

Spatiotemporal variability of suspended sediment concentration in the coastal waters of Yellow River Delta: Driving mechanism and geomorphic implications

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14 **Highlights:**

- 15 • Deltaic and regional scale decreasing trend of sediment concentration is detected.
- 16 • The surface sediment dynamics is strongly related to sediment resuspension process.
- 17 • Contributions of waves and currents on sediment resuspension is quantified.
- 18 • Coarsening of seabed sediment contributes to interannual decrease of resuspension.
- 19 • High sediment concentration zones are accorded with active erosion-accretion areas.

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Abstract

Satellite images have revealed a significant decline in the suspended sediment concentration (SSC) near surface in the coastal waters of Yellow River Delta (YRD) in recent years. However, there is limited information on the spatial disparity in SSC distributions and its dynamic mechanism. In this study, we utilize a well-calibrated SSC retrieval algorithm and a depth-averaged numerical modelling approach to investigate the delta and sub-delta scale variation trends and driving mechanisms of SSC in the coastal waters of YRD over the past few decades. The results of this study demonstrate the existence of high turbidity zones in coastal waters of the northern abandoned delta and the active lobe of the YRD. These zones have experienced general decreasing trends of SSC at the interannual timescale. Additionally, the distribution of SSC is significantly higher in dry seasons compared to that in wet seasons. The magnitude and varying trends of SSC are strongly influenced by the total bottom shear stress (BSS) caused by combined effects of waves and currents, although the wave-induced BSS is found to be less significant than the current-induced one, but vary more significantly due to wind forcing in the Bohai Sea. Furthermore, the grain size of seabed sediments plays a dominant role in the sediment mobilization and resuspension processes over interannual and longer timescales. The distribution of high BSS and sediment mobility zones align with the active areas for morphological changes with the YRD exhibiting net accretion in the active river mouth and erosion in the abandoned delta lobes. These findings highlight the multiscale variations and the close relationship between SSC and BSS, providing valuable insights into sediment dynamics with geomorphic evolution in highly human-interfered deltaic systems.

42 **Keywords**

43 Suspended sediment concentration; Currents and waves; Seabed coarsening; Geomorphic
44 evolution; Yellow River Delta

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1 Introduction

The dynamics of sediment in estuaries and their adjacent coasts are intimately linked to terrestrial sediment transport, deposition, and resuspension processes from the seabed (Xu et al., 2014; Burchard et al., 2018). The suspended sediment concentration (SSC) in these areas is highly dynamic, varying across multiple timescales, including tidal-cycle, seasonal, and longer timescales (Zhou et al., 2017; Wilson and Heath, 2019), due to various influencing factors such as changing river inputs, complex tidal currents, wave climate, and human interventions such as engineering constructions (Wang et al., 2014; Luo et al., 2022; Chowdhury et al., 2023). The SSC also has a significant impact on physical processes in coastal waters and plays a crucial role in regional morphological evolution (Huang et al., 2022). Furthermore, suspended sediment transport can influence biogeochemical recycling, including nutrients and other contaminants, thereby affecting ecological functions in estuarine environments (Bianchi and Allison, 2009; Wang et al., 2017a; Chou et al., 2018). Therefore, understanding the variations and dynamics of SSC in the coastal regions is of primary concern when considering the sustainability of ecosystem and for coastal planning and management (Xue et al., 2012; Chini and Stansby, 2015), in particular for vulnerable mega-deltas such as Yellow River Delta (YRD) in China.

Considerable attention has been paid to the multi-scale dynamics of SSC in the coastal waters of YRD due to its significant role as a primary sink for a large amount of terrestrial sediment input and its highly dynamic shoreline and morphological evolution (Milliman and Meade, 1983; Wu et al., 2017; Jiang et al., 2017). Satellite remote sensing data has revealed a decreasing trend in the distribution of SSC in the coastal waters of YRD (Li et al., 2022; Zhao et al., 2022; Yu et al., 2023). A decline over 30% in SSC has been observed between 1984 and 2021 (Yu et al., 2023).

However, there is limited information available on the detailed variations of SSC at different spatial scales, considering different geomorphic and sedimentary settings in the region.

Furthermore, previous studies have primarily attributed the long-term decrease in sediment resuspension in the coastal waters of the YRD to changing coastal dynamics and decreased fluvial sediment discharge (Zhang et al., 2014; Wang et al., 2019; Li et al., 2023). In addition, Liu et al. (2020) observed a significant coarsening of seabed sediment in the YRD over the past few decades, which could have profound implications for sediment resuspension. Jin et al. (2023) suggested that sea surface elevation and wave forcing are the dominant factors influencing suspended sediment dynamics, which can contribute to the decline in sediment resuspension and SSC. Since the modern YRD is following the single deltaic channel with less sediment delivery, SSC dynamics in the vicinity of the delta are dominated by bottom sediment resuspension associated with coastal ocean dynamics (Bi et al., 2021; Zhang et al., 2022). However, less consideration has been given to the understanding of spatial and temporal dynamics of SSC distributions in complex delta environments, especially in seasonal and interannual timescale. And the quantification of contributions of main coastal hydrodynamics, including tidal currents and waves, on sediment resuspension processes has rarely been reported.

In this study, by analyzing the recent distributions and variability of SSC in the coastal waters of YRD from 1996 to 2020, considering the changing coastal dynamics, we primarily aims: (1) to quantify the seasonal and interannual variations of SSC in the coastal waters at both delta and sub-delta scales; (2) to quantify the contributions of tidal currents and waves dynamics on the distribution of SSC; (3) to identify dominant factors that influence the SSC dynamics at different timescales, and their effects on the morphological evolution of the YRD. This research is to

provide valuable insights into sediment transport dynamics in the highly human-interfered delta system, particularly in the new geomorphic settings resulting from recent engineered diversion.

