

Research papers

Extreme basin-scale flood-dry events induce dramatic alterations in water–sediment dynamics within the Yangtze Estuary

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ABSTRACT

Against the backdrop of increasing attention to the frequent occurrences of global extreme flood and dry events, understanding how these extreme hydrological events impact estuarine water and sediment dynamics remains insufficient. To address this, this study focuses on the Yangtze Estuary, a typical estuarine system governed by the hydrological processes of the Yangtze Basin, and selects the North Channel (NC), a representative bifurcated branch, as the study area. Based on continuous hydrological observations conducted at eight monitoring stations during the flood seasons of an extreme flood year (2020) and an extreme dry year (2023), combined with water–sediment analyses and the Empirical Orthogonal Function (EOF) method, the spatiotemporal variation characteristics of water and sediment dynamics under extreme hydrological conditions were systematically diagnosed. The results show that the average flow velocity during the extreme flood year reached 1.08 m/s, exhibiting a three-peak longitudinal structure. In contrast, during the extreme dry year, a double-peak structure was observed, with the flow velocity decreasing to 0.85 m/s and stagnant flow characteristics beginning to emerge. In Turbidity Maximum Zone (TMZ), peak flow velocities during the flood year exceeded 1.20 m/s, with Suspended Sediment Concentration (SSC) reaching up to 1.26 kg/m³ and showing a “peak dilution effect.” Conversely, during the dry year, flow velocity significantly weakened, with a peak of only 0.95 m/s, while SSC decreased to 0.66 kg/m³, its high-concentration layer exhibited a more vertically extended distribution. These variations in water and sediment dynamics reveal that during extreme flood year, river runoff suppresses marine tidal effects, leading to an overall increase in estuarine flow velocity and sediment supply. During extreme dry year, tidal effects are significantly amplified, causing the TMZ to migrate upstream. Accordingly, sediment resuspension and deposition are modified, jointly reshaping the estuarine water and sediment transport patterns. This study provides empirical evidence for understanding the response mechanisms of large river estuaries under extreme hydrological conditions.

1. Introduction

Against the backdrop of global climate change and intensifying human activities, addressing the impacts of extreme flood and dry events on estuarine environments has emerged as a critical challenge to sustainable coastal development (Wetz and Yoskowitz, 2013; Dai et al., 2011; Sánchez-García and Francos, 2022; Kreibich et al., 2022). Excessive freshwater and sediment inputs during flood periods can lead to abrupt changes in salinity structure, imbalances in geomorphic processes, and disruptions in ecosystem functions (Herbert et al., 2015; Bomer et al., 2020; Feher et al., 2023; Zhao et al., 2025). Conversely,

prolonged dry-year events tend to exacerbate saltwater intrusion, interrupt sediment supply, and worsen coastal erosion, triggering a series of cascading responses that pose multiple threats to freshwater resource security, habitat integrity, and coastal protection (Li et al., 2023a; Wu et al., 2023; Li et al., 2024; Su et al., 2025). Currently, over 600 million people worldwide live in low-lying coastal areas (McGranahan et al., 2007), where such extreme events threaten human safety and undermine socio-economic stability (Weilhammer et al., 2019; Butsch et al., 2023; Tradowsky et al., 2023). However, significant limitations remain in understanding the intrinsic processes linking extreme flood and dry events with variations in estuarine water and

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sediment fluxes. Particularly, knowledge of estuarine water and sediment responses driven by different types of extreme events remains poorly understood.

Some studies suggest that the water and sediment fluxes in estuaries exhibit significant seasonal variation patterns during flood and dry periods (Thi Ha et al., 2018; Lu et al., 2025). Runoff-dominated estuaries, where river discharge plays a primary role, typically show a “high water-high sediment” mode during the rainy season, with sediment loads entering the estuary during flood periods accounting for over 90% of the annual total (Thi Ha et al., 2018). Suspended sediment concentrations in estuaries are significantly higher during flood periods than in low-flow periods (Lu et al., 2025; Song et al., 2025), and corresponding sediment fluxes scale with runoff following a well-documented power-law relationship (Thi Ha et al., 2018; Guo et al., 2020; Xie et al., 2022). However, during extreme flood years, not only does runoff dominate sediment transport, but its enormous kinetic energy suppresses the modulation effect of oceanic tides (Ji et al., 2020; Xie et al., 2022). This intense runoff can significantly shift the estuary’s Turbidity Maximum Zone (TMZ) seaward beyond the estuary mouth. The turbid water body in the inner section of the estuary, which is typically sustained by the tidal pump mechanism, becomes diluted, resulting in a temporary “clear-water estuary” state (Wang et al., 2010; Tien et al., 2020; Yang et al., 2020). More importantly, the enormous amounts of coarse sediment transported during extreme floods can overcome the constraint of estuarine sandbars, delivering sediment directly to the deep water areas of the continental shelf where event beds are formed. For instance, during the extreme runoff following Hurricane Katrina, significant instantaneous accretion was observed at the foredeltas of the Mississippi River estuary (Swarzenski et al., 2005; Day Jr et al., 2007). Similarly, during the flood season in the Amazon estuary, the diffusion range of suspended sediment can expand significantly compared to normal years, with large amounts of fine-grained materials transported to the outer continental shelf, forming prominent seasonal sedimentary layers (Nittrouer et al., 2021).

During the dry season, when river discharge significantly diminishes, marine dynamics such as tides and waves become the primary drivers of sediment resuspension and transport in estuaries, often leading to siltation in inner estuarine areas. Meanwhile, the combined effects of tidal asymmetry and density-driven gravitational circulation pump marine sediments into the estuary, resulting in a unique geomorphic process of “dry-season estuarine siltation” (Olabarrieta et al., 2018; Hou et al., 2024). During the rainy season of extreme dry years, persistently low runoff enhances the relative influence of marine forces, significantly amplifying the tidal pump effect. Observations during dry periods in the Mississippi River indicate that, despite a significant reduction in river discharge, suspended sediment concentrations in the inner estuary remain at relatively high levels, primarily due to tidal resuspension of bed sediments (Zhu et al., 2022; Elsey-Quirk et al., 2024). At the same time, in the absence of sufficient riverine dynamics, sediment transported from offshore tends to accumulate in the estuary, which may exacerbate siltation in channels or estuarine TMZ areas (Wei et al., 2021; Wang et al., 2025).

In contrast, small to medium-sized estuaries respond more moderately to seasonal changes between flood and dry periods. Their water and sediment fluxes are primarily governed by the tidal pump effect and wave-induced sediment resuspension, allowing them to maintain a relatively high concentration of near-bed turbid layers even during dry seasons. The annual variation in sediment flux for these estuaries is relatively small, with seasonal changes more apparent in the vertical distribution of sediments and the adjustment of transport pathways rather than in dramatic fluctuations in total volume (Uncles et al., 2002; Bailey et al., 2025). However, deepening of estuary channels, such as in the Ems Estuary due to upstream dredging, can easily lead to strong stratification and stagnant flow, with bottom hypoxia causing an expansion of the estuarine “dead zone” (Talke and de Swart, 2011). During dry years, the strong tidal dynamic regime may extend into the

rainy season, resulting in a more stable annual sediment flux. The prolonged period of low sediment input poses a risk of estuarine erosion (Uncles et al., 2002).

Meanwhile, some studies have found that flood periods typically result in the seaward migration or dissipation of the TMZ, while dry periods cause the TMZ to retreat landward. For instance, in the Amazon tidal estuary, multiple field observations have shown that the TMZ shifts seaward and merges with offshore high-turbidity waters during flood or high-runoff periods (Asp et al., 2016; Gomes et al., 2021; Silva et al., 2023). Research on the Mississippi River during extreme flood years found that when discharge exceeded 20,000 m³/s, the Suspended Sediment Concentration (SSC) inside the estuary decreased, exhibiting a “peak dilution effect” (Yang et al., 2022). At this stage, the structure of the TMZ is easily disrupted, with high flow velocities preventing sediment from settling near the estuary mouth, resulting in sediment being “ejected” directly into deeper water areas (Falcini et al., 2012; Nittrouer, 2013). Recent studies have further revealed that sediment trapping efficiency in estuaries does not increase monotonically with peak flood discharge. Instead, it reaches a peak within a certain flow range, beyond which the system transitions to a regime dominated by scouring and seaward sediment export (Downing-Kunz et al., 2021; Du et al., 2023; Hsueh et al., 2024). These spatiotemporal variations indicate that during extreme flood years, there may exist an “optimal discharge window” at which sediment retention and morphological accretion within the estuary and on adjacent tidal flats are maximized. Beyond this threshold, the system transitions into an “ineffective scouring” or “offshore deposition” mode. In macrotidal estuaries controlled by mountainous small watersheds, as river discharge increases, the main channel bed thickness first increases and then decreases. Once discharge exceeds 4,000 m³/s, scouring becomes dominant, and the TMZ shifts offshore, facilitating significant sediment deposition in deep water regions (Du et al., 2023). Both model simulations and field measurements have further demonstrated that the sediment trapping ratio of the estuary-nearshore system is higher at moderate to high flows but decreases significantly under extreme high flows, with more sediment transported to offshore areas (Downing-Kunz et al., 2021; Hsueh et al., 2024).

During extreme dry periods, the significant reduction in river discharge results in a dramatic landward contraction of the TMZ. In the Loire Estuary in Europe and the Gironde Estuary in France, weakened riverine forces cause the TMZ to rapidly contract landward and transition into a tide-dominated system. Continuous observations and numerical simulations have shown that once low-flow or dry conditions set in, the TMZ is driven significantly landward by the tidal pump effect. The upstream boundary of the TMZ can shift tens of kilometers inland compared to flood periods, exhibiting higher suspended sediment concentrations and longer sediment residence times (Jalón-Rojas et al., 2015; Jalón-Rojas et al., 2016). However, in river-dominated estuaries such as the Mekong Estuary, the suppression of marine dynamics by river discharge diminishes during dry periods. As a result, a strong saltwater wedge, carrying high-concentration turbid bottom waters, intrudes landward, with gravitational circulation becoming the dominant mechanism. The siltation center undergoes abrupt relocation, and inside the estuary, especially near the tip of the saltwater wedge, the net landward sediment flux at the bottom dramatically increases. This leads to the formation of a new “siltation bar” at a position much farther inland than usual (Tien et al., 2020).

Extreme flood and dry events have a significant impact on the water and sediment dynamics of estuaries (Voyanova et al., 2017; Luo et al., 2025), yet few studies have analyzed both types of events within the same estuary, especially in the case of China’s largest estuary, the Yangtze Estuary. This paper focuses on the North Channel (NC), a relatively natural distributary of the Yangtze Estuary that is characterized as a typical bifurcated estuary. Using data from eight continuous monitoring stations, this study examines the changes in water and sediment dynamics during the extreme flood year of 2020 and the dry year of 2023. The primary objectives are: 1. To identify the changes in

water and sediment characteristics during extreme flood and dry periods; 2. To discern the variations of the TMZ near the estuary mouth bar; and 3. To diagnose the mechanisms controlling the alterations in the water and sediment structure within the North Channel.

2. Study area

The Yangtze River originates from the Tibetan Plateau, with a total length of over 6,300 km and a drainage area of approximately 1.8 million square kilometers. It is the third longest river in the world and the largest river in Asia (Chen, 1988). The Datong Hydrological Station, located at the final high-grade hydrological station of the Yangtze River mainstream (Fig. 1A), also serves as the boundary for the dry-season tidal zone. Its runoff reflects the variation characteristics of the entire river basin (Shen, 2001). In the estuarine section, the region from Xuliujing to the estuary mouth, spanning approximately 160 km, experiences complex interactions between river flow and tidal currents, leading to a highly dynamic riverbed with numerous branching channels (Xie et al., 2022). The main channel is divided by Chongming Island into the South Branch and North Branch. The South Branch is further split by Changxing Island and Hengsha Island into the South Channel and North Channel. The South Passage and North Passage are separated at the South Channel by Jiuduan Shoal (Chen, 1988), ultimately forming a three-level branching system with four outlets to the sea (Fig. 1B).

This study focuses on the North Channel, the second branch of the “three-branch system” in the Yangtze Estuary. The North Channel stretches approximately 60 km in length (Mei et al., 2018). After the collapse of the coastline of Chongming Island, the North Channel gradually developed a meandering pattern, with the northern bank closely bordering Chongming Island and the southern bank near Changxing Island. It is also connected to the deep-water channel through the Hengsha Passage. Moreover, variations in sediment distribution among the branches of the Yangtze Estuary can influence the migration of the main deposition center of the submarine delta over decades (Dai et al., 2014). The North Channel lies in an area affected by both river runoff and tidal currents, with the upstream section being more affected by river flow and the downstream mouth section being more dominated by tidal currents (Mei et al., 2018). The interaction of these forces contributes to the formation of longitudinal underwater sand ridges.

3. Data and methods

3.1. Data acquisition

This study utilized hydrological measurements obtained from eight observation sites—XQTD, BG1, BG2, BG3, BG4, BG5, BG6, and BG7, and established along the North Channel during the flood seasons of 2020 and 2023 (Fig. 1C). The measurements included hydrological data such as flow velocity, flow direction, sediment concentration, and the grain size distribution of suspended sediment. The details of the station locations and deployment times are provided in Table 1. Each site ensured that data was collected during two tidal cycles to meet the tidal flow closure requirements. The original hydrological measurement data and tidal level data were provided by the Changjiang Estuary Waterway Administration Bureau.

