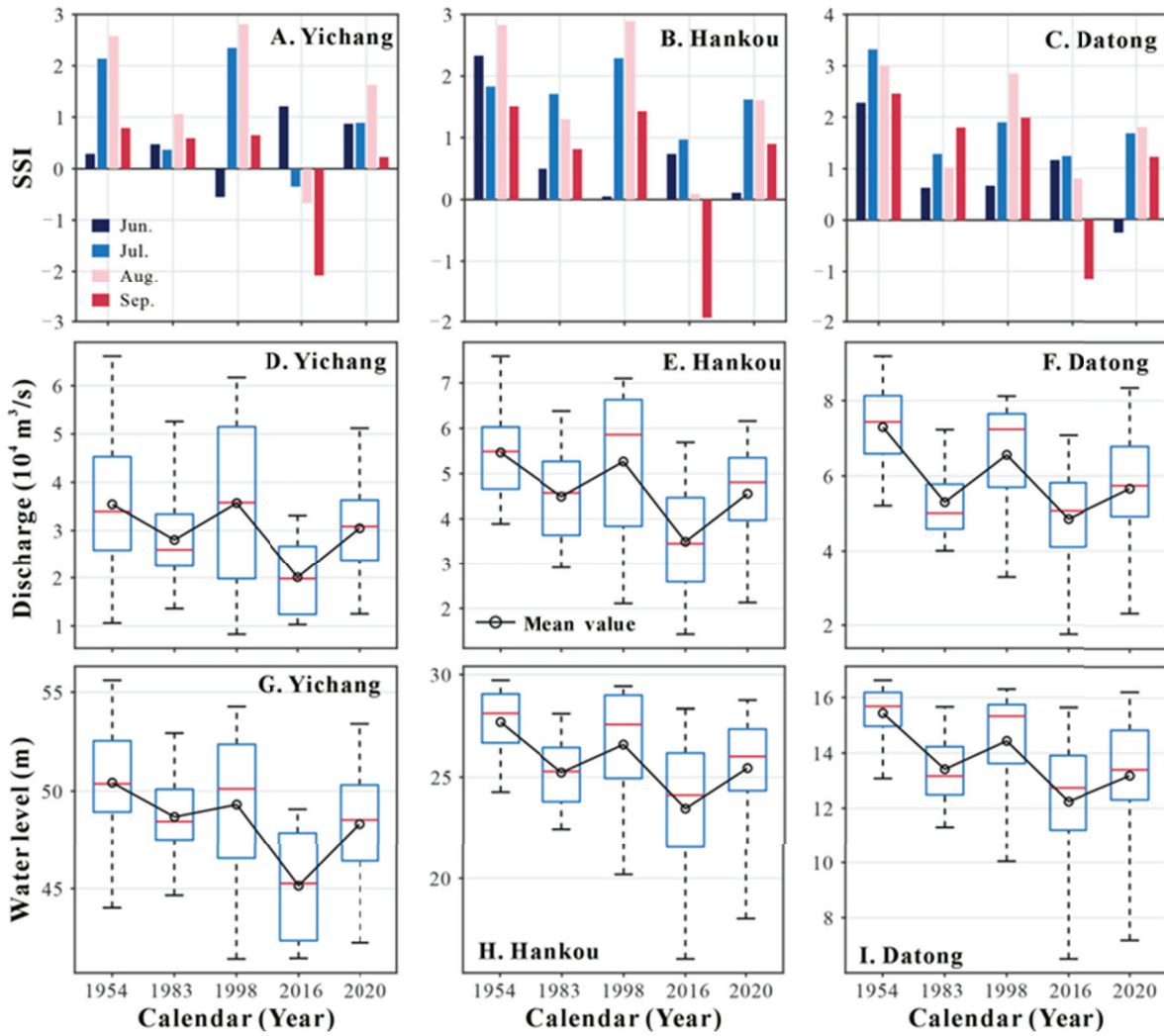
Four scenario experiments compared the relative roles of the 2020 flood hydrograph and long-term bathymetric change in the Datong-Xuliujing Reach (DXR) (Table 1). The 2002 and 2020 bathymetries were paired with mean runoff ( $30,000 \text{ m}^3 \text{ s}^{-1}$ ) and the 2020 flood hydrograph, with a peak discharge of  $83,400 \text{ m}^3 \text{ s}^{-1}$ . S1 represents the pre-incision bathymetry under mean runoff, S2 the 2020 bathymetry under mean runoff, S3 the 2002 bathymetry under flood forcing, and S4 the modern coupled condition with 2020 bathymetry and flood forcing. Analyses focused on flood, ebb and total diversion ratios, mean tidal range, peak currents and residual sediment transport, with positive values indicating landward transport. The model is therefore interpreted as a process-based tool for comparing scenario responses, rather than as a direct predictor of absolute bed-evolution magnitude or a fully closed event-scale sediment budget.

### 3. Results

#### 3.1. Hydrological characteristics of the 2020 extreme flood

Monthly standardized streamflow index SSI values were calculated for Yichang, Hankou and Datong using monthly mean discharge records from the 1950s to 2020. Together with historical flood-stage records, the extreme floods in 1954, 1983, 1998 and 2016 were selected as benchmarks and compared with the 2020 flood events (Figure 2). The SSI results show that the 2020 flood represented one of the strongest basin-scale discharge anomalies since the 1950s (Figure 2(A–C)). Its mean SSI was lower only than those of the 1954 and 1998 extreme floods, indicating that the 2020 event was exceptionally rare under the present hydrological regime shaped by large reservoirs and dams. The anomaly strengthened downstream, with higher SSI values at Datong than at Hankou and Yichang. In 2020, positive SSI values persisted from July to September at all three stations, and the August SSI reached approximately 1.6 at Yichang, 1.6 at Hankou and 1.8 at Datong. Consistently, the mean monthly discharge during the 2020 flood increased downstream from about  $3.0 \times 10^4 \text{ m}^3 \text{ s}^{-1}$  at Yichang to  $4.6 \times 10^4 \text{ m}^3 \text{ s}^{-1}$  at Hankou and  $5.7 \times 10^4 \text{ m}^3 \text{ s}^{-1}$  at Datong, with corresponding mean flood water levels of approximately 48.4, 25.6 and 13.2 m, respectively (Figure 2(D–I)). These values confirm that the 2020 flood was a rare extreme event in the Changjiang River basin and provide a clear hydrological context for the subsequent morphodynamic response of the North Branch.

The 2020 flood hydrographs showed distinct upstream-downstream differences among the three key control stations, Yichang, Hankou and Datong (Figure 3(A–C)). A compound flood peak occurred at the Yichang hydrological station (Figure 3(A)), and the peak discharge reached  $83,400 \text{ m}^3 \text{ s}^{-1}$  on 13 July at Datong (Figure 3(C)). In contrast, the discharge at Hankou was  $55,800 \text{ m}^3 \text{ s}^{-1}$  when the peak water level occurred. The annual maximum discharge of  $61,600 \text{ m}^3 \text{ s}^{-1}$  was not reached until 28 July (Figure 3(B)). Moreover, all three stations entered a sustained rising stage from June. At Yichang, the water level rose rapidly then declined sharply in early July, without a peak water level in mid-July (Figure 3(A)). By contrast, Hankou and Datong continued to rise and reached their peak water levels on