2. Study Area

This research is centered in the coastal area of the modern YRD, as shown in [Figure 1](#). This area has experienced rapid development since 1855, when the Yellow River breached at Tongwaxiang and shifted to the Daqinghe River Course, eventually entering the Bohai Sea. This has led to rapid accretion and frequent channel avulsions, driven by a significant influx of flow and sediment from the Yellow River. As a result, the deltaic channel shifted from the Shenxiangou channel (1953-1964) to the Diaokouhe (DKH) (1964-1976) and the Qingshuigou (QSG) channel (1976-present). More recently, an engineered diversion was implemented at the Q8 mouth channel to ensure the stability of the QSG channel ([Chu et al., 2006](#); [Peng et al., 2010](#)).

The evolution of the delta and its river mouth is significantly influenced by natural and human-induced changes in river input, tidal forcing, and wave dynamics ([Jiang et al., 2013](#)). From 1950-2022, the water discharge to the sea is measured as 1784 m³/s during flood seasons and 567 m³/s in the dry seasons. Since the implementation of Water–Sediment Regulation Scheme (WSRS), peaks of water discharge with high SSC appear in late June and early July, contributes 28% and 54% of annual water discharge and sediment load in average ([Wang et al., 2017b](#)). The coastal regions of YRD is dominated by irregular semi-diurnal tides with average tidal ranges of 0.73–1.77 m ([Yang et al., 2011](#)). Tidal currents are generally parallel to the coastline, which flow southward during flood tide and northward during ebb tide with an average speed of 0.5–1.0 m/s ([Bi et al., 2010](#)). As regards the wave condition in the coastal waters of the YRD, is dominated by northerly wind waves with an average wave height of 0.57 m and an average wave period of 4.3 s indicated by multi-year observations during 2006-2019 ([Ji et al., 2022](#)).

To examine the distributions of SSC under combined riverine and oceanic forcing in detail, including tides, waves and wind, as well as their geomorphic impacts, the study area is divided into five littoral zones. These zones cover different types of erosion-accretion patterns from the northern YRD to the south as: Zone P1 for the abandoned DKH delta lobe, Zones P2 and P3 for engineering-protected coasts, Zone P4 for the active river mouth (Q8 delta lobe), and Zone P5 for the abandoned QSG delta lobe, as indicated in Figure 1.

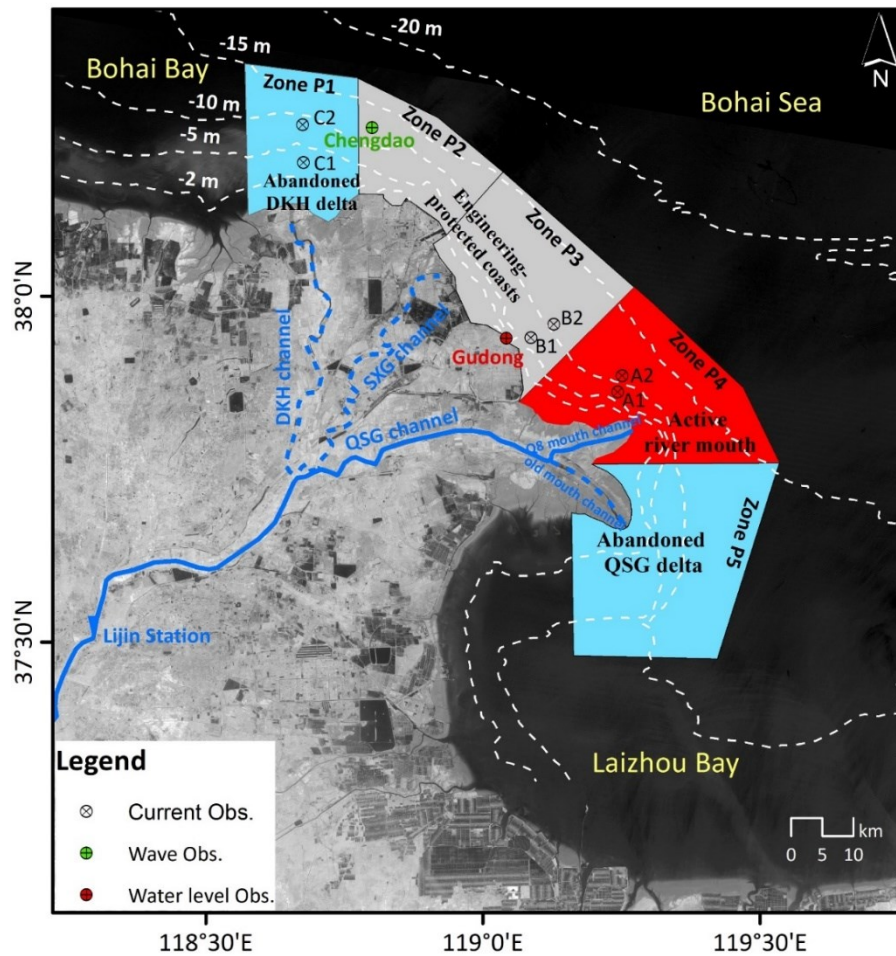


Figure 1. Map of the YRD, with locations of in-situ observation sites for waves, water levels, and currents (A, B, C) and zoning (Zones P1-P5).

3. Materials and methods

3.1. Data collection

Multi-year hydrographic surveys were conducted to collect data on water levels, tidal currents, and wave climate in the vicinity of the YRD, as shown in Figure 1. Water level changes were recorded at the Gudong tide-gauge station, which is located near the Gudong oilfield in the north of the active Q8 delta lobe. In-situ current observations were carried out during flood seasons from July 8-11 and October 14-15 in 2009 at well distributed 6 locations: two stations (C1 and C2) in the northern abandoned delta (Zone P1), two stations (B1, B2) in the engineering-protected coast (Zone P3), and two stations (A1, A2) in the active river mouth (Zone P4). Hourly data for wind and waves were measured and recorded at the Chengdao platform throughout 2018.