In addition, the upstream runoff was referenced to the corresponding flow at the Datong station during hydrological measurements. Given its location 600 km from the estuary, the water travel time required consideration (Mei et al., 2019). In this study, the water travel time was set to 7 days, meaning that the flow corresponding to the hydrological measurements at the observation sites was based on the flow data from Datong station recorded 7 days prior. The flow data were provided by the Yangtze River Water Resources Commission.

3.2. Methods

3.2.1. Hydro-sediment analysis

The suspended sediment concentration was collected using a horizontal sampler with a sampling volume of 1000 ml. When the water depth was greater than 5.0 m, a six-point sampling method was employed, with sampling synchronized to the velocity measurements. The suspended sediment concentration was analyzed using the drying method (Xu and Hu, 2017), and the sediment concentration at each sampling point was calculated by weighing the dry sediment. The vertical average sediment concentration is typically calculated using the velocity-weighted average of the sediment concentrations at each measurement point along the vertical. For periods near quiescent flow, where the velocity is relatively low, the arithmetic weighted average of the sediment concentrations at the stratified measurement points is used for calculation (Zhang et al., 2010).

The flow velocity and direction at each site were measured using a current meter, with measurements taken at the top of each hour. Since the actual water depth at each site was greater than 5.0 m, the six-point method was employed for both inbound and outbound measurements. The average flow velocity was calculated using the vector composition method, with the flow direction referenced to true north (Xiao et al., 2012; Fan, 2014).

The dominant flow and dominant sediment were used to reflect the strength relationship between the flood and ebb tides in the tidal current area. The relationship is represented by the ratio of the area of the ebb tide portion to the total tidal current area, calculated from the enclosed area between the tidal current or sediment transport process curve and the time axis (Wan et al., 2014). The results of dominant flow and dominant sand provide useful reference for determining sediment deposition and the direction of channel morphology evolution.

Suspended sediment samples for grain size analysis were collected synchronously with concentration measurements across peak flood, slack flood, peak ebb, and slack ebb. The six-point sampling method was applied vertically, corresponding to velocity measurement points. Grain size analysis was performed using a Master Sizer 3000 laser diffraction particle size analyzer. The vertical median grain size difference was used to quantify gravitational sorting intensity, with positive values indicating bedward coarse particle enrichment. The peak ebb phase of spring tides was selected for interannual comparisons, as it corresponds to maximum bottom shear stress and sediment resuspension, where vertical sorting is most pronounced (Li et al., 2022).

3.2.2. Percentile calculation

The IPCC Fourth Assessment Report defines hydrological anomalies in which climate- or weather-related variables exceed the 75% threshold or fall below the 25% threshold, and applies these criteria to delineate flood and dry years (IPCC, 2007). A two-tier threshold-based framework was established to classify hydrological years according to severity. The 25% and 75% thresholds of annual mean runoff were used to define moderately dry and moderately flood years, respectively, consistent with conventional runoff classification schemes (Bonsal et al., 2001), while the 10% and 90% thresholds were further adopted to identify extreme dry and extreme flood years, following widely applied criteria in global-scale extreme runoff studies (Gudmundsson et al., 2019). This classification follows established hydrological condition assessment approaches, where more stringent thresholds represent events with greater severity (Van Loon, 2015). Although several historical years met the criteria for extreme events, their use was restricted by the lack of complete synchronous hydro-sediment observations across all eight North Channel monitoring stations. Thus, 2020 and 2023 were chosen as representative recent extreme years for comparative analysis (Fig. 2).

3.2.3. SSC vertical distribution discreteness method

To quantitatively characterize the vertical distribution pattern of suspended sediment concentration at different fixed vertical lines, this

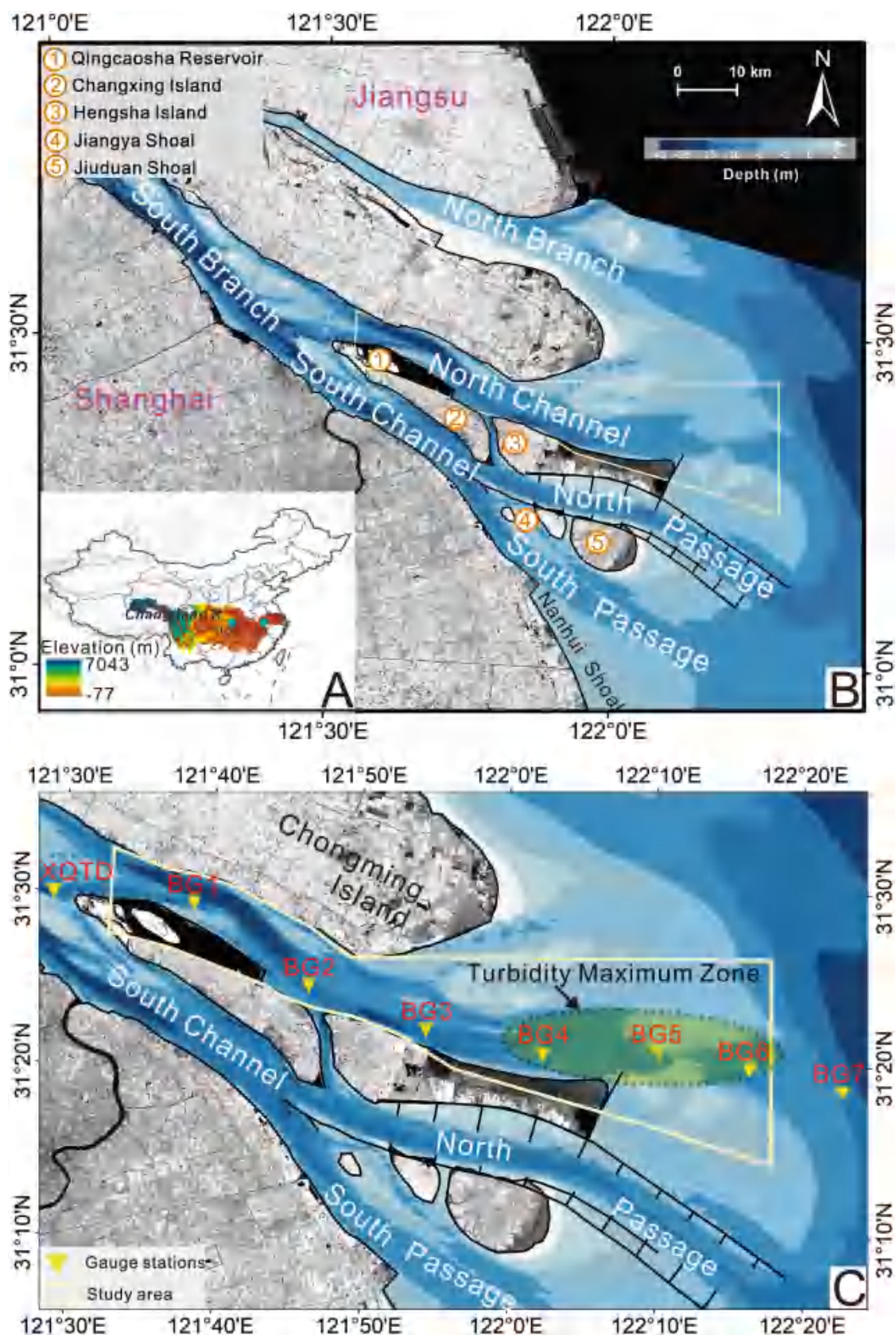


Fig. 1. Maps of (A) the Yangtze River and its basin; (B) the Yangtze Estuary; (C) study Area and hydrological observation stations.

Table 1
Information of the observation sites.

Serial No.	Name	X-coordinate	Y-coordinate	Survey period	Location
1	XQTD	3487218.88	355950.37	2020.08.05–2020.08.06	Xinqiao Channel
2	BG1	3485940.34	371021.16	2023.08.20–2023.08.21	North Channel
3	BG2	3477022.34	383360.49		Below the Bridge
4	BG3	3472231.25	395965.92		North of Hengsha Island
5	BG4	3469582.01	408511.56		Tidal Bar of North Channel
6	BG5	3469804.07	420923.60		Tidal Bar of North Channel
7	BG6	3467891.64	430760.57		Tidal Bar of North Channel
8	BG7	3465404.24	440750.37		Offshore of North Channel

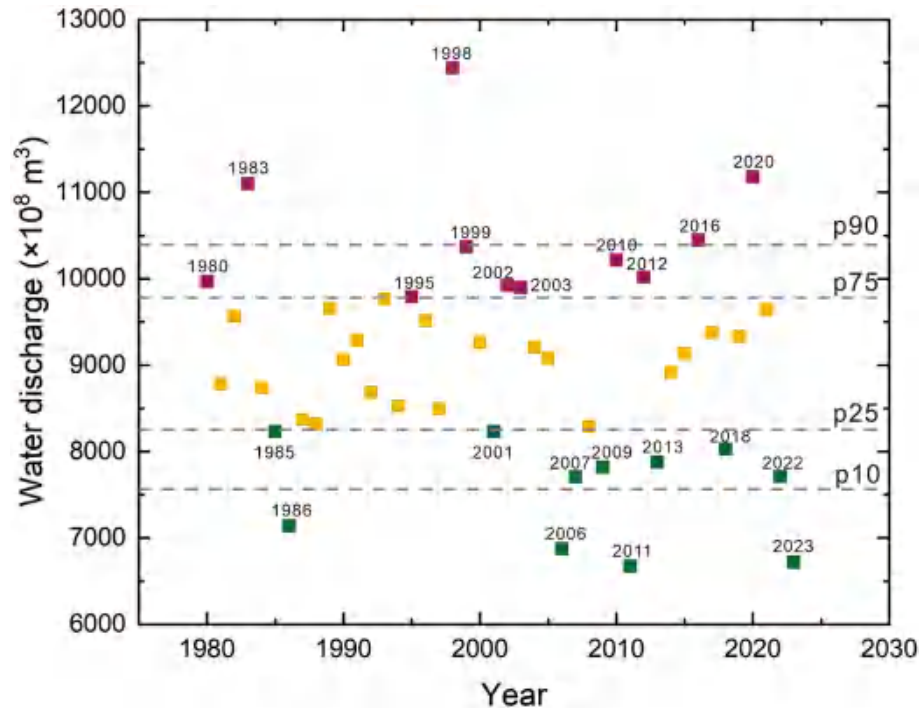


Fig. 2. Extreme flood and dry events between 1980 and 2023.

study introduces the coefficient of variation (CV) from statistics as an evaluation index. The CV is used to represent the degree of discreteness in suspended sediment concentrations across different water layers, as well as the representativeness of the mean value for the overall data. The value of the coefficient of variation is positively correlated with the unevenness of the vertical distribution of suspended sediment concentration; that is, a larger CV value indicates a more significant difference in suspended sediment concentration between vertical layers (Xie et al., 2021). The specific calculation formula is as follows:

$$CV = \frac{\sqrt{\frac{1}{n-1} \sum_{i=1}^n (C_i - \bar{C})^2}}{\bar{C}} \quad (1)$$

Where n is the number of water layers; $\bar{C}$ is the vertical mean suspended sediment concentration; and C_i is the suspended sediment concentration of the i -th water layer.

3.2.4. Empirical orthogonal function analysis

Empirical Orthogonal Function (EOF) analysis, first introduced by the statistician Pearson (Pearson, 1901), was later adapted for geophysical studies by Lorenz, who applied it to meteorological analyses (Lorenz, 1956). EOF is similar to Principal Component Analysis (PCA), but it focuses on spatial variability (Aubrey, 1979). In this study, the EOF method is used to decompose the observed flow velocity and

sediment concentration, with the core idea being to orthogonally decompose time-varying field variables into two parts: spatial modes and time coefficients (Hannachi et al., 2007). Taking flow velocity analysis as an example, the specific procedure is as follows:

- (1) Calculate the time-mean to eliminate the influence of the long-term average state of the flow velocity data and highlight its anomalous variation characteristics. The calculation formula is as follows:

$$\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i \quad (2)$$

Where n denotes the number of time steps, and X_i represents the flow velocity vector at the i -th time step.

- (2) Construct an anomaly data field matrix to quantify the fluctuations of flow velocity relative to the mean value:

$$V = X_i - \bar{X} \quad (3)$$

Where $\bar{X}$ denotes the time-mean flow velocity derived from Eq. (2).

- (3) The covariance matrix C is constructed to reflect the degree of correlation between the anomalies in flow velocity at different measurement stations:

$$C = \frac{1}{n} VV^T \quad (4)$$

Where V^T denotes the transpose matrix of V .

(4) Eigenvalue decomposition: Solve for the eigenvalues and eigenvectors of matrix C :

$$Cv_k = \lambda_k v_k \quad (5)$$

Among them, v_k denotes the k -th spatial mode (eigenvector), which characterizes the spatial distribution characteristics of flow velocity; λ_k represents the corresponding eigenvalue, reflecting the variance contribution of the mode. The variance contribution rate ($\lambda_k / \sum \lambda_k$) is used to determine the importance of the mode.

(5) Construct the spatial mode matrix A and the principal component matrix T . Combine the first m dominant eigenvectors V_k as column vectors to obtain the spatial mode matrix:

$$\begin{cases} A = [V_1, V_2, \dots, V_m] \\ T = VA^T \end{cases} \quad (6)$$

Where m is the number of extracted modes.