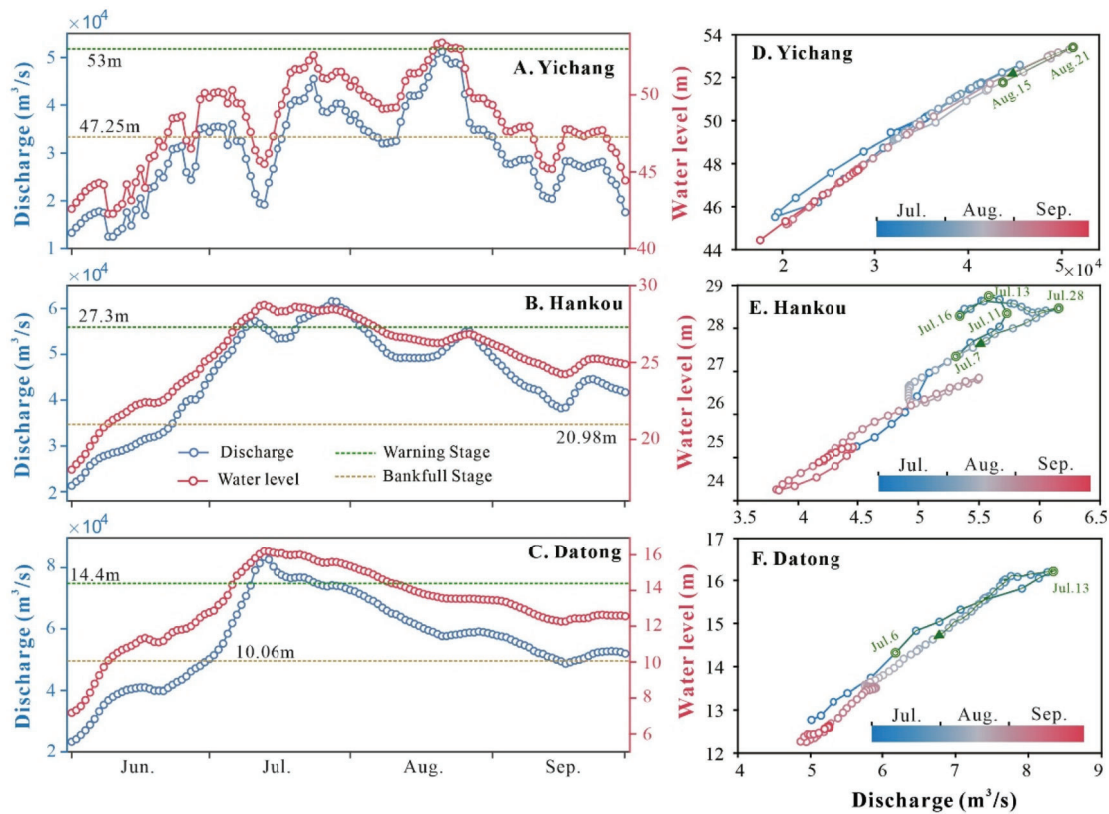


**Figure 2.** Comparison of hydrological characteristics of historical extreme floods (1954, 1983, 1998 and 2016) and recent extreme floods in 2020. (A–C) Standardized streamflow index (SSI); (D–F) boxplots and mean discharge; (G–I) boxplots and mean water level.

13 July, with values of 28.75 and 16.21 m, respectively, exceeding their corresponding warning levels of 27.3 and 14.4 m (Figure 3(B, C)). During the rising stage, the total water-level rise reached 10.72 m at Hankou and 9.03 m at Datong, with mean daily rises of 0.25 and 0.21 m d<sup>-1</sup>, respectively (Table 2). At Yichang, the rising stage lasted 82 days, markedly longer than in the other flood events. The falling stage at Hankou and Datong lasted 79 days, with total water-level drops of 3.86 and 3.65 m, respectively. At Datong, the rising- and falling-stage water-level gradients were  $1.50 \times 10^{-4}$  and  $1.16 \times 10^{-4}$  m per m<sup>3</sup> s<sup>-1</sup>, respectively, indicating a slower water-level response during recession than during the rising stage. Overall, the 2020 flood was characterized by a high flood peak, long duration, rapid water-level rise and relatively slow recession.

The stage-discharge relationships further revealed different flood responses along the middle and lower Changjiang River (Figure 3(D–F)). At Yichang, the 2020

stage-discharge relationship was close to a single-valued linear curve, although the water level at a given discharge increased by up to approximately 0.24 m after the main flood peak in late August (Figure 3(D)). At Hankou, repeated rising and falling stages produced a complex hysteresis pattern (Figure 3(E)). During the early to mid-July flood period, the stage-discharge trajectory formed a counterclockwise loop, with the flood-peak water level lagging behind the discharge peak. The maximum water-level increase at the same discharge was approximately 0.87 m. During the 16–28 July flood-peak period, discharge increased by 8,200 m<sup>3</sup> s<sup>-1</sup>, whereas the water level rose only slightly from 28.28 to 28.47 m. At Datong, the stage-discharge relationship also developed a clear counterclockwise hysteresis loop in mid-July (Figure 3(F)). The water level at the same discharge increased before and after the flood peak, with a maximum increase of approximately 0.37 m. These results indicate that, after the passage of the 2020 main flood peak, all three stations



**Figure 3.** Daily discharge and water-level variations (A–C) and stage-discharge relationships (D–F) at Yichang, Hankou and Datong stations during the June–September 2020 flood.

**Table 2.** Rising- and falling-stage water-level characteristics at Yichang, Hankou and Datong stations during the 2020 extreme flood.

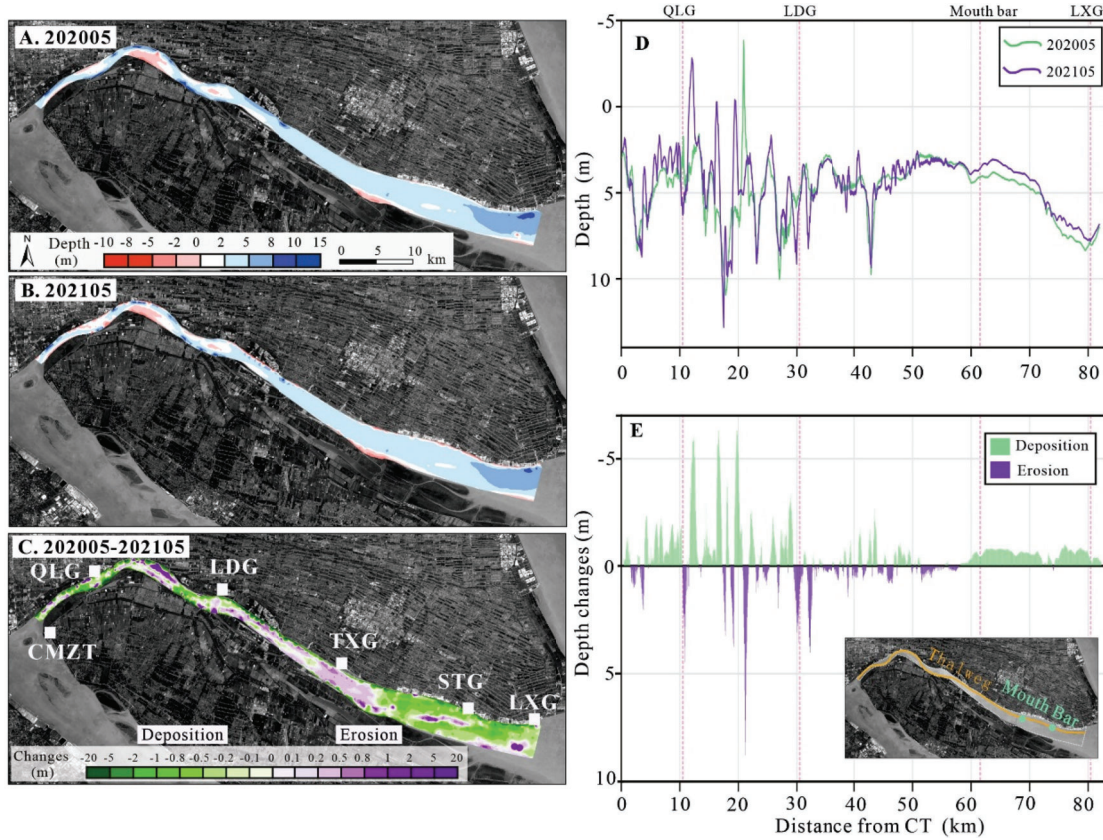
| Stations | Peak water level (m)    | Water-level rise (m) | Duration of water-level rise (d) | Mean daily water-level rise ( $\text{md}^{-1}$ ) | Rising-stage water-level gradient ( $\times 10^{-4} \text{m/m}^3 \text{s}^{-1}$ )  |
|----------|-------------------------|----------------------|----------------------------------|--------------------------------------------------|------------------------------------------------------------------------------------|
| Yichang  | 53.41                   | 11.15                | 82                               | 0.14                                             | 2.85                                                                               |
| Hankou   | 28.75                   | 10.72                | 43                               | 0.25                                             | 3.11                                                                               |
| Datong   | 16.21                   | 9.03                 | 43                               | 0.21                                             | 1.50                                                                               |
| Stations | Sep. 30 water level (m) | Water-level drop (m) | Duration of water-level drop (d) | Mean daily water-level drop ( $\text{md}^{-1}$ ) | Falling-stage water-level gradient ( $\times 10^{-4} \text{m/m}^3 \text{s}^{-1}$ ) |
| Yichang  | 44.44                   | 8.97                 | 40                               | 0.22                                             | 2.67                                                                               |
| Hankou   | 24.89                   | 3.86                 | 79                               | 0.05                                             | 2.74                                                                               |
| Datong   | 12.56                   | 3.65                 | 79                               | 0.05                                             | 1.16                                                                               |

showed higher water levels under comparable discharge conditions.

### 3.2. Observed morphological responses of the North Branch

Over the annual comparison period (May 2020–May 2021), the North Branch showed net shoaling with spatially heterogeneous erosion and deposition, rather than system-wide erosion (Figure 4(A, B)). The mean water depth decreased from 3.35 m to 2.91 m over the annual comparison period, indicating net shoaling at the branch scale. The erosion-deposition pattern indicates that

deposition dominated the upper reach (CMZT-QLG), with thicknesses commonly exceeding 1 m, whereas scattered erosion patches occurred locally (Figure 4(C)). Around the bend apex in the middle reach (QLG-LDG), marked erosion occurred in the main channel, followed by deposition near LDG. In the straight middle reach (LDG-TXG), the main channel was weakly erosional, generally by less than 0.5 m. The lower reach (TXG-LXG) experienced widespread deposition, mostly greater than 0.5 m, whereas the mouth bar was erosional and shifted seaward. Overall, the flood-induced adjustment was not expressed as a simple landward-to-seaward gradient, but



**Figure 4.** Water-depth changes (A–C) and thalweg-depth variations (D, E) in the North Branch between May 2020 and May 2021 (Data were provided by the Changjiang Waterway Bureau).