During the study period, high-resolution bathymetric surveys were carried out in the subaqueous YRD in 2000, 2007, and 2015. The surveys included the measurement of 130 transects perpendicular to the deltaic coasts by the Yellow River Conservancy Committee. Additionally, surface seabed sediments were collected using a bottom sediment sampler, with 124 samples collected in 2000, 156 samples in 2007, and 136 samples in 2015, respectively (Figure S1).

3.2. Retrieval of SSC

A total of 541 satellite images, taken from Landsat-5 TM, Landsat-7 ETM, and Landsat-8 OLI image data with cloud cover <10%, are utilized to retrieve the distribution of SSC dynamics near the YRD during the period of 1996-2020 (Figure S2). Level-1 30-m resolution Landsat images are downloaded from the U.S. Geological Survey's remote sensing image database (<https://earthexplorer.usgs.gov/>) and are atmospherically corrected using the dark spectrum fitting (DSF) algorithm (Vanhellemont and Ruddick, 2018) embedded in the ACOLITE software package

(<http://odnature.naturalsciences.be/remsem/acolite/>). The SSC retrieval algorithms developed purposely for the YRD is employed (Li et al., 2019). The SSC retrieval models for TM, ETM+, OLI are expressed by Eqs. (1), (2) and (3), respectively:

$$lgSSC = 0.7603 \times X_1 + 21.7036 \times X_2 + 0.6547 \quad (1)$$

$$lgSSC = 0.7460 \times X_1 + 21.2955 \times X_2 + 0.6654 \quad (2)$$

$$lgSSC = 0.8079 \times X_1 + 23.062 \times X_2 + 0.6258 \quad (3)$$

where $X_1=R_{rs}(\text{red})/R_{rs}(\text{green})$, $X_2=R_{rs}(\text{NIR})$, which is correspond to the remote sensing reflectance of the red, green, and NIR bands of the satellite images respectively. The SSC retrieval model has been validated against in-situ observed SSC from water samples and further details can be found in Li et al. (2019) and Li et al. (2021).

3.3. Numerical model set-up and validation

3.3.1 Hydrodynamic and wave model of TELEMAC suite

To investigate the tidal and wave processes and their interactions off the YRD, a numerical modeling method based on the TELEMAC suite (Hervouet, 2007) is employed. The TELEMAC2D module, which is the coastal circulation module in TELEMAC, is used to solve shallow-water equations and compute two-dimensional coastal hydrodynamics. The wave module, on the other hand, is calculated using TOMAWAC, a third-generation spectral wave-propagation model that accounts for key processes such as wave refraction, white capping, bottom friction, and wave breaking.

The internal coupling of the TELEMAC-TOMAWAC modules considers wave-current interactions in both directions. TELEMAC2D transfers the updated values of current velocities

and water depths to TOMAWAC, while TOMAWAC solves the wave action density conservation equation with reference to those current and water depth values. TOMAWAC then returns the updated values of the wave driving forces acting on the coastal currents to TELEMAC2D.

Due to the long-term calculation time span and to save computation costs, the coupled TELEMAC2D and TOMAWAC module is utilized to compute 2D depth-averaged coastal dynamics and wave propagation processes. This approach is used because the coastal waters of YRD are well-mixed, but only partially-mixed during flood seasons concentrated at the active river mouth (Wang et al., 2017c).

3.3.2 Model set-up

Due to the significant changes of underwater geometry, shoreline positions, and seabed sedimentary environments in the study site during the periods of 1996-2006, 2007-2015, and 2015-2020, three computational mesh systems are created at each period, namely 2000, 2007, and 2015 (Figure 2). For the boxed area in Figure 2a, the mesh includes 11,052 nodes with 20,161 elements for 2000 (Figure 2b), 17,565 nodes with 32,011 elements for 2007 (Figure 2c), and 21,732 nodes with 42,015 elements for 2015 (Figure 2d). The river boundary is set at the section of Q8 mouth channel located 20 km from the river mouth outlet. No river input is imposed at the old mouth channel. The open ocean boundary is located in the northern Yellow Sea and is driven by tidal levels and depth-averaged velocities from the TPXO 8.0 database.

In the hydrodynamic model, varying wind velocities across the Bohai Sea are sourced from the ECMWF-ERA5 database (<https://cds.climate.copernicus.eu>), with a spatial distribution of 0.125° and a time interval of 6 hours each day. These wind velocities are implemented at every mesh node and at each time step. The wind effect on water surface variations is evaluated using

the coefficient of wind influence, which varies with wind speed ranging from 0.565×10^{-3} to 2.513×10^{-3} . The bottom roughness has been calibrated to 0.016 of the Manning coefficient based on previous research (Ji et al., 2020). In the wave model, the time step is set to 30 seconds. Wind waves are also generated by modified ECMWF wind field, which is validated against observations. The wave spectrum is discretized into 12 directions and 25 frequencies. The minimal frequency is 0.0417 Hz (24 seconds), and the frequency ratio is 1.1.