3.2.5. Quantitative stratification intensity analysis

To quantitatively compare the relative strengths of buoyancy-driven stratification and tidal shear mixing between flood and dry years, the Bulk Richardson Number (R_{i0}) was introduced as a dimensionless indicator of stratification intensity. Physically, R_{i0} represents the ratio between vertical buoyancy potential energy and turbulent kinetic energy, and is widely used to characterize water column stability in estuarine hydrodynamic studies (Simpson et al., 1990; Geyer and MacCready, 2014). It is calculated as follows:

$$R_{i0} = -\frac{\Delta\rho gh}{\rho(\Delta U)^2} \quad (7)$$

Where $\Delta\rho$ is the density difference between surface and bottom waters; ΔU is the difference in horizontal velocity between surface and bottom layers; h is the local water depth; g is gravitational acceleration; and ρ is the reference water density.

According to linear stability theory, $R_{i0} = 0.25$ represents the critical threshold for active vertical mixing. When $R_{i0} < 0.25$, tidal shear turbulence dominates and the water column remains well mixed; when $R_{i0} > 0.25$, buoyancy-driven stratification prevails and a stable vertical structure develops. To eliminate dimensional effects and facilitate interannual and inter-site comparisons, R_{i0} was normalized using $\lg(R_{i0}/0.25)$ as a unified stratification index. Positive values indicate stratification-dominated conditions, whereas negative values indicate tidal mixing dominance.

3.2.6. Partial regression analysis

To quantitatively separate the independent contributions of runoff and tidal range to suspended sediment concentration and flow velocity, partial regression analysis was performed. The partial coefficient of determination (Partial R^2) was calculated to quantify the independent variance explained by each predictor while controlling for other covariates (Quinn and Keough, 2002; Montgomery et al., 2022). The calculation is as follows:

$$\text{Partial } R^2 = \frac{\text{SSE}_{\text{reduced}} - \text{SSE}_{\text{full}}}{\text{SSE}_{\text{reduced}}} \quad (8)$$

Where SSE_{full} represents the residual sum of squares of the full regression model including all predictors, and $\text{SSE}_{\text{reduced}}$ represents the residual sum of squares of the reduced model after excluding the predictor of interest.

Multiple linear regression models were developed to analyze the

relationships of suspended sediment concentration and flow velocity with runoff and tidal range. R^2 values and significance levels of individual drivers were calculated based on Type-II sums of squares. Type-II sums of squares are independent of predictor entry order and are therefore suitable for evaluating the relative importance of multiple drivers.

3.2.7. Topographic change analysis

To identify the temporal extent of geomorphic evolution in the North Channel induced by the 2020 extreme flood, four bathymetric datasets acquired in November 2019, May 2020, November 2020, and May 2023 were analyzed. The datasets were categorized into three stages, including the pre-flood period, extreme flood period, and post-flood adjustment period, to characterize erosion-deposition dynamics. Water depth was measured using a dual-frequency echo sounder with a precision of 0.1 m combined with GPS positioning. The data were obtained from the Changjiang Estuary Waterway Administration Bureau (CJWAB, <https://www.cjkh.com/>), with an overall measuring point density of approximately 8–15 points per square kilometer, which can ensure the accuracy of underwater topographic changes (Dai et al., 2015). Based on Surfer software developed by Golden Software, the Kriging interpolation method was used to interpolate the discrete water depth points into a grid with a resolution of 50 m $\times$ 50 m to generate a Digital Elevation Model (DEM).

4. Results

4.1. Variations in flow velocity

4.1.1. Quantitative structure of flow velocity

In the flood year of 2020, the flow energy was relatively high, and the average flow velocity remained around 1.08 m/s. The vertical velocity at each station exhibited a stratified pattern, with a decrease from the surface to the bottom, and significant differences between layers (Fig. 3A). The BG5 and BG6 stations in the core area of the TMZ both showed high velocities above 1.20 m/s and high vertical velocity differences above 0.84 m/s (Fig. 3A). In terms of the horizontal flow field, the velocity vectors at the XQTD, BG5, and BG6 were noticeably longer, with flow velocities generally exceeding 2.0 m/s (Fig. 4A).

In the dry year of 2023, the flow energy was weaker, and the average flow velocity decreased to 0.85 m/s. The vertical velocity stratification weakened significantly compared to the flood year. Although the vertical velocity difference between layers was reduced, the flow velocity at BG5 and BG6 remained above 0.95 m/s, a speed that was still relatively high (Fig. 3B). In the horizontal flow field, the velocity vectors were significantly shorter, with most areas having flow velocities below 1.5 m/s (Fig. 4B).

It is worth noting that the vertical average flow velocity at BG4, located at the uppermost section of the TMZ, was only 0.90 m/s, slightly lower than the 0.93 m/s recorded in 2023, making it the only station where the flow velocity in the flood year was lower than in the dry year (Fig. 3).

4.1.2. Dominant flow characteristics

In the flood year of 2020, the flow field exhibited a relatively consistent vector direction, showing a clear ebb tide flow pattern. The high-velocity flow maintained stronger continuity and directionality, and the hydrodynamic structure was relatively stable (Fig. 4A). All stations displayed a dominant ebb tide flow, with the dominance at BG1, BG2, and BG3, located in the main channel of North Channel, under the bridge, and around the islands, reaching 94.9%, 92.6%, and 95.5%, respectively (Fig. 5A).

In the dry year of 2023, the flow field vectors showed more flood tide directions, and the flow became more intermittent and random (Fig. 4B). The proportion of dominant flow decreased across the board, with the high-dominant flow stations BG1, BG2, and BG3 from the flood

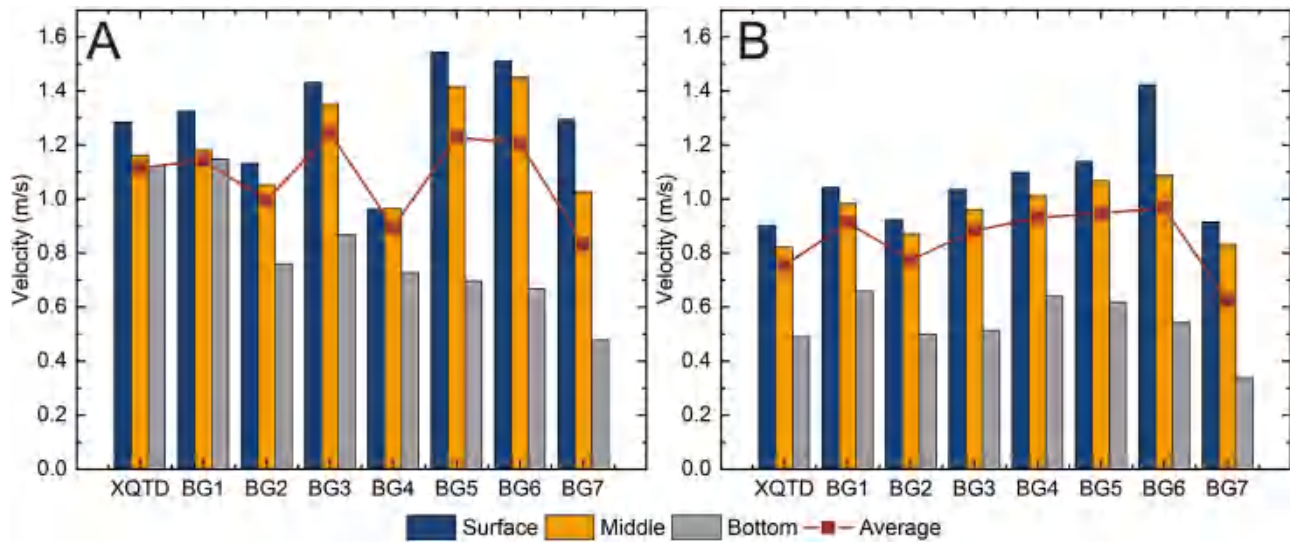


Fig. 3. Velocity distribution by layer and vertical mean (A: 2020; B: 2023).

year dropping to 59.8%, 68%, and 71.4%, respectively (Fig. 5B).

4.1.3. Spatial structure of flow velocity

In the flood year of 2020, the longitudinal flow velocity exhibited a typical three-peak structure, with distinct high-velocity peaks forming in the BG1, BG3, and BG5-BG6 intervals. The range of high-velocity coverage extended from the surface to a depth of approximately 5 m. In the mid-upper regions where the depth is less than 5 m, the velocity generally remained above 1.2 m/s, particularly in the BG5-BG6 segment where the peak velocity exceeded 1.5 m/s (Fig. 6A).

In the dry year of 2023, the longitudinal flow velocity evolved into a double-peak structure, retaining only two relatively weaker velocity peaks in the BG1 and BG5-BG6 intervals. The vertical range of velocity narrowed to within 2–3 m of the surface, with peak velocities dropping below 1.54 m/s. Moreover, the velocity peak at BG3 significantly diminished and shifted to BG4, thereby making BG4 a transition zone. In addition, although there were low-velocity zones below 10 m in 2023, these low velocities were more pronounced, with the lower limit reduced to 0.34 m/s and the range of the low-velocity zone expanded (Fig. 6B).

4.2. Variations in suspended sediment concentration

4.2.1. Quantitative structure of suspended sediment concentration

In the flood year of 2020, the overall SSC remained at 0.52 kg/m^3 , with the average value ranging from 0.23 to 1.26 kg/m^3 , and the maximum value observed at BG6. The SSC exhibited a significant vertical stratification, with concentrations in the bottom layer being much higher than those in the surface and middle layers. At locations such as BG5, BG6, and BG7, which are near the TMZ and channel mouth, the peak SSC in the bottom layer exceeded 3.0 kg/m^3 , while surface-layer SSC remained below 0.4 kg/m^3 . Notably, the bottom-layer SSC at BG6 was 11.24 times higher than the surface-layer SSC at the same station (Fig. 7A).

In the dry year of 2023, the overall SSC significantly decreased to 0.29 kg/m^3 , with the average SSC ranging from only 0.07 to 0.66 kg/m^3 , and the degree of vertical stratification was also notably weakened. The SSC ratio between the bottom and surface layers at BG6 dropped to 3.18, and the peak SSC in the bottom layer was less than 0.2 kg/m^3 . Meanwhile, comparing areas such as BG5-BG7, which showed significant SSC declines, BG1-BG3 maintained relatively stable SSC levels, with differences from the flood year less than 0.1 kg/m^3 . At BG4, a slight increase in SSC was even observed. Additionally, compared to the flood year, the

SSC peak in the dry year shifted upstream, appearing earlier at BG5 (Fig. 7B).

4.2.2. Dominant sediment characteristics

In the flood year of 2020, the proportion of dominant sediment at all stations remained relatively high, ranging from 61.7% to 98.2%. Among these, BG3 exhibited the highest proportion of dominant sediment at 98.2%, followed by BG2 and BG1 with 95.8% and 96.0%, respectively. From a longitudinal perspective, the proportion of dominant sediment remained stable above 90% from XQTD to BG3. However, a gradual decline was observed starting from BG4 at the TMZ, where the synergistic relationship between dominant flow and dominant sediment became apparent across the entire cross-section (Fig. 8A).

In the dry year of 2023, the proportion of dominant sediment at all stations decreased significantly, ranging from 42.9% to 79.9%, with more pronounced variability along the longitudinal axis. Notably, the proportion at BG5 sharply dropped to 42.9%, shifting from an ebb-tide dominance to a flood-tide dominance, which disrupted the synergy between dominant flow and dominant sediment (Fig. 8B).

4.2.3. Spatial structure of suspended sediment concentration

In the flood year of 2020, the spatial distribution of SSC exhibited distinct stratification with localized high-concentration areas. High SSC zones were mainly concentrated in the mid-lower water layers at a depth of 5–10 m in the BG5-BG6 stion of the TMZ, where the maximum SSC exceeded 3.0 kg/m^3 . In contrast, SSC in other areas and surface waters generally remained below 0.5 kg/m^3 , with vertical concentration differences reaching over 2.5 kg/m^3 (Fig. 9A).

In the dry year of 2023, the spatial distribution of SSC was characterized by low-concentration widespread aggregation. High SSC zones shifted upstream, appearing before BG4 and extending further upstream. The SSC in the BG1-BG3 slightly increased. Across the entire cross-section, SSC was generally below 1.32 kg/m^3 , with high SSC zones only appeared in the extremely narrow near-seabed area at a depth of 8–10 m in the BG4-BG6 stion. The maximum SSC was observed at the bottom of BG5. Vertical concentration differences diminished to within 1.0 kg/m^3 , but the coverage area extended upwards, reaching near the surface at a depth of approximately 2 m (Fig. 9B).

4.2.4. Vertical grain-size sorting of suspended sediments

In the flood year of 2020, ΔD_{50} exhibited distinct longitudinal variability. From XQTD to BG2, vertical sorting remained stable, with surface-bottom grain-size differences of 0.004–0.005 mm (Fig. 10A–C).