**Table 3.** Channel volumes within different depth ranges of the North Branch in May 2020 and 2021.

| Depth range (m)                  | > 0                | 0–2                | 2–5                | 5–8                | 8–10               | > 10               |
|----------------------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| 202005 Volumes (m <sup>3</sup> ) | $6.56 \times 10^8$ | $3.36 \times 10^8$ | $2.64 \times 10^8$ | $5.31 \times 10^7$ | $2.93 \times 10^6$ | $2.81 \times 10^5$ |
| 202105 Volumes (m <sup>3</sup> ) | $5.96 \times 10^8$ | $3.25 \times 10^8$ | $2.33 \times 10^8$ | $3.74 \times 10^7$ | $1.39 \times 10^6$ | $2.04 \times 10^5$ |

as reach-scale sediment redistribution between adjacent erosion and deposition cells.

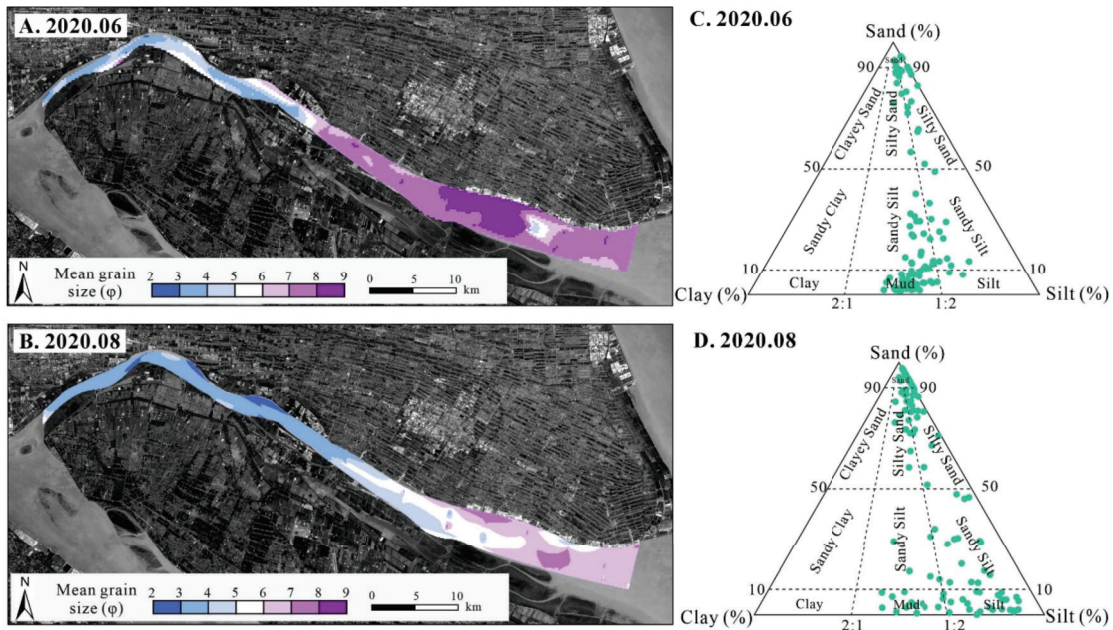
Thalweg and channel-volume changes further confirmed net infilling of the North Branch over the annual comparison period. The mean thalweg depth decreased by 0.37 m, with shoaling of 0.62 m in the upper reach, 1.17 m around the middle-reach bend apex, 0.31 m in the straight middle channel and 0.37 m in the lower reach (Figure 4(D, E)). Over the same period, the channel volume within the 0 m depth contour decreased from  $6.56 \times 10^8$  to  $5.96 \times 10^8$  m<sup>3</sup>, giving a total reduction of  $0.60 \times 10^8$  m<sup>3</sup> (Table 3). The 2–5 m and 5–8 m depth intervals accounted for most of this reduction, decreasing by  $0.31 \times 10^8$  and  $0.16 \times 10^8$  m<sup>3</sup>, respectively. Together, these two intervals contributed 78.4% of the total volume loss, whereas the deepest channel changed only slightly and the 0–2 m interval increased slightly. Thus, net infilling mainly occurred through adjustment of shallow to

intermediate-depth channels, rather than through uniform bed aggradation or wholesale migration of the deep channel.

### 3.3. Hydro-Sediment dynamic changes

#### 3.3.1. Sediment variations

Before the extreme basin flood (June 2020), bed sediment generally became finer downstream in the North Branch. Mean grain size in the upper and curved middle reaches was mostly 3–5  $\phi$  (Figure 5(A)), whereas the lower straight reach commonly exceeded 7  $\phi$  and contained abundant silt and clay. The Folk ternary classification further showed that samples from the upper and middle reaches were mainly classified as sand, silty sand and sandy silt, whereas those from the lower reach clustered in the silt and mud-dominated fields (Figure 5(C)). Across the branch in June, sand, silt and clay accounted for 31.38%, 41.48% and 27.14% (Table 4), respectively.



**Figure 5.** Spatial distribution (A, B) and textural variation (C, D) of surficial sediments before (June) and after (August) the 2020 flood.

**Table 4.** Comparison of sediment grain-size characteristics and composition in different reaches of the North Branch in June and August 2020.

| Time   | Section | Mean grain size( $\phi$ ) | Sorting coefficient | Skewness | Kurtosis | Clay (%) | Silt (%) | Sand (%) |
|--------|---------|---------------------------|---------------------|----------|----------|----------|----------|----------|
| June   | Upper   | 4.55                      | 2.00                | 0.30     | 1.80     | 13.23    | 30.94    | 55.83    |
|        | Middle  | 4.98                      | 2.03                | 0.37     | 1.55     | 16.20    | 31.54    | 52.26    |
|        | Lower   | 7.53                      | 2.88                | 0.28     | 0.90     | 37.02    | 50.03    | 12.95    |
|        | Total   | 6.31                      | 2.49                | 0.31     | 1.23     | 27.14    | 41.48    | 31.38    |
| August | Upper   | 3.94                      | 1.51                | 0.46     | 2.49     | 8.83     | 18.65    | 72.52    |
|        | Middle  | 3.59                      | 1.21                | 0.37     | 1.87     | 4.70     | 18.01    | 77.30    |
|        | Lower   | 6.21                      | 2.07                | 0.20     | 1.05     | 20.69    | 55.76    | 23.55    |
|        | Total   | 5.06                      | 1.71                | 0.29     | 1.49     | 13.85    | 38.64    | 47.51    |

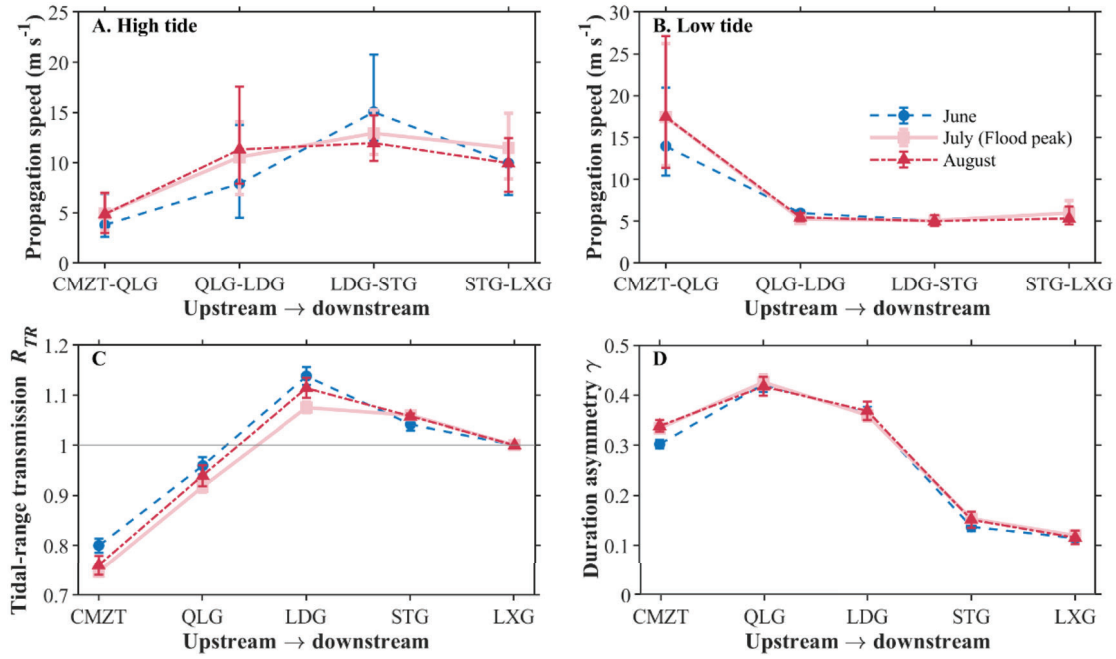
After the flood (August 2020), the bed sediment coarsened and became better sorted. Branch-mean grain size decreased from 6.31 to 5.06  $\phi$  (Figure 5(B)), sorting improved from 2.49 to 1.71, and sand content increased from 31.38% to 47.51%. The upper and middle reaches showed the strongest response, with the August mean sizes being 3.94 and 3.59  $\phi$ . Sand contents reached 72.52% and 77.30%, and many samples shifted towards the sand-rich field in the Folk ternary diagram (Figure 5(D)). The lower reach also coarsened, but silt plus clay still accounted for 76.45%, consistent with continued deposition under comparatively weak lower-reach bed stress. From June to August, mean size coarsened by 0.61  $\phi$  in the upper reach, 1.39  $\phi$  in the middle reach and 1.32  $\phi$  in the lower reach (Table 4), while sorting improved by 0.49, 0.82 and 0.81, respectively. The increase in sand fraction was greatest in the middle reach, from 52.26% to 77.30%, whereas the lower reach remained mud-dominated despite measurable coarsening. The textural response therefore records both selective removal of fines from energetic reaches and retention of fine sediment in