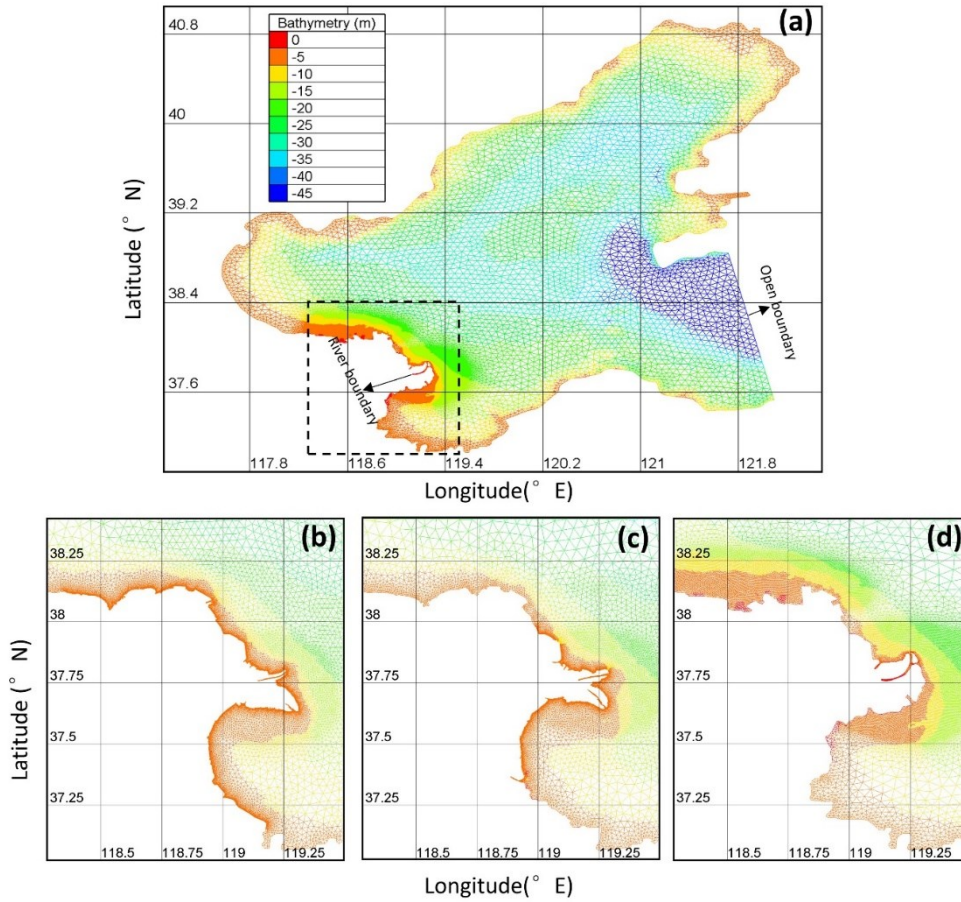


Figure 2. Overall computational domain with bathymetry in the Bohai and Yellow Seas (a) and model mesh in the coastal area at (b) 2000; (c) 2007; and (d) 2015

3.3.3 Model validations

The model performance is evaluated by calculating the root-mean-square error (RMSE) and the correlation coefficient (CC) between the computed variables and the observations:

$$RMSE = \sqrt{\frac{\sum (X_{cal} - X_{obs})^2}{N}} \quad (4)$$

$$CC = \frac{\sum (X_{cal} - \overline{X_{cal}})(X_{obs} - \overline{X_{obs}})}{\sqrt{\sum (X_{cal} - \overline{X_{cal}})^2 \sum (X_{obs} - \overline{X_{obs}})^2}} \quad (5)$$

Here, X_{cal} and X_{obs} are calculated and observed variables. N is the variables of calculated/observed variables. $\overline{X_{cal}}$ and $\overline{X_{obs}}$ denote the average values of the calculated and observed qualities.

For hydrodynamic validation, the changes in water levels at 12 tide gauges along the coast of the Bohai Sea were compared with the computed water level changes in previous studies (Ji et al., 2020). Additionally, the observed water level variations at the Gudong Station during the period of 15 June to 15 July 2017 are compared with the computed results (Figure 3a). The computed water levels generally agree well with the observations, with a RMSE of 0.11 m and a CC of 0.92. This indicates that the model is able to accurately reflect the water level changes near the YRD (Table 1).

Figure 3b shows the comparisons between the calculated and observed velocities along the coast of the YRD. The RMSE of the current velocities are all less than 0.17 m/s, and the CC ranges from 0.74 to 0.97 (Table 1). It can also be observed that the current directions from the model calculations agree well with the observations.