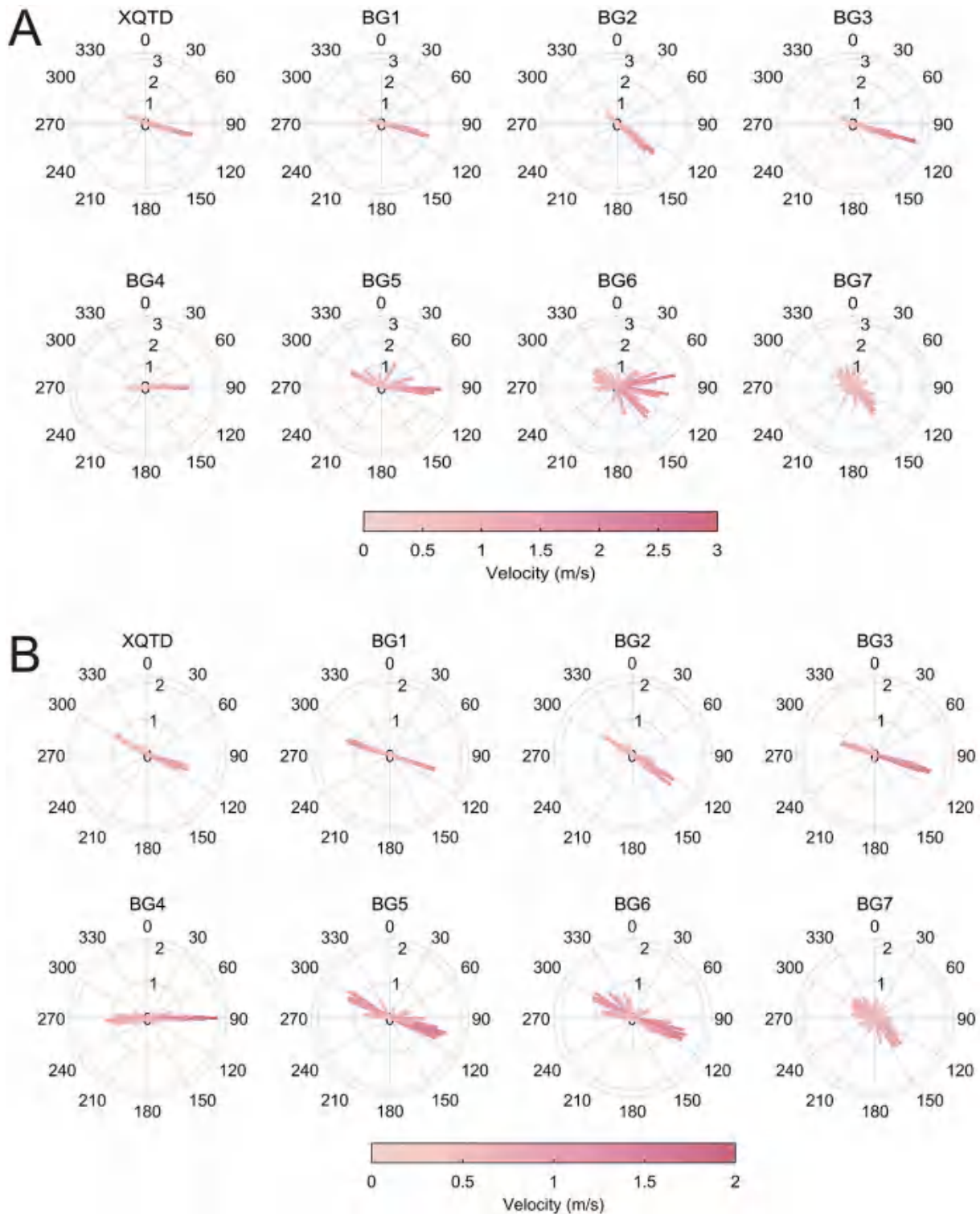


Fig. 4. Vector diagram of average flow velocity at each station (A: 2020; B: 2023).

Sorting intensity remained nearly unchanged at BG3 and slightly increased at BG4 (Fig. 10D–E). From the TMZ core to the tidal-bar region, sorting weakened rapidly, and the surface-bottom grain-size difference became negligible at BG6 (Fig. 10F–G). An inverse vertical grain-size pattern was observed at BG7 in the offshore section (Fig. 10H). Thus, vertical sorting during the flood year followed a downstream transition from relative stability to progressive weakening.

In the dry year of 2023, the longitudinal distribution of ΔD_{50} differed markedly from that in the flood year. Sorting intensity from XQTD to

BG2 was lower than that during the flood year (Fig. 10A–C), whereas higher values occurred at BG3 and BG6, with vertical grain-size differences of 0.010 and 0.004 mm, respectively (Fig. 10D, Fig. 10G). The pattern at BG7 remained consistent with that of the flood year (Fig. 10H). Overall, ΔD_{50} exhibited pronounced spatial heterogeneity between flood and dry years rather than uniform longitudinal changes along the channel.

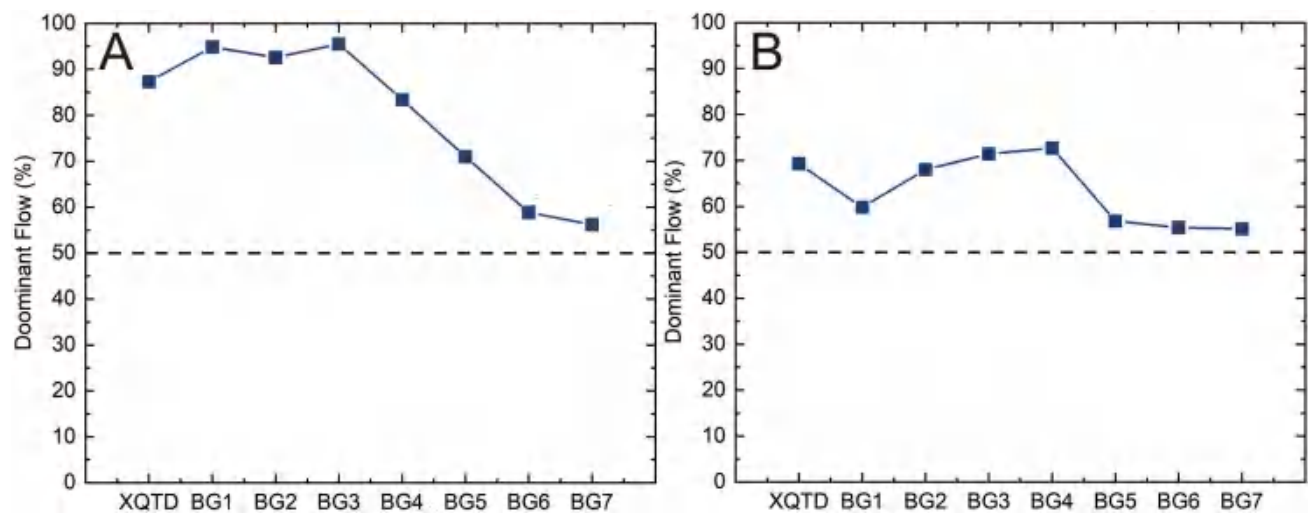


Fig. 5. Dominant flow at each station (A: 2020; B: 2023).

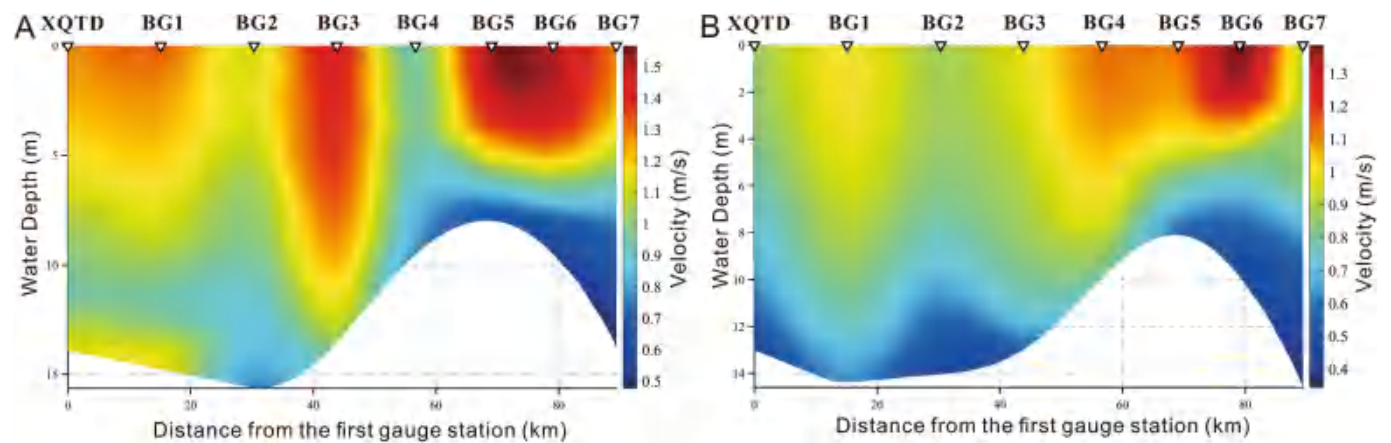


Fig. 6. Mean flow velocity along North Channel (A: 2020; B: 2023).

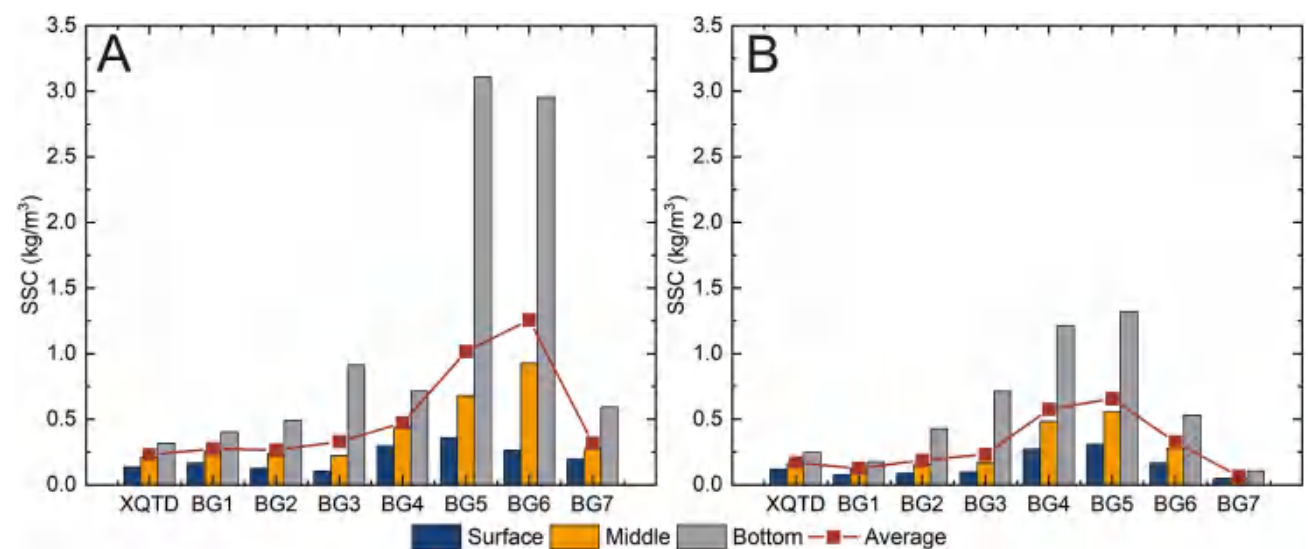


Fig. 7. Sediment Concentration Distribution by Layer and Vertical Mean (A: 2020; B: 2023).

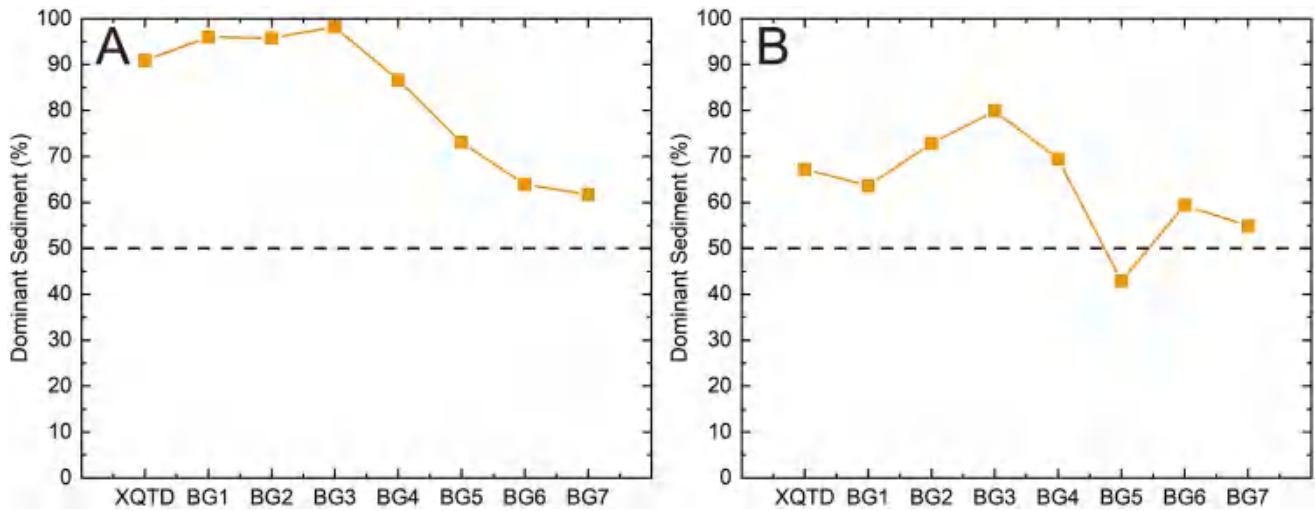


Fig. 8. Dominant sediment at each station (A: 2020; B: 2023).