the lower depositional zone, coarsening and improved sorting are consistent with selective removal of fines in energetic reaches and continued retention of fine material downstream.

### 3.3.2. Hydrodynamic changes

The hydrodynamic analysis from June to August 2020 indicates that tidal propagation in the North Branch changed spatially during the 2020 flood (Figure 6(A, B)). For high water, the median propagation speed over the LDG-STG segment decreased from 15.06 m s<sup>-1</sup> in June to 11.94 m s<sup>-1</sup> in August, whereas that over the QLG-LDG segment increased from 7.92 to 11.31 m s<sup>-1</sup>. For low water, propagation speed remained relatively stable at approximately 5–6 m s<sup>-1</sup> over the three downstream segments, but increased over the CMZT-QLG reach from 13.98 m s<sup>-1</sup> in June to 17.47 m s<sup>-1</sup> in July and August.

To compare tidal-range transmission along the North Branch, the tidal-range transmission ratio at station  $i$ ,  $R_{TR,i}$ , was defined as the daily tidal range at that station normalized by the corresponding tidal range at



**Figure 6.** Monthly tidal propagation (A-B), tidal-range transmission (C) and duration asymmetry (D) variability in the North Branch during the 2020 flood.

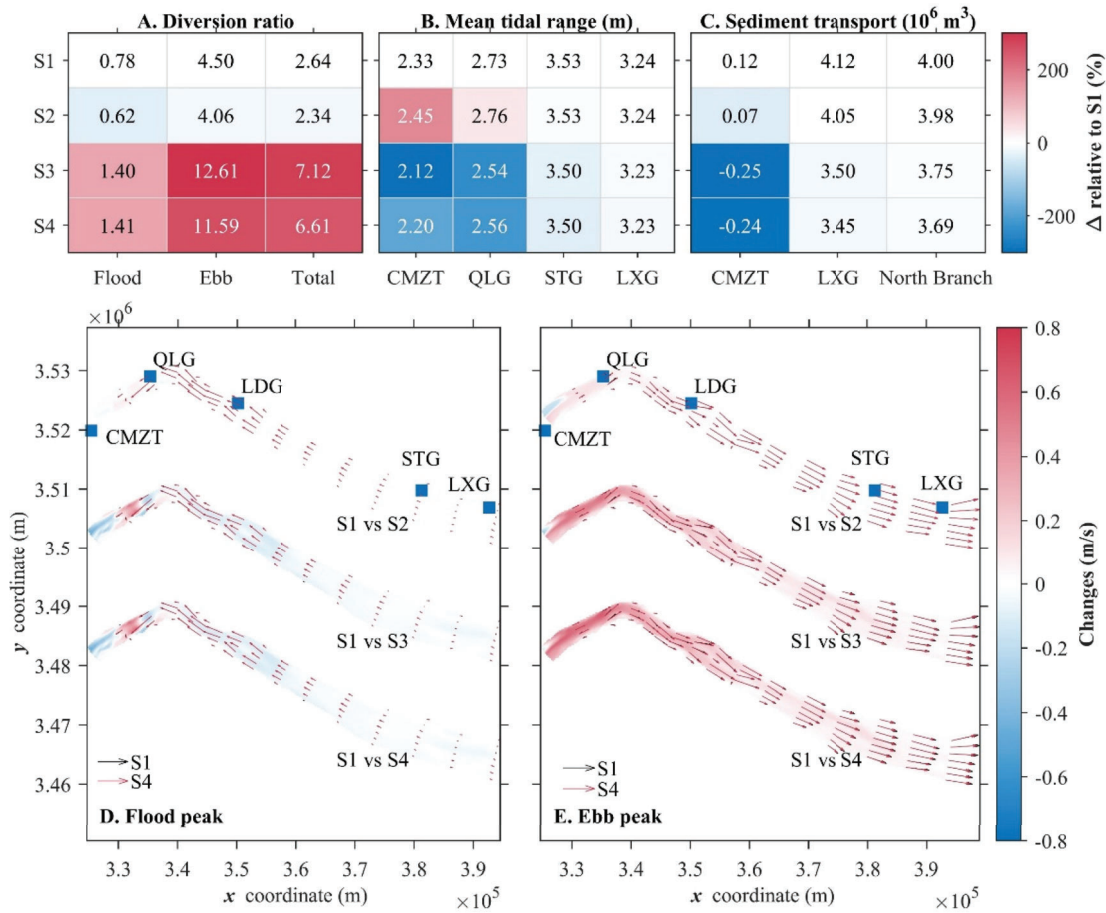
LXG,  $R_{TR,i} = TR_i/TR_{LXG}$ . During the July flood peak,  $R_{TR}$  increased from 1.000 at LXG to 1.075 at LDG, but then decreased landward to 0.917 at QLG and 0.747 at CMZT (Figure 6(C)). Moreover, duration asymmetry,  $\gamma$ , was defined as the relative difference between ebb and flood durations,  $\gamma = (T_{ebb} - T_{flood}) / (T_{ebb} + T_{flood})$ , where positive values indicate a longer ebb duration than flood duration. Duration asymmetry remained positive throughout the branch, increasing from approximately 0.12 at LXG to 0.42 at QLG, before declining slightly at CMZT (Figure 6(D)), these shifts imply that the flood modified tidal propagation and ebb-dominant drainage differently across reaches.

### 3.4. Scenario-based attribution of incision, flooding, and interaction

The morphodynamic response during the 2020 extreme flood in the North Branch occurred under both extreme basin flooding and mid-lower Changjiang channel incision, yet field observations alone could not distinguish flood forcing from antecedent bed adjustment. We therefore designed four numerical scenarios to compare the relative contributions of flood forcing, antecedent bathymetric adjustment and their coupled response (Figure 7 and Table 5). Simulated results indicate that bathymetry-related adjustment alone produced a limited but non-negligible hydrodynamic response. Compared with S1, S2 reduced the flood, ebb and total diversion ratios by

20.7%, 9.6% and 11.3% (Figure 7(A)), respectively, indicating that the incised-bed condition did not increase branch-scale diversion under mean runoff. Mean tidal range increased only slightly by 1.19% (0.035 m; Figure 7(B)), peak flood current changed by 0.49%, peak ebb current increased by 6.23%, and residual sediment transport changed by only  $-0.37\%$  (Figure 7(C-E)). Given the absence of a formal parameter-uncertainty analysis, these small changes are interpreted cautiously as secondary modelled tendencies rather than primary mechanistic evidence.

In contrast, the flood-only scenario produced much larger responses. Relative to S1, S3 raised flood, ebb and total diversion ratios by 79.1%, 180.4% and 170.0% (Table 5), with peak ebb current up 37.03% and mean tidal range down 3.75% (0.111 m). Branch-scale sediment transport fell 6.16%, with sediment transport shifted seaward at CMZT but remaining landward near LXG, indicating a local reversal in the upper branch without altering net landward import. Under coupled flood-incision conditions, S4 showed only modest additional changes relative to S3, including flood diversion of +1.0%, ebb and total diversion of  $-8.1\%$  and  $-7.1\%$ , tidal range of +0.80%, peak ebb current of +4.75%, and sediment transport of  $-1.55\%$ . Under extreme floods, the mid-lower Changjiang channel incision may act as a secondary modulator, enhancing tidal propagation while constraining branch-scale diversion and residual sediment export.