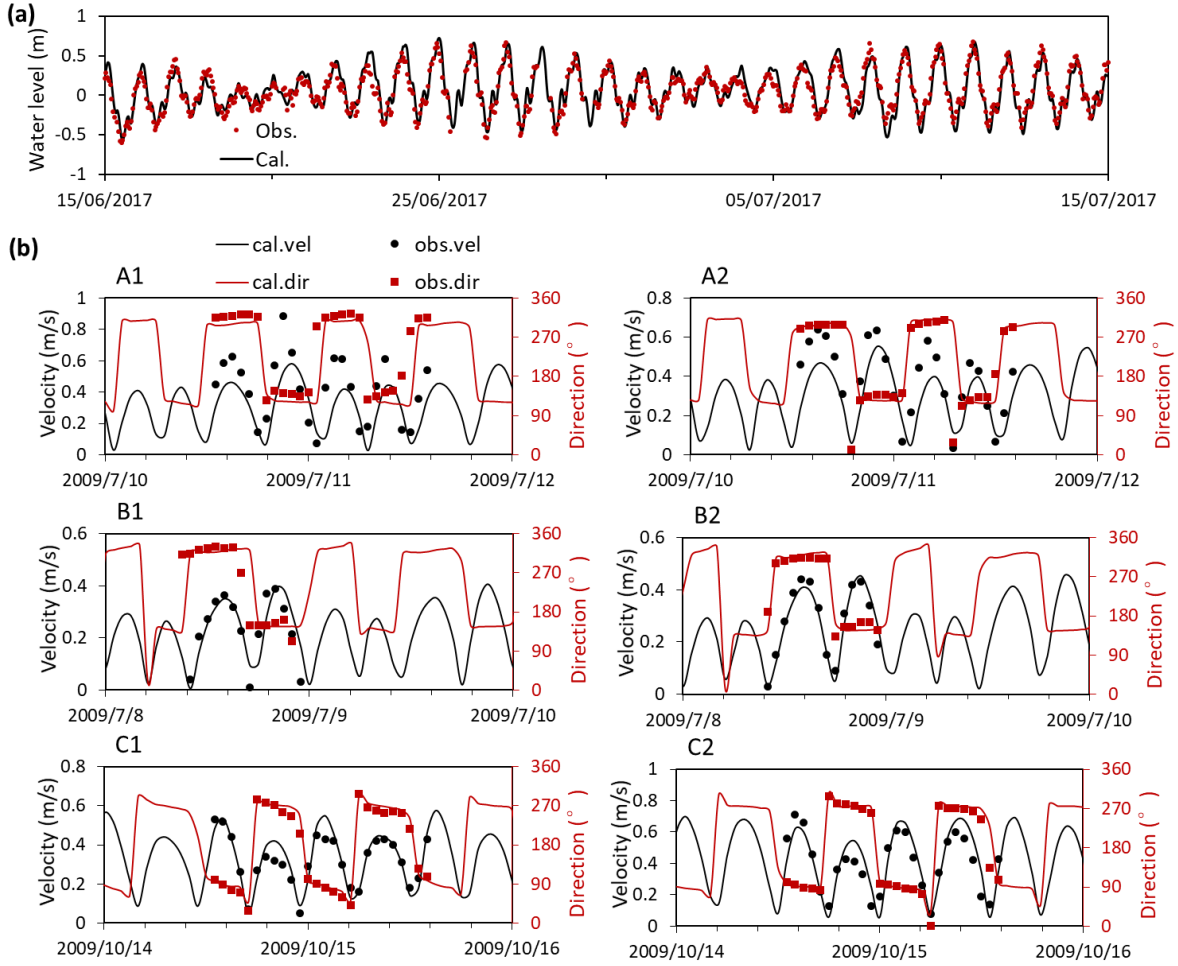


Figure 3. Comparisons in time series of (a) water levels between observations (Obs.) and computations (Cal.) during June and July in 2017, (b) Comparisons between the calculated and in-situ observed velocities during July and October in 2009.

Figure 4 illustrates the validation of wave parameters using the observed wind and waves at the Chengdao Platform of the northern abandoned DKH delta. Since the ECMWF database is insufficient in representing strong wind events (Li et al., 2018), the wind intensity is calibrated and multiplied 1.5 times based on ECMWF dataset. The modified wind speeds and computed directions in the numerical model accord well with the observations. The simulated wave height and mean wave period are in good agreement with the observed data during 2018, with a RMSE

of 0.46 m and a CC of 0.91 in significant wave height (Hs), and an RMSE of 0.77 s and a CC of 0.82 in mean wave period (Tp) (Table 1). Overall, the model validation indicates that the model performs well in reconstructing tide dynamics and wave climate in the coastal waters of YRD.

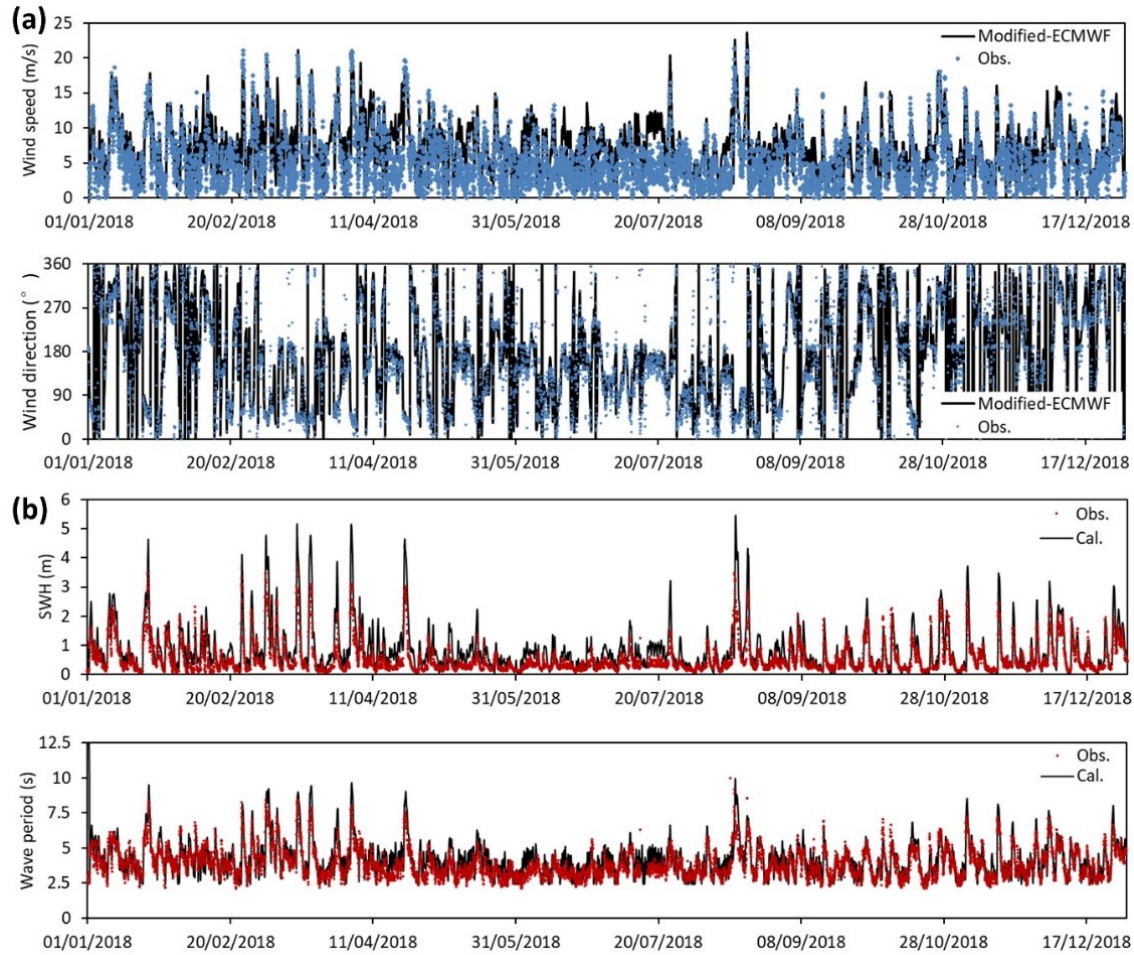


Figure 4. Comparisons between observed and computed (a) wind speed, (b) wind direction, (c) significant wave height, and (d) mean wave direction at the northern YRD during 2018.