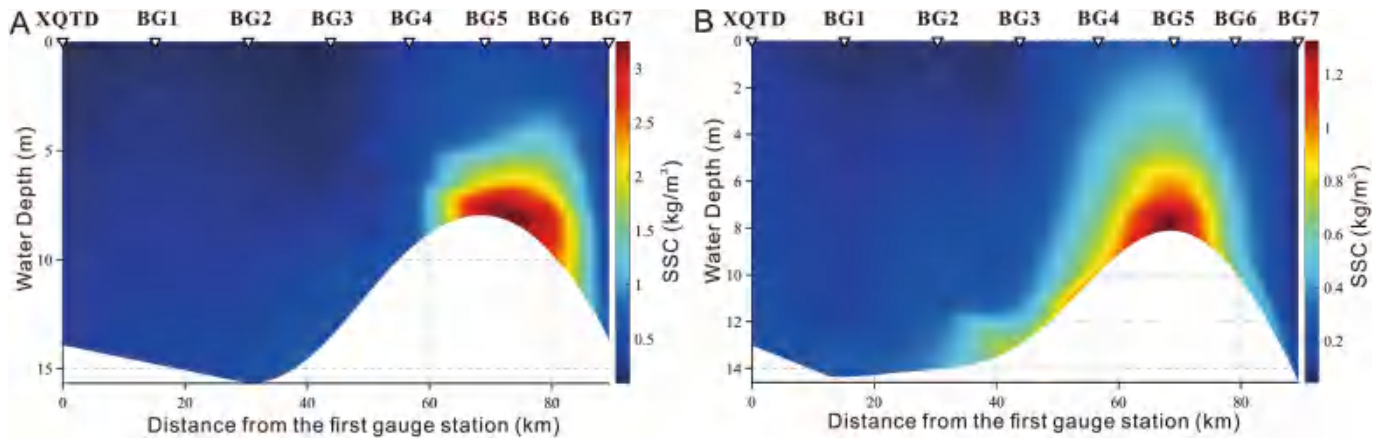


Fig. 9. Mean suspended sediment concentration along North Channel (A: 2020; B: 2023).

4.3. Variations in EOF modes of hydrodynamics and sediment

4.3.1. Variation patterns of flow velocity

The variance contribution of EOF1 for 2020 and 2023 was 78.84% and 81.92%, respectively, making it the most dominant variation mode. It primarily reflects a synchronous ebb and flood tide pattern characterized by “tidal flow periodicity, runoff amplitude modulation” (Fig. 11A1, B1). Spatially, EOF1 showed positive eigenvectors across all stations for both years, with the TMZ area exhibiting the most sensitive response, where eigenvector values exceeded 0.4 (Fig. 11A1, B1). In terms of temporal coefficients, the flood year of 2020 magnified the difference in flow velocity between ebb and flood tides, with the absolute feature weight reaching up to 4.19. Conversely, in the dry year of 2023, the symmetry of ebb and flood tides was restored, reducing the flow velocity differences and resulting in smaller feature weights, with a maximum value of 3.49 (Fig. 11A2, B2).

EOF2 accounted for 21.16% and 18.08% of the variance in 2020 and 2023, respectively, representing a secondary variation mode. This mode captures the spatial differentiation pattern of “runoff control upstream, tidal flow control downstream” (Fig. 11A3, B3). In both flood and dry years, the eigenvectors showed negative values in the upper reaches XQTD-BG3 and positive values at the offshore stations BG4-BG7, indicating contrasting flow velocity changes across different regions (Fig. 11A3, B3). Temporal coefficients for EOF2 also exhibited a semi-diurnal periodicity, but the phase was shifted relative to the first mode (Fig. 11A4, B4).

4.3.2. Variation patterns of suspended sediment concentration

The variance contribution of EOF1 was 74.00% and 68.89% for the flood year of 2020 and the dry year of 2023, respectively, representing the most dominant mode of variation in the SSC field (Fig. 12A1, B1). In 2020, the eigenvectors were predominantly negative, especially in the downstream TMZ core areas at BG5 and BG6, where strong sediment accumulation was observed, with eigenvector values of -0.61 and -0.78 , respectively. Only the furthest offshore site, BG7, showed a slightly positive eigenvector (Fig. 12A1). In 2023, the abnormal sediment response occurred earlier and was concentrated at BG5, with a strongly negative eigenvector (Fig. 12B1). Additionally, the temporal coefficient for the dry year displayed smaller fluctuations compared to the flood year (Fig. 12A2, B2).

EOF2 indicated that anomalous sediment responses were concentrated around the TMZ. In the flood year of 2020, a reverse dynamic pattern emerged at BG5 and BG6, with a particularly strong response at BG5, where the absolute eigenvector value reached 0.79 (Fig. 12A3). In the dry year of 2023, the spatial differentiation became more pronounced, with the reverse pattern shifting upstream to BG4, where the value reached 0.98, indicating localized sediment accumulation at this single station (Fig. 12B3).

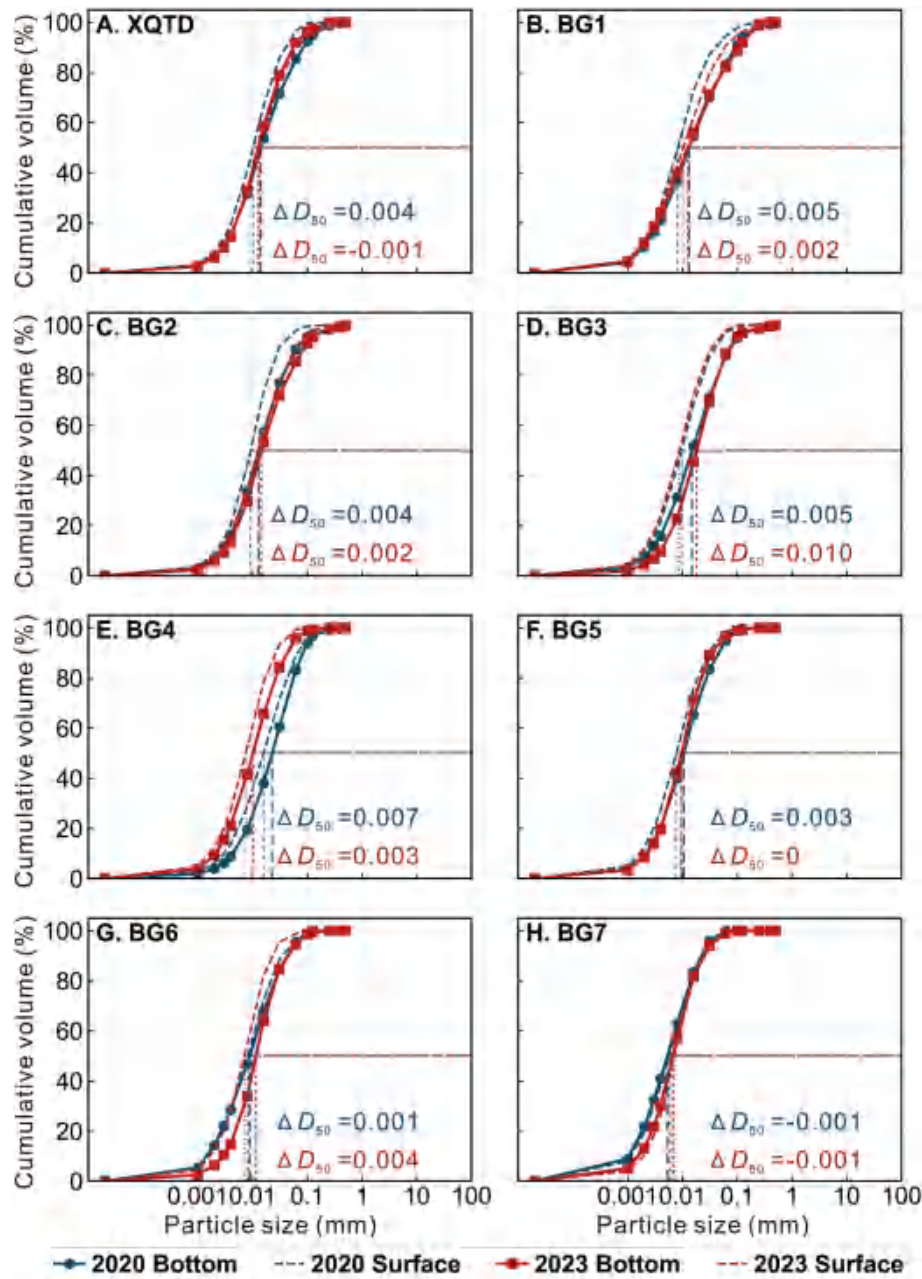


Fig. 10. Vertical cumulative grain-size distribution curves of suspended sediment at each station.

5. Discussion

5.1. Influence from upstream

The average SSC ratio across eight stations in the North Channel was 2.18, comparable to the flood-to-dry year runoff ratio of 2.73 at Datong Station (Fig. 13A–B). The parameter exceeded the stratification threshold in both years, reaching 0.393 in the flood year and 0.173 in the dry year, indicating strong suppression of tidal mixing by buoyancy stratification (Fig. 14). Partial regression analysis showed that runoff explained 40.5% of SSC variability ($P < 0.001$), whereas tidal range contributed only 3.8% without statistical significance, confirming runoff as the dominant driver of interannual SSC variations (Fig. 15A–B). Similar relationships have been reported in other estuaries, such as the Mekong River Estuary (McLachlan et al., 2017; Xie et al., 2022; Zhang et al., 2024). The slightly lower SSC ratio than runoff ratio likely results from the “peak dilution effect” during flood years, when large amounts

of sediment are exported offshore (Fig. 9A). During dry years, enhanced tidal mixing promotes local bed sediment resuspension, extending suspended sediment toward the surface layer (Li et al., 2012; Fig. 9B).

Similarly, the average flow velocity ratio in the North Channel was 1.28, comparable to the ebb tidal range ratio of 1.07 (Fig. 13C–D). Runoff and tidal range often jointly influence estuarine water levels and flow velocities (Khojasteh et al., 2021; Xie et al., 2022). Partial regression analysis showed that runoff and tidal range had significant independent contributions to ebb velocity, explaining 40.6% and 35.8% of its variance, respectively (Fig. 15C–D), indicating their joint control of interannual flow variability. Tidal range establishes the baseline tidal forcing, whereas runoff enhances flow velocity and tidal asymmetry by modulating tidal wave interactions (Zhang et al., 2016; Xie et al., 2022). During the flood year, increased runoff further amplified flow velocity, resulting in a velocity ratio slightly higher than the tidal range ratio, consistent with dynamic responses observed in the Qiantang River and Pearl River estuaries (Xie et al., 2022; Li et al., 2023b).

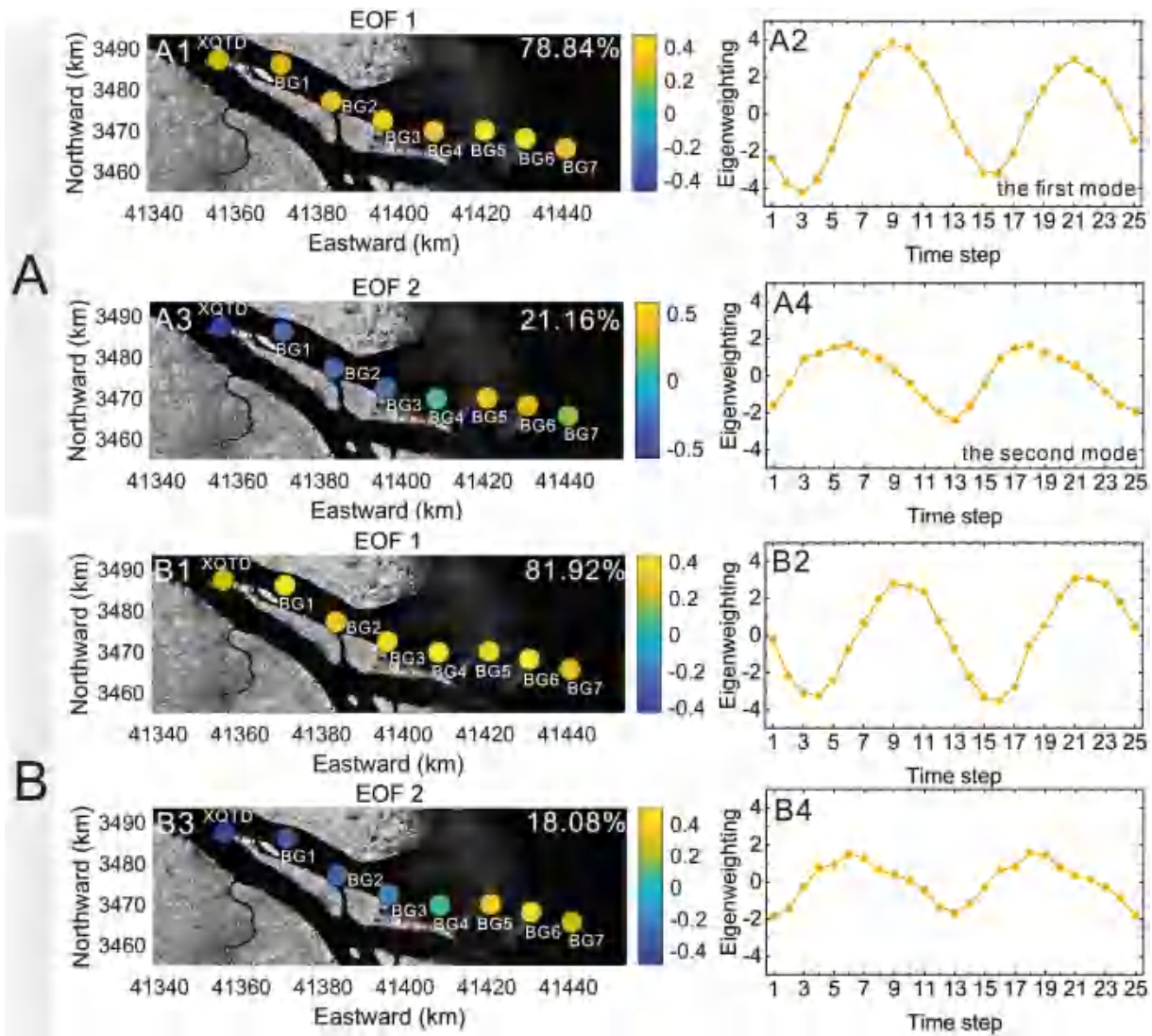


Fig. 11. EOF analysis results of flow velocity between 2020 (A) and 2023 (B): (A1, B1) the first mode eigen vectors; (A2, B2) the first mode eigen weightings curve; (A3, B3) the second mode eigen vectors, and (A4, B4) the second mode eigen weightings curve.