**Figure 7.** Hydrodynamic and sediment-transport responses under four numerical scenarios. (A) Diversion ratios; (B) Mean tidal range; (C) Sediment transport; (D, E) Spatial changes in peak flood and ebb currents relative to S1. Positive sediment transport denotes landward transport.

**Table 5.** Relative changes in hydrodynamic and sediment-transport indicators among the numerical scenarios (units: %).

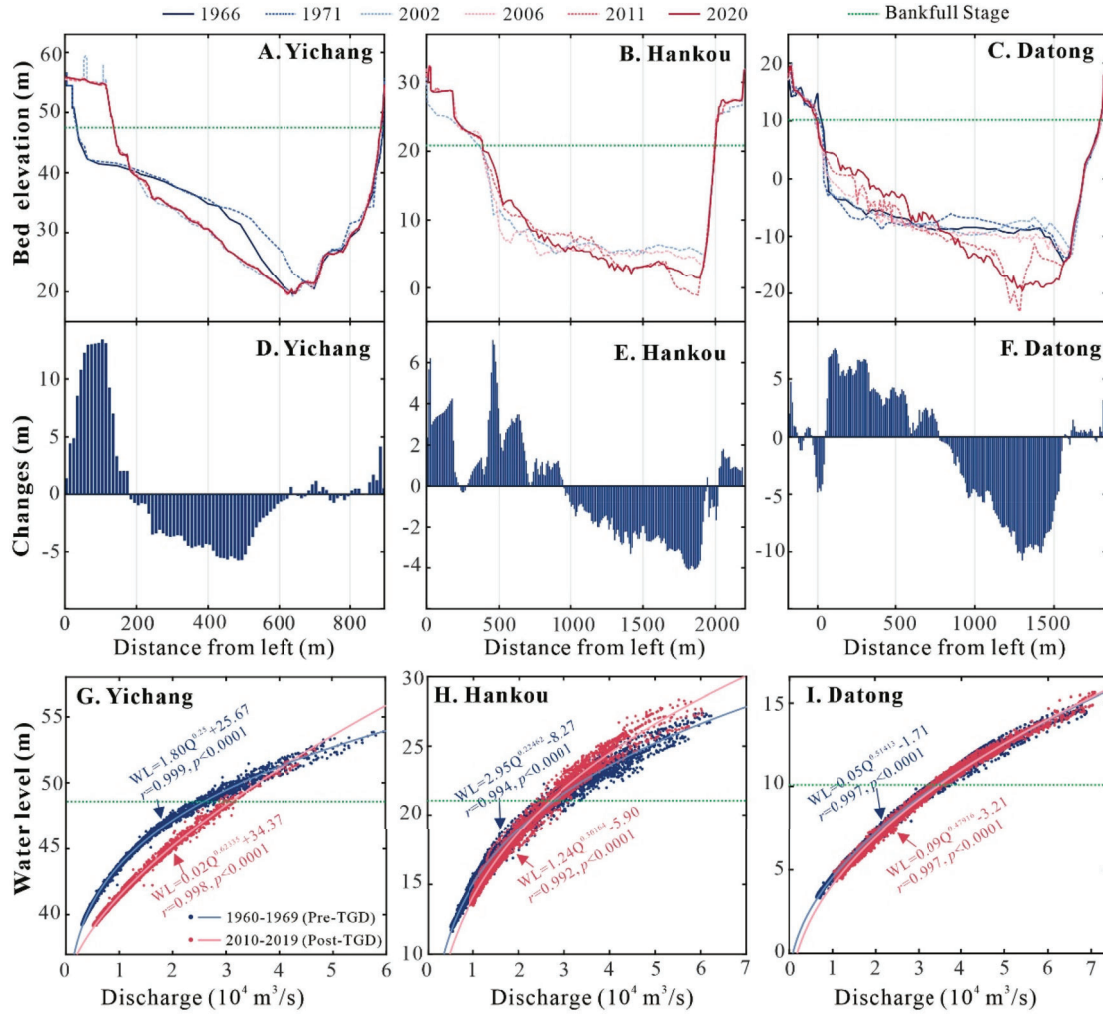
| Scenario | Interpretation                              | Diversion ratio |        |        | Mean tidal range | Tidal current |          | Sediment transport |
|----------|---------------------------------------------|-----------------|--------|--------|------------------|---------------|----------|--------------------|
|          |                                             | Flood           | Ebb    | Total  |                  | Flood peak    | Ebb peak |                    |
| S2 vs S1 | Bathymetry-related response                 | -20.7           | -9.6   | -11.3  | +1.19            | +0.49         | +6.23    | -0.37              |
| S3 vs S1 | Flood response                              | +79.1           | +180.4 | +170.0 | -3.75            | -4.80         | +37.03   | -6.16              |
| S4 vs S1 | Coupled flood + bathymetry-related response | +80.9           | +157.8 | +150.7 | -2.98            | -4.28         | +43.63   | -7.61              |
| S4 vs S3 | Bathymetry modulation under extreme flood   | +1.0            | -8.1   | -7.1   | +0.80            | +0.13         | +4.75    | -1.55              |

## 4. Discussion

### 4.1. Impacts of the Three Gorges Dam and downstream geomorphic adjustment on flood response

The response of the North Branch to the 2020 flood is best understood in the context of a sediment-starved system whose flood wave had already been modified by basin regulation (Besset et al., 2019; East et al., 2015; Edmonds et al., 2023; Wang et al., 2025). Since the impoundment of the Three Gorges Dam, downstream sediment supply in the middle and lower Changjiang has declined markedly, limiting the amount of fluvial

sediment available for estuarine export during extreme floods (Chen et al., 2010; Dai et al., 2014, 2018; Tang et al., 2023). During the 2020 event, reservoir operation further reshaped the flood wave (Figure 3(A–C)). Routine TGD operation in early July had only a limited influence, whereas stronger mid-July impoundment attenuated the main flood peak and reduced downstream water levels at Yichang, Hankou, and Datong (Table S1 in the Supplementary Material). Subsequent late-July releases lowered reservoir levels for operational safety but likely helped prolong elevated downstream water levels because they occurred on an already high hydraulic background (Table S2 in the Supplementary Material). This combination



**Figure 8.** Changes in cross-sectional morphology (A–F) and stage-discharge relationships (G–I) at Yichang, Hankou and Datong stations from the 1960s to 2020. Panels (D–F) present deposition thickness at 5 m intervals and green dashed lines indicate the bankfull stage. Note that panel I is modified from Tang et al., 2023.

of long-term sediment depletion and event-scale flood-wave regulation suggests that the 2020 flood was more likely to enhance local resuspension and sediment redistribution within the estuary than to generate sustained system-wide seaward export.

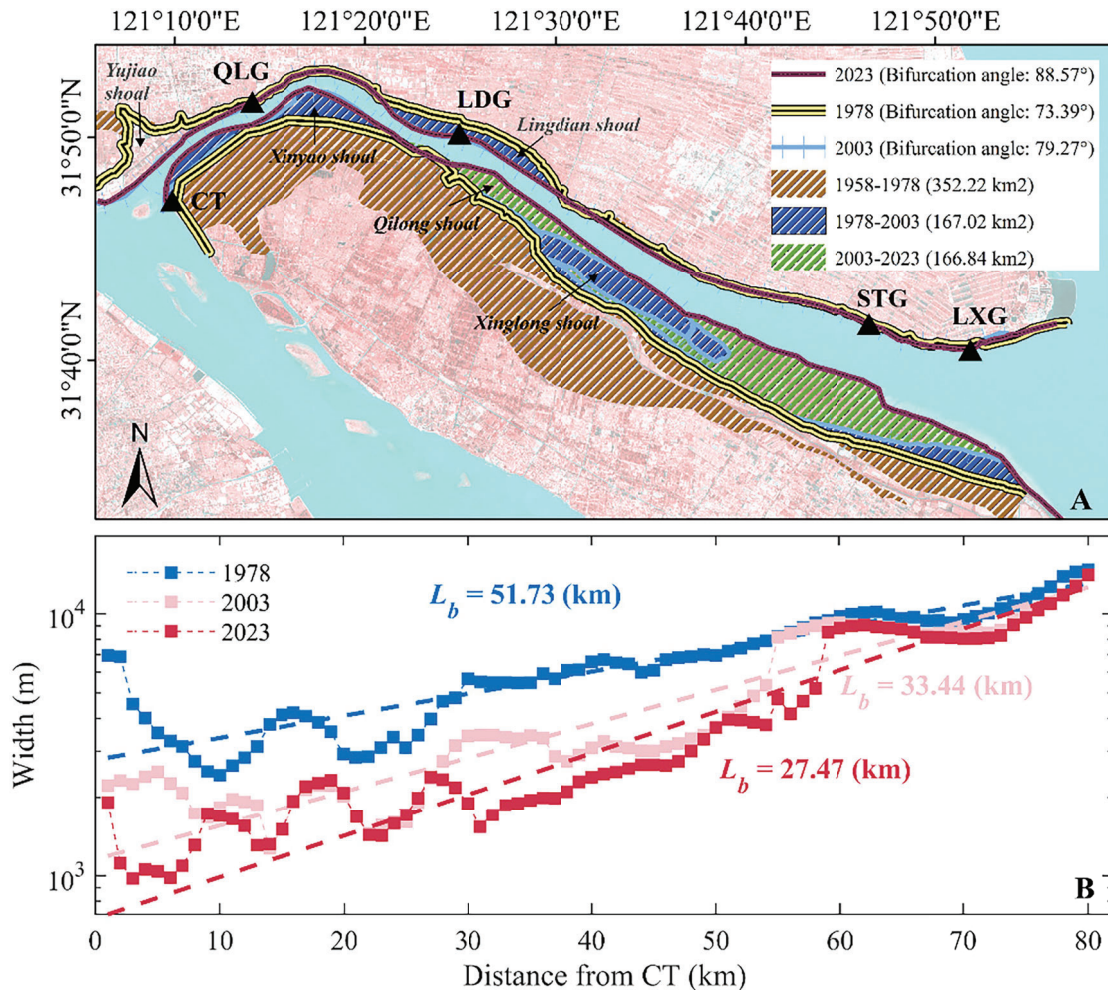
This interpretation is consistent with the downstream hydraulic adjustments shown in Figure 8. Beyond direct sediment trapping by the Three Gorges Dam (TGD), widespread bank protection, reclamation, and lake regulation have further curtailed floodplain and lake storage across the Middle and Lower Changjiang. Post-dam channel (after 2011) adjustments include left-bank advancement ( $\sim 90 \text{ m}$ ) and deposition (8.15 m) juxtaposed with mid-channel scour (3.33 m) at Yichang, alongside thalweg incision and marginal deposition at Hankou and Datong (Figure 8(A–F)). Rating-curve analysis confirms a nonlinear hydraulic shift post-TGD