Table 1. Evaluation of model performance (2007-2015) with RMSE and CC

	Hydrodynamics							Wave		
Variables	Water level (m)	Current velocity (m/s)						Wind speed (m/s)	Hs (m)	Tp (s)
Sites	Gudong	A1	A2	B1	B2	C1	C2	Chengdao		
RMSE	0.11	0.17	0.13	0.07	0.03	0.05	0.09	3.27	0.46	0.77
CC	0.92	0.74	0.86	0.85	0.97	0.95	0.9	0.77	0.91	0.82

3.3.4 Bottom shear stress (BSS)

The bottom shear stress (BSS) is a key hydrodynamic parameter to determine sediment transport and morphological changes (Kösters and Winter, 2013). Under the combined tide and wave conditions, the BSS can be divided into current-induced stress (τ_c) and wave-induced stress (τ_w), which can be calculated as follows:

$$\tau_c = \rho C_D \bar{U}^2 \quad (6)$$

where ρ is the water density, $\bar{u}$ is depth-averaged velocity. C_D is the dimensionless drag coefficient for rough turbulence flow, which is calculated using the formula:

$$C_D = \left[\frac{0.4}{\ln\left(\frac{h}{Z_0}\right) - 1} \right]^2 \quad (7)$$

where h is the water depth, Z_0 is near-bed roughness length, which is related to the Nikuradse roughness and median grain size (D_{50}) (Kösters and Winter, 2013; Coughlan et al., 2021):

$$Z_0 = \frac{K_s}{30} = \frac{D_{50}}{12} \quad (8)$$

The bottom stress induced by waves can be calculated as a function of the wave orbital velocity (U_w):

$$\tau_w = \frac{1}{2} \rho f_w U_w^2 \quad (9)$$

where U_w can be computed based on linear theory using the intrinsic angular frequency (ω) and wave number (k):

$$U_w = \frac{H_s \omega}{2 \sinh(kh)} \quad (10)$$

f_w is the wave friction factor, which is proposed by Swart (1976) as:

$$f_w = \exp \left[5.213 \left(\frac{K_b}{A_b} \right)^{0.194} - 5.977 \right] \quad (11)$$

where $A_b = U_w T / 2\pi$ is the semi-orbital excursion and K_b is evaluated as the grain roughness (Z_0).

The combined current and wave induced BSS (τ_{cw}) can be calculated by the following equation (Jia et al., 2014; Rosales et al., 2008; Li et al., 2017; Franz et al., 2017; Green and Coco, 2014; Guillou et al., 2016):

$$\tau_{cw} = [(\tau_m + \tau_w |\cos \theta|)^2 + (\tau_w |\sin \theta|)^2]^{0.5} \quad (12)$$

where θ represents the angle between the wave and current directions, τ_m is the mean shear stress in the current direction, which is calculated as:

$$\tau_m = \tau_c \left[1 + 1.2 \left(\frac{\tau_w}{\tau_w + \tau_c} \right)^{3.2} \right] \quad (13)$$

In model implementation, the user defined critical BSS (τ_{cr}) is used, based on the formula proposed by Guo (2020), which extends shields diagram and presents a generalized empirical model for the critical shear stress for the incipient motion of both coarse and fine sediments:

$$\tau_{cr} = \tau_* (\gamma_s - \gamma) D \quad (14)$$

where γ and γ_s represent the specific weight of water and sediment respectively, D is the median grain size, which can vary in space, τ_* is the critical shields parameter and is denoted by:

$$\tau_* = \frac{R_*^2}{D_*^3} \quad (15)$$

where D^* is dimensionless sediment diameter and can be defined in Eq. (16), R^* is critical grain Reynolds number, and can be solved in Eq. (17)

$$D_* = D \left[\frac{\left(\frac{\gamma_s}{\gamma} - 1 \right) g}{\nu^2} \right]^{\frac{1}{3}} \quad (16)$$

$$R_*^4 + \frac{195}{7} R_*^3 + \left(\frac{162}{7} - \frac{D_*^3}{18} \right) R_*^2 - \frac{11}{42} D_*^3 R_* - \frac{81}{14} D_*^3 = 0 \quad (17)$$

where g is the gravitational acceleration, ν is the kinematic viscosity of water. The map of deltaic seabed τ_{cr} calculated by the Eqs. (14-17) during different periods can be found in Figure S3.

3.3.5 Sediment mobilization frequency index

The sediment mobilization frequency index (MFI) represents the frequency of bottom sediment mobilization or resuspension within specific time periods under combined waves and current processes in estuarine environments (Coughlan et al., 2021). To assess whether τ_{cr} is exceeded at each point within the computation domain, the total BSS induced by currents and waves can be compared with τ_{cr} . This allows for the evaluation of the spatial disparity of seabed sediment mobilization frequency and its variations.

3.3.6 Model conditions

The validated model is then applied to examine the changing hydrodynamics and wave climate in the coastal waters of the YRD. A flow discharge of 1500 m³/s, which represents the multi-year averaged flow to the sea, is imposed at river boundary at the Q8 mouth channel. Each model configurations is run beginning on 1 January at each year from 1996 to 2020. Hourly

hydrodynamic (current velocity, water level) and wave parameters (H_s , T_p , bottom velocity, wave direction) are extracted to analyze the hydrodynamic and wave conditions in the study area.