5.2. Impact of flood and dry years on suspended sediment

While upstream runoff exerts a dominant control on the interannual variability of suspended sediment concentration (SSC) in the North Channel, the response of SSC to flood and dry year conditions is not spatially uniform. Instead, it varies markedly across different geomorphic settings, reflecting the combined effects of hydrodynamic forcing and local topographic context.

XQTD, BG5, BG6, and BG7, located at topographically sensitive areas such as the mouth bar and channel mouth, experience significantly increased flow velocity during flood years due to combined upstream runoff and spring tides, enhancing sediment resuspension (Fig. 16A), which aligns with the observed high flow velocity and strong resuspension at the edges of estuarine sandbars or tidal channels in other studies (Nowacki et al., 2019; Du et al., 2025). The coefficient of variation (CV) of SSC at BG5, BG6, and BG7 during flood years is 1.83–2.13 times that in dry years (Fig. 16B), and the Turbidity Maximum Zone (TMZ) migrates approximately 10 km offshore (Fig. 17D–F). In dry years, reduced flow velocity slows suspended sediment exchange, weakens concentration fluctuations, promotes sediment accumulation, and shifts the TMZ peak upstream (Fig. 17), as special estuarine geomorphology becomes more sensitive to hydrodynamic changes under low flow conditions (Ji et al., 2024).

In contrast, BG1, BG2, and BG3, located in the main channel of North Channel, the area beneath the bridge, and around the island, showed higher CV values during the dry year (Fig. 16B). Concentrated flood-year runoff drives strong unidirectional ebb flow that overwhelms obstacle-induced small-scale turbulent mixing, resulting in a more laterally uniform advective transport pattern (Fig. 17). During the dry year, however, as water levels dropped, the influence of shallow shoals, bridge piers, and islands became more pronounced. These obstructions created localized eddies and secondary flows (Wang et al., 2024; Kundu et al., 2025), which maintained relatively high fluctuations in SSC even under low flow conditions (Fig. 18).

BG4, situated at the uppermost part of the TMZ (Fig. 1C), is sheltered by surrounding sandbars, which mitigates the combined effects of flood year runoff and spring tides. This results in lower flow velocities and more uniform water flow compared to dry years (Fig. 16A, Fig. 17A–C), and suppresses SSC fluctuations, thereby forming localized “clear water” zones (Fig. 17D–F). In contrast, during a dry year, the relative influence of tidal forcing increases (Du et al., 2025), leading to a marked increase in SSC variability (Fig. 16B), which reflects the differential responses of microtopography within the TMZ to hydrological changes (Fig. 17D–F, Fig. 18).

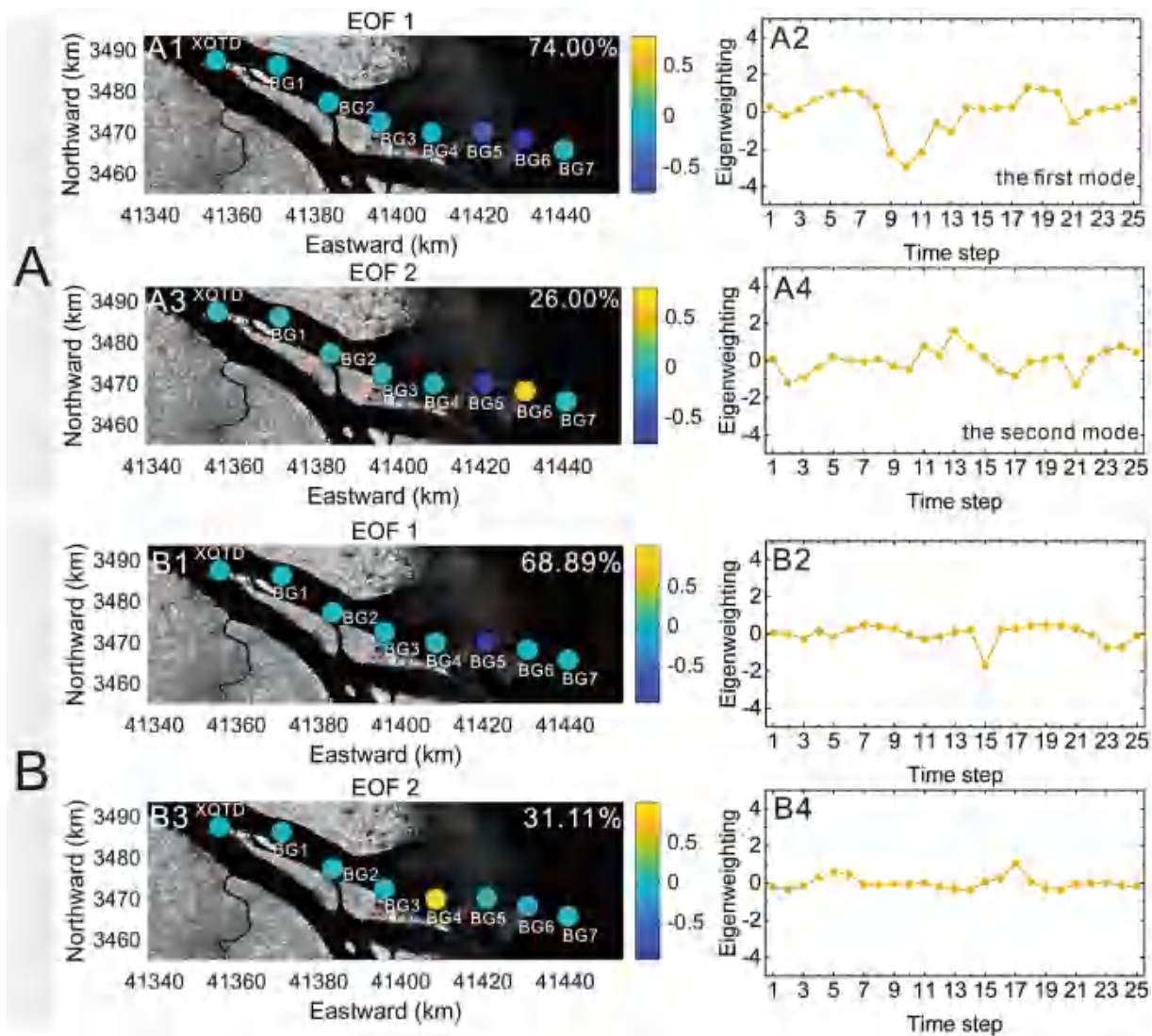


Fig. 12. EOF analysis results of SSC between 2020 (A) and 2023 (B): (A1, B1) the first mode eigen vectors; (A2, B2) the first mode eigen weightings curve; (A3, B3) the second mode eigen vectors, and (A4, B4) the second mode eigen weightings curve.

5.3. Influence of estuarine topography

The North Channel exhibits a “slightly curved” channel morphology, with the deep channel skewed northward in the upper segment and southward in the lower segment. This morphology, combined with features such as sandbars and cross-channel gullies (Fig. 1C), creates significant lateral water depth differences. These topographic characteristics further amplify or moderate the spatiotemporal variations in flow velocity by altering hydrodynamic conditions (Friedrichs and Hamrick, 1996; Xu et al., 2023).

Under high runoff conditions, estuaries commonly experience enhanced hydrodynamic forcing, amplified tidal currents, and intensified sediment transport (van Maanen and Sottolichio, 2018; Xie et al., 2022). Similarly, during the 2020 extreme flood, strong ebb currents were concentrated along the pre-existing deep channel of BG3, generating pronounced high-velocity zones (Fig. 3A, Fig. 5A). The sustained high discharge also maintained relatively uniform velocities across the TMZ, giving rise to a three-peak longitudinal distribution of flow velocity (Fig. 6A). Meanwhile, the flood event induced rapid morphological adjustments (Fig. 19A–C). The subaqueous sand ridge near BG4 remained relatively stable before the flood (Fig. 19A–B), whereas its –5 m isobath retreated substantially after the flood, accompanied by

localized deposition in the tidal-bar region (Fig. 19B–C, E).

In dry years, reduced discharge amplifies the constraining effect of shoals, sandbars, and floodplains on flow paths (Liu et al., 2020). In the upper deep-channel reach near BG3, the post-flood flow spread laterally, resulting in the disappearance of the previously concentrated high-velocity jet (Fig. 6B). During the prolonged post-flood adjustment period, the BG4 sand ridge underwent gradual retreat and progressive morphological smoothing, while temporary deposits at the tidal mouth were progressively redistributed seaward by persistent tidal currents, leaving a gradually more open channel (Fig. 19D, F). This reflects the progressive tidal destabilization of flood-induced unstable slopes (Gasparotto et al., 2023; Du et al., 2023). Estuarine morphological evolution regulates water–sediment transport via cross-sectional adjustments (Fagherazzi et al., 2015). Through these cross-sectional adjustments, flood erosion and subsequent morphological relaxation widened the channel and smoothed the downstream velocity transition, ultimately producing the double-peak velocity structure observed in the 2023 dry year (Fig. 6B).

5.4. Patterns of water and sediment dynamics

The water and sediment dynamics in North Channel are jointly

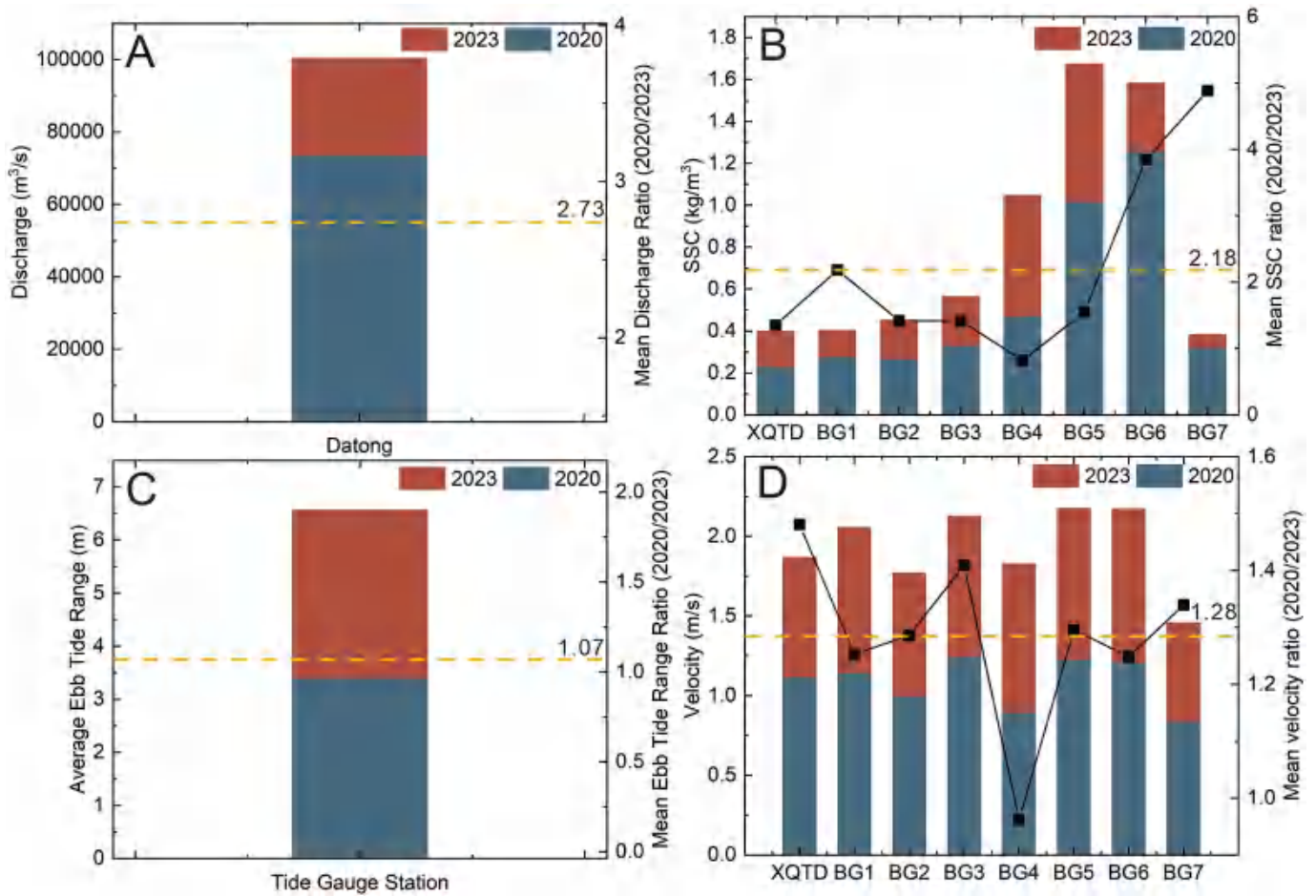


Fig. 13. Hydro-sediment and tidal variations at North Channel stations.