(2010–2019 vs. 1960–1969) enhanced low-stage conveyance contrasts with elevated high-stage water levels, peaking at Hankou (+1.62 m overall; +1.64 m peak) and Datong (+0.08 m; +0.11 m), whereas Yichang exhibits stage-dependent effects ( $-0.69 \text{ m}$  below,  $+0.40 \text{ m}$  above warning stage) (Figure 8(G–I)). Channel deepening thus yields no uniform flood-stage reduction its impact hinges on the trade-off between improved low-flow conveyance and constrained high-flow capacity from narrowing and roughness (Chai et al., 2021; Hu et al., 2022). These adjustments may have changed conveyance, flood-wave transmission, and water-level sensitivity in ways that preconditioned the estuarine response to the 2020 event. In this sense, the North Branch response reflects not only extreme discharge itself, but also the legacy of long-term channel adjustment and regulation in the upstream basin.

#### 4.2. Effects of land reclamation

Land reclamation is a primary long-term boundary condition in estuaries, narrowing channels and removing intertidal storage to modify convergence and tidal dynamics (Beemster et al., 2026; Schrijvershof et al., 2024; van Maren et al., 2025). In macro-tidal funnel-shaped systems, such modifications amplify currents and alter flood-ebb asymmetry, shifting sediment dynamics from export towards trapping (Cheng et al., 2020; de Vriend et al., 2011; Teng et al., 2021). The North Branch has experienced persistent reclamation over recent decades, which progressively reshaped its floodplain and channel convergence (Figure 9). The reclaimed area reached 352.22 km<sup>2</sup> during 1958–1978, followed by 167.02 km<sup>2</sup> during 1978–2003 and 166.84 km<sup>2</sup> during 2003–2023 (Figure 9(A)). This reclamation mainly occupied shoals and marginal tidal flats, including the Xinyao, Qilong, Xinglong and Lingdian shoal systems. As a result, the bifurcation angle increased from 73.39° in 1978–79.27° in 2003 and 88.57° in 2023, indicating a progressively

sharper entrance geometry at the upstream bifurcation. Meanwhile, the width-convergence length  $L_b$  decreased from 51.73 km in 1978–33.44 km in 2003 and 27.47 km in 2023 (Figure 9(B)). These changes indicate that reclamation shortened the convergence length and made the North Branch more laterally confined. Under sediment-starved conditions, this confinement promotes landward sediment pumping (Dai et al., 2016). During the 2020 flood, the fixed geometry constrained discharge-tide interactions. Despite boosted ebb diversion, persistent tidal import near LXG maintained net landward transport and a bidirectional regime. Post-flood morphology confirmed reach-dependent erosion-deposition cells rather than systemic reorganization, with volume loss concentrated in 2–8 m depth bins (Figure 4). Reclamation thus acts as a critical boundary condition that limits lateral accommodation, which helps explain why enhanced ebb forcing did not translate into system-wide export.



**Figure 9.** Land reclamation (A) and changes in channel convergence of the North Branch (B).

### 4.3. Basin flood-induced morphodynamic adjustment

Extreme basin floods drive channel erosion via elevated stream power and sediment transport capacity, a response well documented in natural and regulated rivers (Dai et al., 2018; Rinaldi et al., 2016; Rinaldi et al., 2016). In the Middle and Lower Changjiang, flood-season flows typically induce scour, with exceptional events like 2020 triggering substantial adjustment (Chen et al., 2010; Croke et al., 2013; Lai et al., 2017). Flood geomorphic efficacy, however, depends on discharge magnitude, sediment availability, antecedent morphology, duration, recession rates, and the tide-to-river dominance balance. In the sediment-starved, incised, and reclamation-narrowed North Branch, these factors preconditioned the hydraulic boundary before 2020. Model scenarios thus disentangle three coupled mechanisms governing system dynamics, including incision-driven tidal amplification, flood-peak modulation via enhanced channel storage, and sediment-limited morphological adjustment.

#### 4.3.1. Effect of altered tidal propagation pathways

Long-term reclamation and channel incision mainly modified tidal-current structure and channel-scale energy distribution. Despite dampening the tidal range in the upper North Branch, the elevated river discharge during the 2020 flood reinforced ebb-dominant flow while sustaining tidal influx from the lower reach, a persistence anchored by strong convergent topography. In addition, channel incision in the lower Changjiang River can reduce bed friction and increase effective conveyance, thereby weakening tidal damping and allowing tidal energy to propagate farther upstream (Dronkers, 1986; Horrevoets et al., 2004; Savenije, 2005). The S2–S1 comparison illustrates that under the incision-only scenario, the mean tidal range increased slightly, while the ebb peak current increased by 6.23% (Table 5), indicating that the incised channel enhanced tidal propagation and local current intensity. However, incision alone reduced flood-, ebb- and total-water diversion ratios by 20.7%, 9.6% and 11.3%, respectively, and changed net sediment transport only weakly.

This altered tidal-propagation pathway became important during the 2020 flood because river-tide interaction is strongly non-stationary under high discharge. In tide-influenced estuaries, discharge-dependent friction, water-level slope and channel convergence can modify tidal damping and tidal-range transmission, so tidal response cannot be fully represented by a fixed harmonic relationship (Hoitink & Jay, 2016). In the North Branch, the preferential rise in low water and the upstream

strengthening of discharge-water-level correlations indicate that the 2020 flood modified both tidal damping and ebb-drainage capacity. Nevertheless, the flood did not eliminate tidal import from the lower branch. Model results show that sediment transport near CMZT shifted towards seaward transport during the flood, whereas landward sediment transport persisted near LXG (Figure 7(C)). Therefore, the North Branch during the 2020 flood was not converted into a purely river-dominated channel. Instead, flood-enhanced seaward transport from the upper branch coexisted with persistent tidal import from the lower branch, suggesting a hydrodynamic setting favouring internal sediment convergence rather than system-wide erosion.

In addition, propagation speeds derived from observed high- and low-water timing were treated as apparent station-pair speeds, not local linear shallow-water wave celerities. Some observed values exceeded the simple  $c = \sqrt{gh}$  estimate based on whole-branch mean depth because tidal extrema propagate mainly through the deeper thalweg and are affected by nonlinear tidal deformation, channel convergence, bottom friction, tidal-flat storage and pairing uncertainty. Thalweg depths commonly exceeded 5 m and locally approached 10 m, giving theoretical speeds of 7.0–9.9 m s<sup>-1</sup>, consistent with the modelled LXG–CMZT speeds of 7.52–8.13 m s<sup>-1</sup> (Table S3). Scenario results further show that bathymetry-related shoaling reduced propagation speed, whereas flood forcing partly increased it. Thus, effective channel depth provided the first-order control, with additional modulation by flood stage, channel geometry, friction and tidal-flat storage.