4. Results

4.1. Interannual and seasonal variations in SSC

The interannual averaged SSC dynamics are retrieved using multi-year satellite images in the study area. [Figure 5a](#) and [5b](#) shows the average SSC distributions near the surface in the coastal waters of YRD. Generally, a temporal decreasing trend in Zones P1-P5 is detected, from 256.7 mg/L during 1996-2006, 159.0 mg/L during 2007-2014, to 161.0 mg/L during 2015-2020. The high turbidity coastal waters, with SSC exceeding 100 mg/L, are concentrated in the northern abandoned YRD, the active river mouth and the abandoned QSG lobe.

Monthly changes in SSC distributions are analyzed for the three periods aforementioned, as shown in [Figure 6](#). High turbidity zones are consistently observed in the QSG lobe and the northern abandoned delta, which align with the annual and interannual distributions of SSC shown in [Figure 5](#). During the dry season (November-April), the SSC levels were significantly higher than those in the wet season (May-October), with broader spatial ranges (>100 mg/L) and magnitudes of high SSC. [Figure 6b](#) and [6c](#) present the SSC variations in winter and summer for the three periods. The results indicate that, in winter, there is a cascaded decrease in SSC magnitude from 1996 to 2020, with a more pronounced decrease in the northern abandoned delta ([Figure 6b](#)). In summer, no obvious changes are observed in Zones P1-P3, but noticeable fluctuations occur in Zones P4 and P5 ([Figure 6c](#)), primarily due to variations in mouth channel diversion and the amount of sediment discharged into the sea during the three periods. This

analysis also demonstrates that the turbidity in the DKH area is much lower than that at the abandoned QSG delta lobe in summer, influenced by prevailing southerly winds.

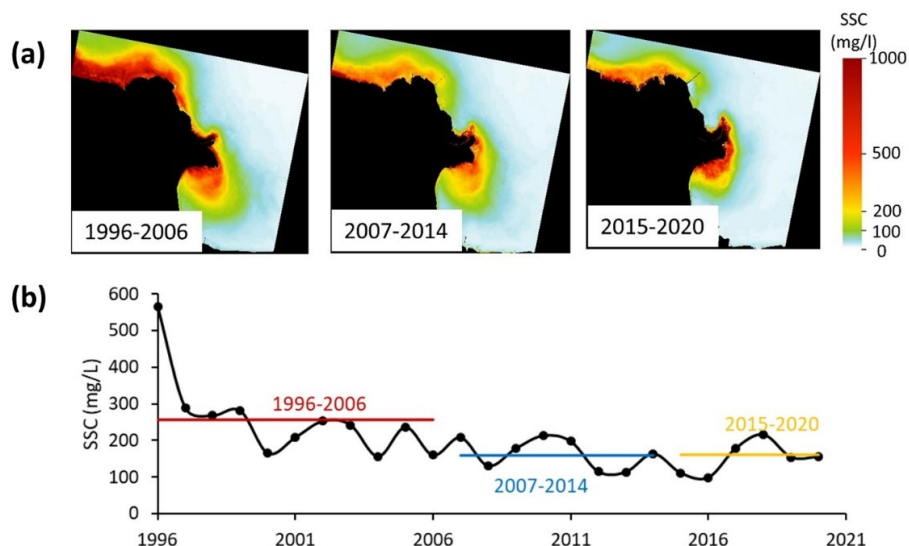


Figure 5. Inter-annual (a) and annual (b) variations in SSC in the coastal waters of YRD.

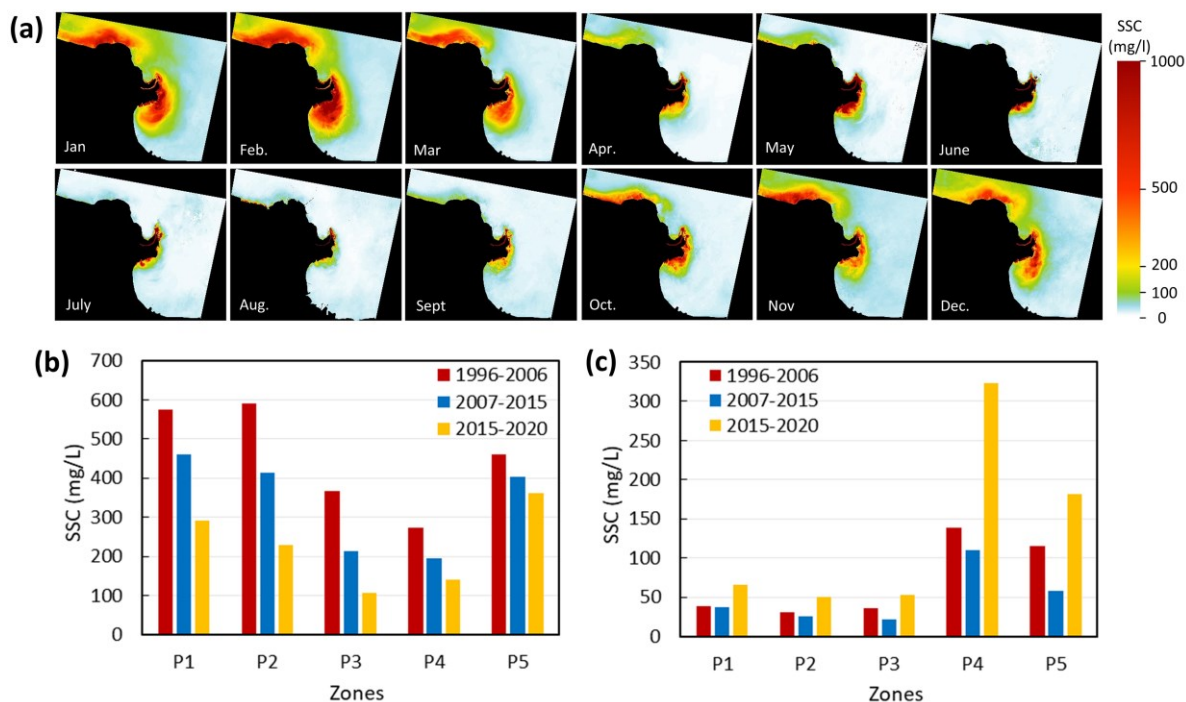


Figure 6. Monthly variability of SSC distributions of the YRD during 2015-2020 (a), and their spatial distributions in Zones P1-P5 during three periods in winter (b) and summer (c).