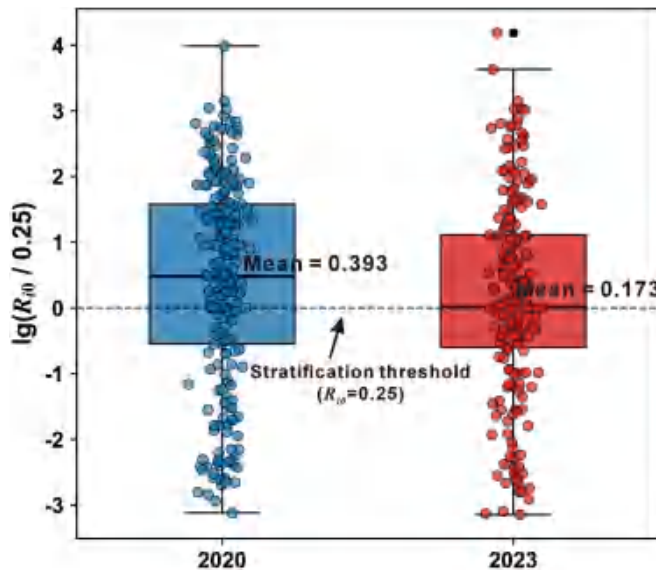


Fig. 14. Statistical characteristics of water column stratification intensity in flood and dry years.

governed by runoff and tidal forces. Under the influence of local topography, distinct hydrodynamic and sediment coupling patterns emerge during flood and dry years (Fig. 20).

In the flood year, high runoff coupled with tidal forces increased the

average flow velocity to 1.08 m/s, forming a three-peak velocity structure along the channel at BG1, BG3, and BG5-BG6 (Fig. 6A, Fig. 20A1). The dominant ebb flow proportion exceeded 90% (Fig. 5A). Initially, BG4 was sheltered by surrounding sandbars, reducing the combined effects of runoff and spring tides (Fig. 19). However, persistent strong runoff gradually eroded the sand ridge near BG4. This erosion allowed upstream sediment to bypass the obstruction and enter the core zone of the TMZ at BG5-BG6. Intense ebb-tide dynamics triggered severe resuspension in this region, with bottom-layer SSC peaks exceeding 3.0 kg/m^3 (Fig. 7A, Fig. 20A1). The vertical stratification over the TMZ became prominent, with sediment progressively transported seawards (Fig. 20A2).

In contrast, during the dry year, reduced runoff resulted in a decrease in average flow velocity to 0.85 m/s, with the velocity structure evolving into a double-peak pattern at BG1 and BG5-BG6 (Fig. 6B, Fig. 20B1). The dominant ebb flow proportion decreased to approximately 70% (Fig. 5B). Tidal influence became more pronounced, highlighting the regulatory role of local topography. By this period, the sand ridge near BG4 had already been eroded (Fig. 19). This geomorphic change widened the channel, dispersed ebb-tide energy, and reduced bottom sediment resuspension. The turbidity maximum zone shifted upstream to BG4, with weakened vertical stratification (Fig. 7B). Sediment transport dominance shifted to flood tides at BG5 (Fig. 8B). Under enhanced tidal diffusion, sediment was redistributed upstream. Consequently, downstream sediment enrichment at BG5-BG6 diminished (Fig. 20B2).

Vertical grain-size sorting of suspended sediments provides independent sedimentological evidence for comparing the two patterns described above. Between 2020 and 2023, ΔD_{50} exhibited pronounced

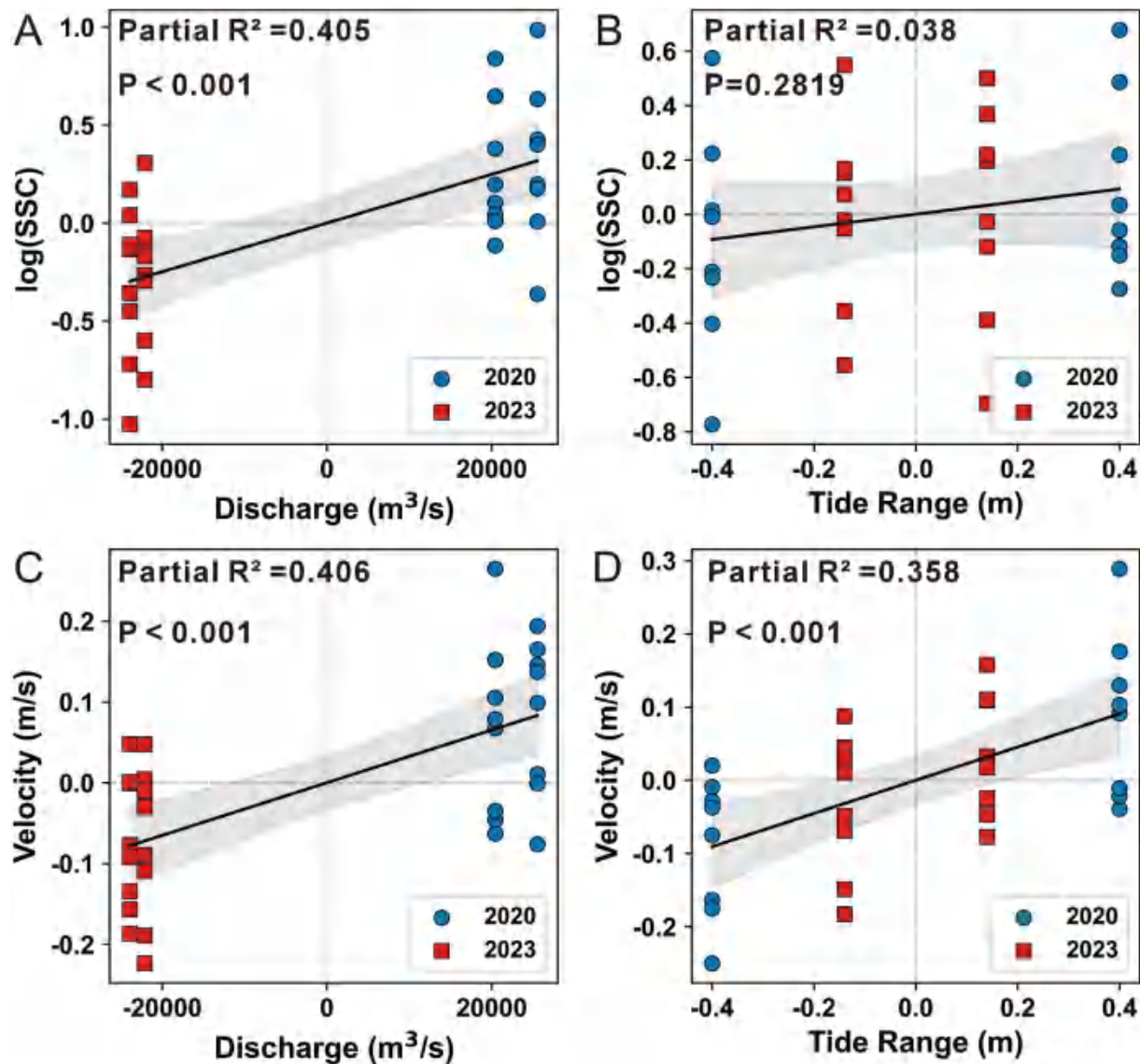


Fig. 15. Partial regression analysis of discharge and tidal range effects on suspended sediment concentration and current velocity in flood and dry years.

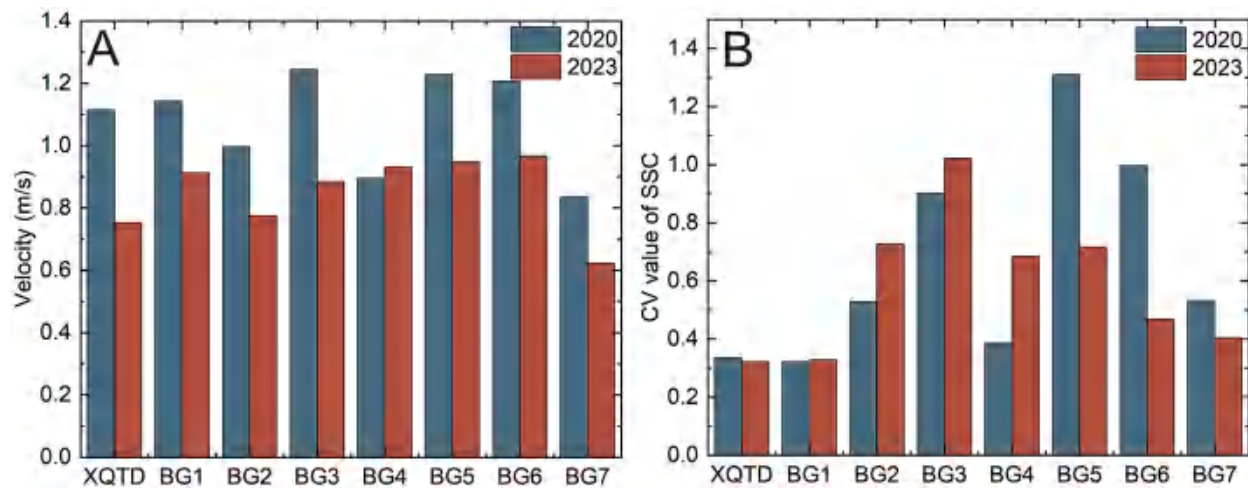


Fig. 16. Variations in flow velocity and SSC CV values at North Channel stations.

spatial differentiation along the channel. Changes were not synchronous throughout the entire reach. In the upper reach from XQTD to BG2,

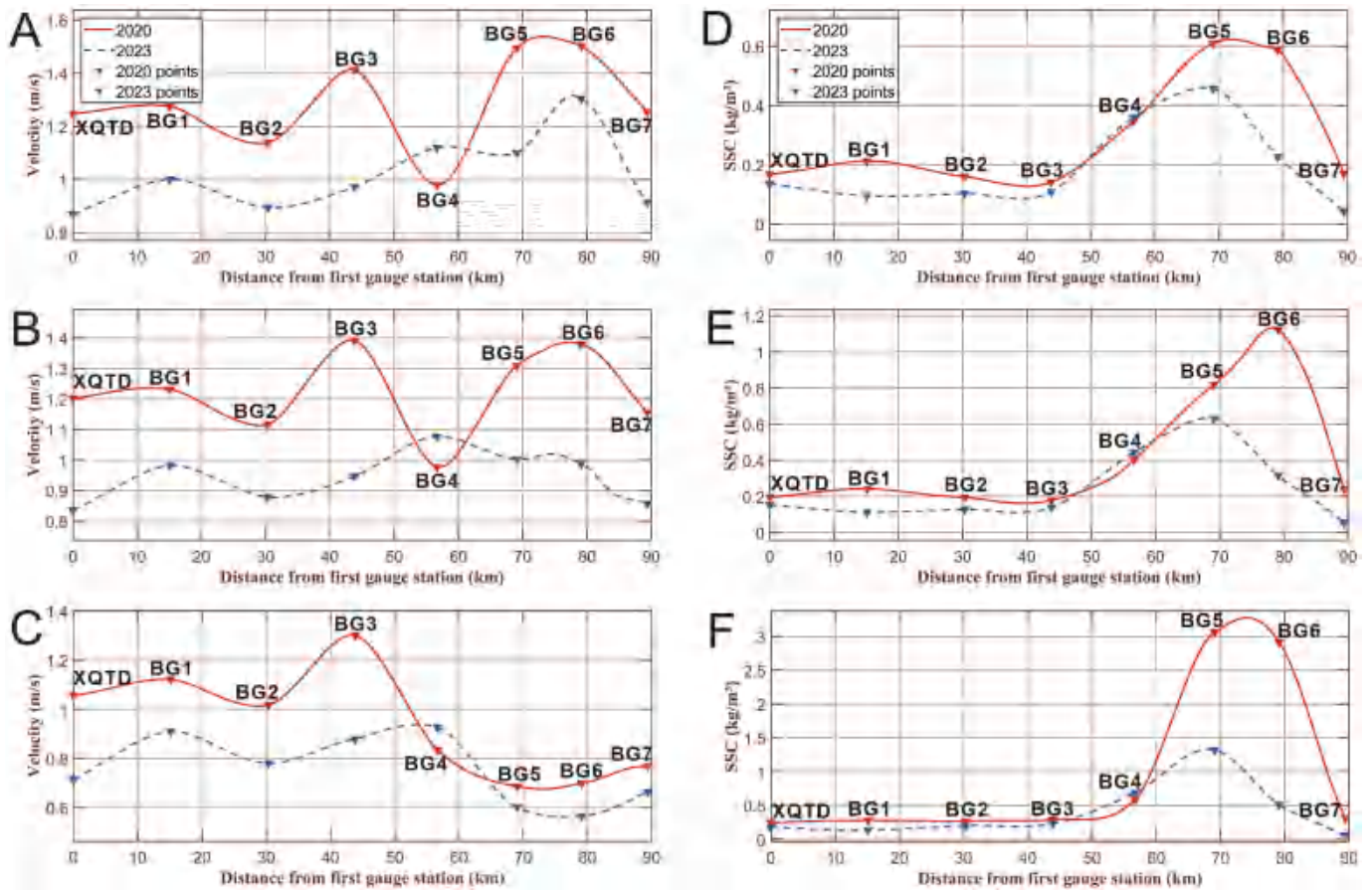


Fig. 17. Longitudinal variations in velocity and SSC at each layers along the North Channel (AD: Surface; BE: Middle; CF: Bottom).