#### 4.3.2. Flood-peak forces on localized scour

Flood peaks commonly increase stream power, bed shear stress, and sediment-transport capacity in alluvial rivers and estuaries, but erosion is usually concentrated where flood energy is focused by channel curvature, thalweg confinement, or mouth-bar morphology rather than distributed uniformly across the whole estuary (Croke et al., 2013; Rinaldi et al., 2016; Rinaldi et al., 2016). In the North Branch, this flood-peak effect is better captured by changes in peak current than by branch-scale residual sediment transport alone. Relative to S1, the flood-only scenario S3 increased the ebb diversion ratio by 180.4% and the peak ebb current by 37.03%, while reducing the peak flood current by 4.80% (Table 5). Similarly, the coupled flood-incision scenario S4 increased the ebb diversion ratio and peak ebb current by 157.8% and 43.63%, respectively, relative to S1. These results suggest that the 2020 flood primarily strengthened ebb-phase erosive forcing rather than uniformly enhancing both flood- and ebb-tide currents. This interpretation is consistent

with the observed concentration of erosion in the bend-apex main channel, the straight middle-channel thalweg and the mouth-bar area, where flood-enhanced ebb flow was likely hydraulically focused. It is also supported by the post-flood sediment coarsening and improved sorting observed in the upper and middle reaches (Figure 5), which suggest selective removal of fine material from the more energetic parts of the channel.

The enhancement of ebb-peak forcing explains the observed localized erosion. The July 2020 field observations showed a net seaward discharge ratio of 3.87%, confirming that the flood imposed a downstream residual component on the tidal exchange. More importantly, the model shows that the flood substantially increased ebb-peak current intensity, which directly controls local bed shear stress and scour potential. Therefore, erosion most likely occurred in zones where the enhanced ebb flow was hydraulically focused, specifically the bend-apex main channel where curvature deflects and concentrates the main flow, the thalweg of the straight middle reach where the deeper channel confines ebb flow, and the mouth-bar area where ebb discharge interacts with bar morphology to promote seaward migration (Figure 4). The role of channel incision of the lower Changjiang River in this process could be interpreted as a modulation of the flood forcing transmitted into the North Branch. Under S4, ebb and total diversion were lower than in S3 by 8.1% and 7.1%, respectively, but the ebb peak current remained higher than in S1 (Figure 7(A)). This suggests that channel incision weakened the branch-scale increase in flushing while flood-enhanced ebb currents may still have been sufficient to favour generating local scour.

#### 4.3.3. Sediment-limited morphological adjustment

Cross-estuary comparisons highlight that flood-induced geomorphic change depends fundamentally on antecedent tidal asymmetry, sediment supply, and accommodation space rather than discharge alone (Choi et al., 2020; Garel et al., 2009), while idealized modelling shows floods primarily relocate sediment convergence zones before reversing net transport. Consistent with this, the 2020 event in the North Branch induced localized seaward transport near CMZT but not near LXG (Figure

7(C)), establishing a bidirectional regime where flood-driven export from the upper branch coexisted with persistent tidal import from the lower branch. Model simulations further reveal that under modern incised conditions, the flood boosted flood-, ebb-, and total-diversion ratios by up to 185% and amplified ebb peak currents by 31.61% (Table 5). However, system-scale sediment transport declined by only 7.27%, indicating that enhanced ebb flow primarily suppressed landward sediment pumping rather than reversing the net budget. Flood-incision interactions I ( $I = S4-S3-S2 + S1$ , Table 6) yielded weak negative effects on diversion ratios (−13.0% to −8.0%) and sediment flux (−1.08%), suggesting incision focused local flow without substantially altering system-wide export. This disconnection between intensified ebb dynamics and limited bulk sediment change may explain why the flood reorganized internal erosion-deposition patterns while producing net shoaling rather than system-wide erosion.

Against the long-term sediment-deficit backdrop of the Changjiang Estuary, the North Branch has shifted from net export to net import due to shoaling and tidal amplification (Dai et al., 2016). Basin-scale reservoir trapping and bed-sediment remobilization have decoupled sediment delivery from runoff (Dai et al., 2018). Thus, while extreme basin floods deliver transient coarse-sediment pulses, the modern estuary lacks the sediment-rich boundary conditions required for substantial geomorphic construction (Carle et al., 2015; Fisk et al., 1954). In the North Branch, flood-enhanced ebb flows likely resuspended, winnowed, and redistributed extant channel sediment, while continued tidal import supplied marine-estuarine sediment. This pattern is consistent with post-flood coarsening and sorting improvements (Figure 5), concurrent with main-channel erosion and shallow/intermediate-depth accretion (Figure 4). Volume loss was concentrated in the 2–8 m depth bins, whereas the thalweg was infilled (Table 3). These observations suggest internal sediment redistribution and net shoaling, rather than uniform erosion, in a sediment-starved, tide-dominated and confined branch.

**Table 6.** Relative changes in hydrodynamic and sediment-transport indicators among the numerical scenarios considering the flooding modulation and interaction between flood and incision (units: %).

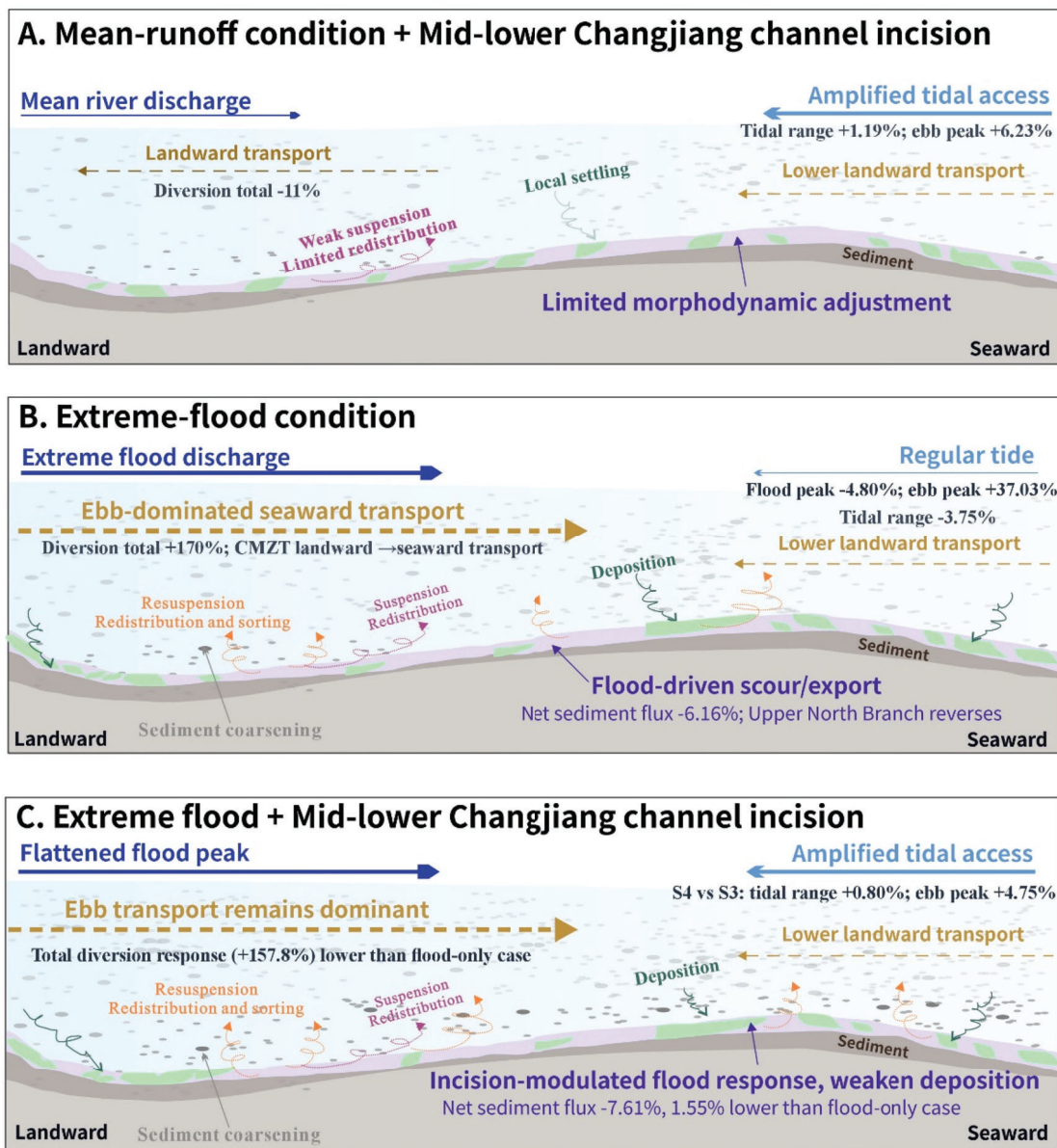
| Scenario            | Interpretation                                    | Diversion ratio |        |        | Mean tidal range | Tidal current |          | Sediment transport |
|---------------------|---------------------------------------------------|-----------------|--------|--------|------------------|---------------|----------|--------------------|
|                     |                                                   | Flood           | Ebb    | Total  |                  | Flood peak    | Ebb peak |                    |
| S4 vs S2            | Flooding modulation under bathymetric changes     | +128.1          | +185.2 | +182.6 | −4.12            | −4.83         | +31.61   | −7.27              |
| $I = S4-S3-S2 + S1$ | Interaction between flood and bathymetric changes | +22.5           | −13.0  | −8.0   | −0.42            | +0.03         | +0.37    | −1.08              |