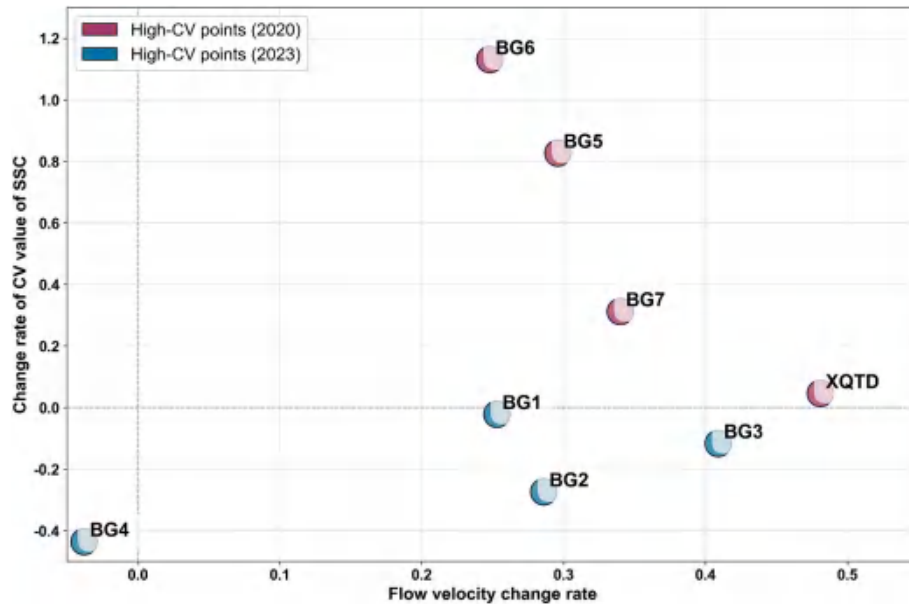


Fig. 18. Relationship between flow velocity change rate and variation in CV of SSC.

sorting was weaker during the dry year. Larger differences between flood and dry years occurred at BG3 and BG6, whereas little change was observed at BG7 (Fig. 10). This asynchronous response indicates that interannual variations in the vertical structure of suspended sediments were not solely controlled by uniform grain-size inputs from the

watershed. Instead, they were closely associated with spatially heterogeneous reorganization of local hydrodynamic sorting.

EOF analysis confirmed that strong runoff during the flood year amplified differences between ebb and flood tides, whereas tidal penetration upstream increased during the dry year (Fig. 11, Fig. 12). In

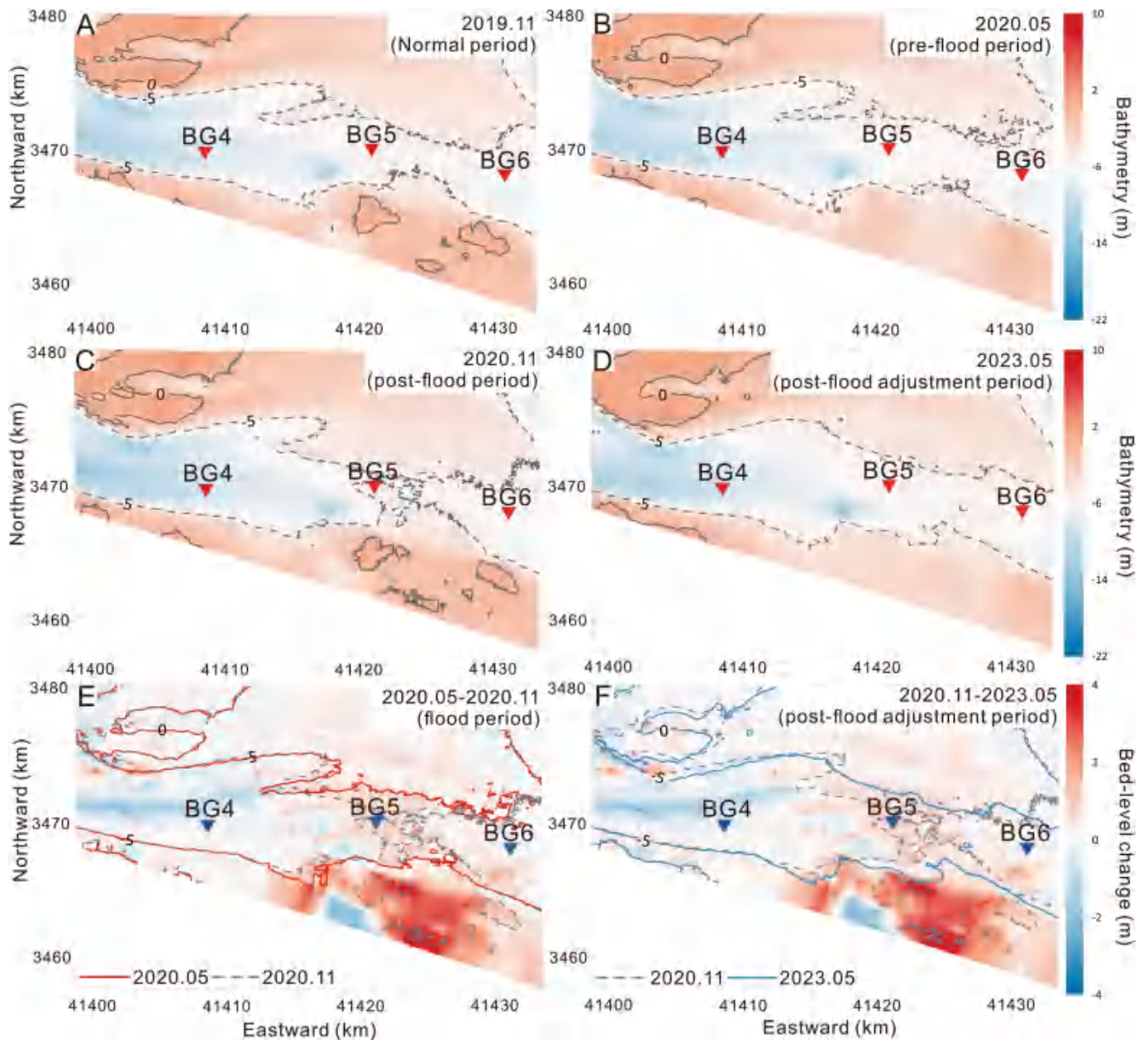


Fig. 19. Subaqueous topography and temporal erosion-deposition patterns during flood-related stages.

summary, the core of water-sediment coupling pattern lies in the hydrodynamic restructuring driven by the competition between runoff and tidal forces. Superimposed on topographic responses, this interplay governs the spatiotemporal differentiation of water and sediment dynamics between flood and dry years.

6. Conclusions

This study focuses on the North Channel in the Yangtze Estuary, analyzing the variations in flow velocity, suspended sediment concentration, and topographical changes during the flood year of 2020 and the dry year of 2023. It explores the driving mechanisms of water and sediment processes, with the main conclusions as follows:

- (1) Differences in water and sediment quantities and structures between flood and dry years: there are significant differences in the quantities and spatiotemporal structures of flow velocity and SSC between flood and dry years. In the flood year, the average flow

velocity was 1.08 m/s, characterized by a three-peak distribution, and SSC ranged from 0.23 to 1.26 kg/m³ with evident vertical stratification. The Turbidity Maximum Zone (TMZ) at the mouth bar migrates seaward compared to the dry year, reaching as far as approximately 10 km offshore. During the dry year, the average flow velocity decreased to 0.85 m/s, showing a double-peak distribution, and SSC reduced to between 0.07 and 0.66 kg/m³, with weakened stratification and the TMZ shifted upstream.

- (2) Changes in dominant flow, sediment, and EOF patterns: the flood and dry years significantly affected the dominant flow, sediment, and EOF change patterns. The flood year was primarily dominated by ebb tides, with the dominant flow proportion exceeding 90% and stable hydrodynamics. In the dry year, enhanced tidal dominance reduced the proportion of the dominant flow, disrupting the coherence of water and sediment interactions. EOF analysis indicated that the primary modes of flow velocity and SSC reflect synchronous changes regulated by runoff and tides and the localized sediment concentration response, respectively.

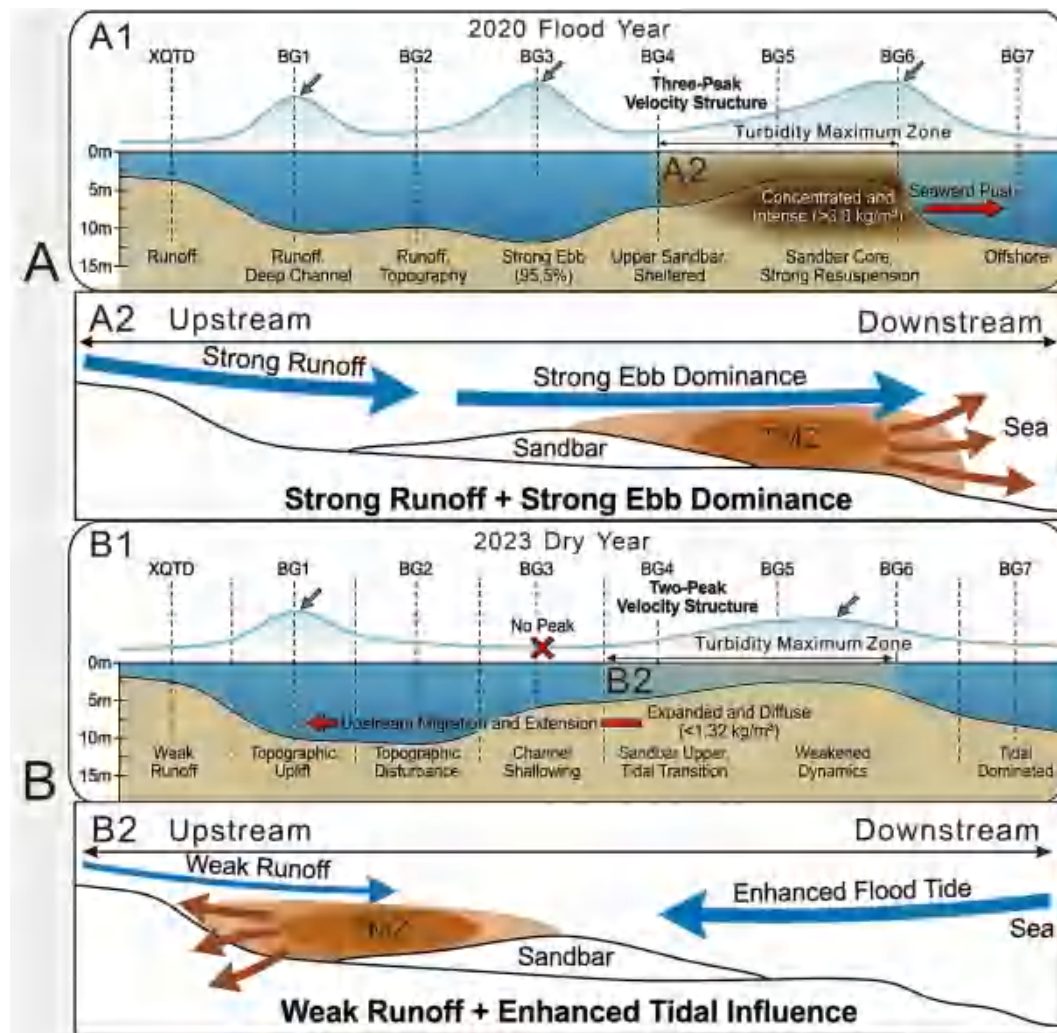


Fig. 20. Hydro-sediment Dynamics and Conceptual Models in the North Channel (A: 2020 flood year; B: 2023 dry year).

- (3) Driving mechanisms of water and sediment changes: the inter-annual changes in water and sediment are primarily driven by upstream runoff, tidal range differences, and local topography. Runoff dominates SSC variations, whereas runoff and tide jointly shape flow velocity with comparable contributions. Local topography further modulates the spatial pattern of water and sediment processes. In the flood year, the scouring of sand ridges formed a three-peak flow velocity pattern, while in the dry year, intensified topographic disturbances led to the attenuation of high-velocity zones.
- (4) Coupled water and sediment change patterns: the flood year is characterized by “high runoff, ebb tide dominance, strong suspended sediment, and outward migration of the TMZ,” whereas the dry year is characterized by “low runoff, tidal dominance, weak suspended sediment, and upward migration of the TMZ.” The hydrodynamic adjustments resulting from the interplay between runoff and tidal forces primarily govern the spatiotemporal differentiation of water and sediment.

CRedit authorship contribution statement

Ying Zhou: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **Zhijun Dai:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Weihua Li: Writing – review & editing, Supervision, Resources, Methodology, Data curation, Conceptualization. **Xuefei Mei:** Writing – review & editing, Project administration, Investigation, Data curation, Formal analysis, Methodology, Software. **Wenjun Zeng:** Supervision, Methodology. **Aoyang He:** Validation, Methodology, Investigation, Data curation.

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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Data availability

Data will be made available on request.

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