#### 4.3.4. Conceptual model of flood response in the North Branch

Under the extreme Changjiang flood, the North Branch developed a compound hydrodynamic regime in which enhanced river discharge and persistent tidal forcing acted together. The resulting morphodynamic response over the annual comparison period was controlled by flood intensity, tidal background, long-term infilling and shrinkage, reclamation-constrained channel geometry and the modern low-sediment-supply condition. During the flood, enhanced river discharge increased resuspension and seaward sediment transport in the upper North Branch and main channel (Figure 10(B)), producing local erosion in flow-concentrated zones, including the bend-apex main channel, the straight middle-channel thalweg

and the mouth-bar area. However, because the North Branch remains a tide-dominated distributary with weak riverine inflow, tidal import from the lower branch persisted. Flood-generated suspended sediment and resuspended bed material could therefore be redeposited in widened channel sections, shallow channels, channel margins and the lower reach. Thus, the flood strengthened local scour and weakened the original landward sediment-transport system, but did not convert the whole branch into a persistently seaward-exporting channel.

The pronounced spatial heterogeneity further reflects a mechanistic decoupling between intensified hydrodynamic forcing and discontinuous sediment export. In the upper branch, flood-enhanced river discharge likely



**Figure 10.** Schematic of morphological change patterns in the North Branch under different scenarios.

promoted bed-material winnowing and local coarsening, but sustained seaward transport was limited by tidal reversal and channel-geometry constraints. Flow concentration in the middle bend, straight thalweg and mouth-bar area is consistent with local erosion. Downstream, channel widening, reduced current speed and persistent tidal import may have favoured suspended-sediment convergence and deposition. Thus, the post-flood pattern is interpreted as reach-scale redistribution, with adjacent erosion and deposition zones, rather than a simple landward-to-seaward gradient.

Mid-lower Changjiang channel incision amplified the mean tidal range and ebb peaks in the North Branch by reducing friction, thereby facilitating tidal access. Yet, it lowered the diversion ratio, confirming that incision enhanced tidal amplitude without increasing the total water volume (Figure 10(A)). Under the coupled flood-incision condition, the ebb and total diversion ratios were lower than in the flood-only scenario, whereas the ebb peak current increased further (Figure 10(C)). This suggests that mid-lower Changjiang channel incision may have weakened the water-volume of the North Branch response by modifying downstream flood conveyance and flood-peak transmission, while still enhancing local ebb-current intensity and scour potential.

Overall, the 2020 flood response of the North Branch can be interpreted as a compound morphodynamic adjustment. Extreme basin flooding likely enhanced river-driven resuspension and local seaward transport, whereas the confined channel geometry formed by long-term reclamation and infilling, persistent lower-branch tidal import, limited exportable sediment under a low-supply regime and reduced post-flood transport capacity promoted internal sediment storage. This interpretation is consistent with the observed stable bar-channel pattern, overall thalweg shoaling, reduced shallow to intermediate-depth channel volume and coarsened surficial sediments.

#### 4.4. Future uncertainties and limitations

Future flood risks in the Changjiang system are poised to escalate under converging climatic and anthropogenic pressures. Global projections forecast a tripling of flood exposure by 2050, with economic losses rising to 240% (Dottori et al., 2023; Jongman et al., 2012). For the Changjiang basin, CMIP6-SWAT models predict increased flood intensity, frequency, and earlier peak timing under SSP5-8.5 (Zhang et al., 2023). In the North Branch, these drivers will interact with ongoing riverine bed adjustments in Changjiang, persistent infilling, reclamation-constrained geometry, sediment starvation, sea-level rise, and typhoon surges. Although the 2020

flood temporarily enhanced scour and weakened landward pumping, the branch remains locked in a long-term degradational trajectory. Future sea-level rise and storm surges threaten to amplify tidal ingress and sediment import, potentially accelerating infilling and exacerbating saltwater intrusion into the South Branch and urban water supplies.

While this study elucidates the mechanisms governing the 2020 flood response, several limitations warrant consideration. First, the May 2020–May 2021 bathymetric comparison integrates both the flood's direct impact and nine months of post-flood recovery; thus, results reflect an annual-scale response rather than instantaneous bed change. Second, while water-sediment partitioning is observation-based, spatial hydrodynamics and residual transport were model-derived (Delft3D), limiting conclusions to relative attribution rather than absolute sediment budgets. Third, the model inferred sediment response from net fluxes at CMZT and LXG, potentially overlooking internal resuspension, bedload dynamics, and shallow-water storage. Finally, focusing on a single event constrains mechanistic inference; responses may vary significantly with different flood magnitudes, tidal phases, sea levels, or storm-surge couplings.

Future work should therefore combine event-scale continuous bathymetric monitoring with synchronous measurements of velocity profiles, suspended sediment concentration, bedload transport and bed-material texture across key sections of the North Branch. Morphodynamic models that directly simulate bed evolution under coupled river flood, tide, storm surge and sea-level-rise scenarios are also needed. Such work would help test whether the two-stage mechanism proposed here, namely flood-driven local scour followed by tide-modulated sediment redistribution and storage, persists under future hydroclimatic conditions, and whether continued lower-river incision and sea-level rise will accelerate the long-term decline of the North Branch.

#### 5. Conclusions

The 2020 extreme basin flood was associated with spatially heterogeneous erosion and deposition within the engineered, tide-dominated North Branch of the Changjiang Estuary, with net shoaling over the annual comparison period. Using observations and Delft3D scenario experiments, this study examined how flood forcing and significant channel incision of the lower Changjiang River jointly shaped this response. The main conclusions are as follows:

- (1) The 2020 flood delivered intense and prolonged forcing to the estuary, with peak discharge and water

level at Datong reaching  $83,400 \text{ m}^3 \text{ s}^{-1}$  and 16.21 m, respectively. Despite this strong forcing, the North Branch showed net shoaling rather than reach-wide erosion. Mean water depth decreased from 3.35 to 2.91 m with volume loss over the annual comparison period, and post-flood surficial sediments became coarser and better sorted.

- (2) Scenario experiments separated the effects of flooding, the mid-lower Changjiang channel incision and their interaction. Extreme flooding increased the ebb-tide and total diversion ratios by 180.4% and 170.0%, respectively, and enhanced peak ebb current by 37.03%, indicating stronger flood-driven seaward transport potential. Mid-lower Changjiang channel incision slightly enhanced tidal access under mean-runoff conditions, but under coupled flood-incision conditions, it weakened the flood-induced total diversion response while further increasing peak ebb current by 4.75%.
- (3) The 2020 observed response of the North Branch reflects an incision-modulated and tide-filtered mechanism. Flood-enhanced ebb currents likely contributed to local erosion in the bend-apex main channel, straight middle-channel thalweg and mouth-bar area, whereas persistent lower-branch tidal import, limited exportable sediment and reclamation-constrained geometry promoted sediment trapping and redeposition within the branch. Thus, in this case, the 2020 flood reorganized sediment storage within the North Branch without producing reach-wide erosion.

This study addresses a case-based mechanism for understanding how an extreme basin flood can reshape engineered, tide-dominated estuaries under strong tidal asymmetry, sediment supply, and human-constrained channel geometry. Its main added value is to show that flood-enhanced ebb transport, persistent tidal import, limited exportable sediment, and human-constrained channel geometry can jointly produce localized scour and internal sediment storage, rather than simple system-wide erosion. These findings refine understanding of flood-driven morphodynamics in modified estuarine systems, but their broader applicability should be tested across different flood magnitudes, tidal phases, sea levels, and storm-surge conditions. In addition, the annual bathymetric comparison used here cannot fully separate direct flood-induced bed change from post-flood recovery. Event-scale monitoring and coupled morphodynamic observations are therefore still needed to resolve the timing and persistence of these responses more precisely.

## Author contributions

CRedit: **Ping Zhang:** Data curation, Formal analysis, Investigation, Visualization, Writing – original draft; **Runan Tang:** Formal analysis, Investigation, Resources, Visualization; **Xiaoqiong Ren:** Data curation, Visualization; **Xuefei Mei:** Methodology, Resources; **Ao Chu:** Software, Validation; **Zhijun Dai:** Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing

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No potential conflict of interest was reported by the author(s).

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## Data access statement

Data openly available in a public repository that issues datasets with DOIs: 10.17632/97vsvmjrtf.1 (Morphodynamics dataset for the 2020 extreme Changjiang flood – Mendeley Data).

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