4.2. Distributions of currents, waves and their BSS

Figure 7a and 7b show distributions of tidal currents in the study area during spring tides with the 2015 mesh. The tidal currents generally run parallel to the coastline, flowing southward during flood tides and northward during ebb tides. Strong tidal currents are observed off the northern DKH lobe and the abandoned QSG lobe during the maximum flood and ebb, with velocity magnitudes exceeding 0.5 m/s. Figure 7c depicts the distributions of the average wave heights off the YRD. The impact of waves generally decreases from the northeast in the outer sea to the southwest in the nearshore area. However, during extreme storm events, the maximum Hs can exceed 5.6 m outside of the delta as shown in Figure 7d.

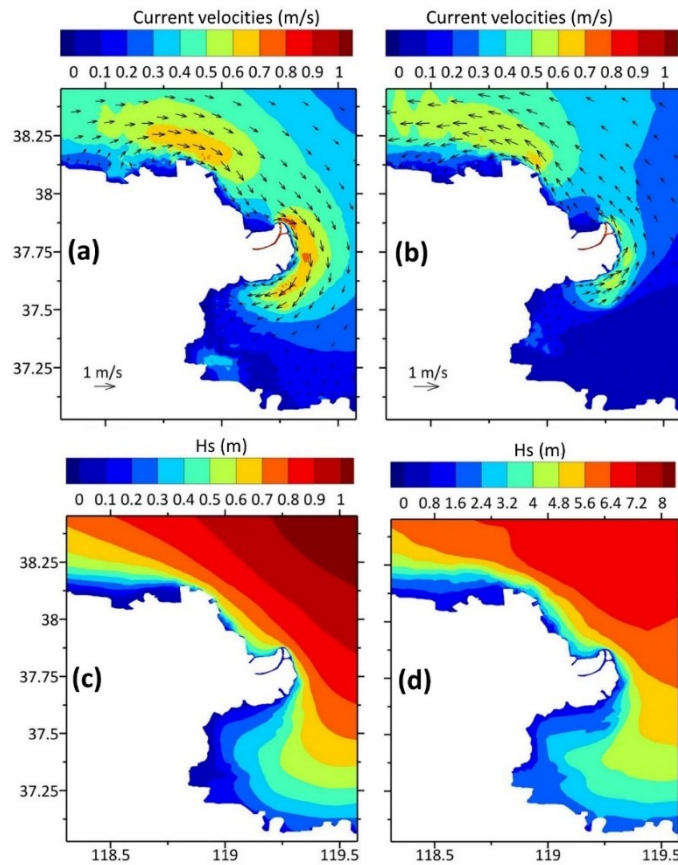


Figure 7. Distributions of currents and waves around the YRD, with flood currents (a) and ebb currents (b) during spring tides; Mean (c) and temporal maximum (d) significant wave heights (H_s) during 2015

The BSS induced by tidal currents, waves, and their combination can be calculated using Eqs. (6-13). Figure 8 depicts the total BSS induced by combined currents and waves during three different periods. The total BSS exceeds 0.15 Pa in the abandoned DKH and the abandoned QSG lobes. In addition, after the mouth channel diversion in 1996, the active river mouth has become a high BSS zone due to direct river discharge delivery.

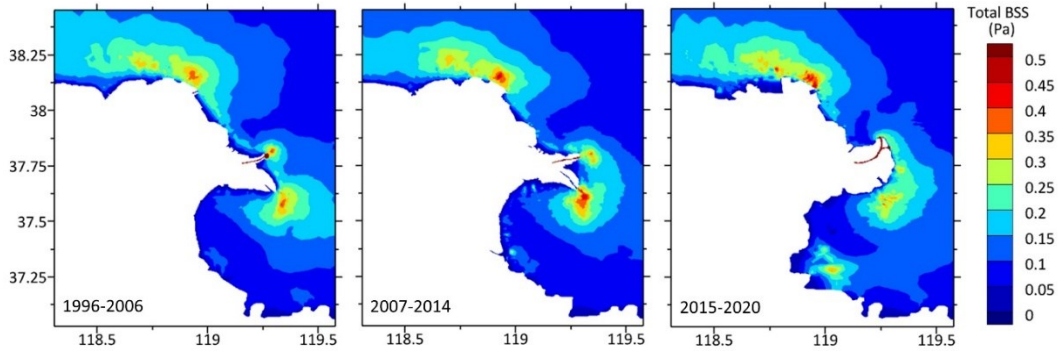


Figure 8. Distributions of total BSS during the three periods

Monthly-averaged BSS are derived from the validated coupled wave-current numerical TELEMAC model across simulations of recent 25 years (Figure 9 and Figure S4). Figure 9 displays the wave-induced BSS and the total BSS induced by combined waves and currents at the seasonal scale during 2015-2020. The high BSS zones (>0.15 Pa) induced by waves are restricted to areas shallower than 10-m depth and exhibit strong seasonal variability, with higher BSS values in dry seasons compared to wet seasons (Figure 9a). The high total BSS zones are located at the northern YRD and the abandoned QSG lobe (Figure 9b), where tidal currents exert strong forcing

(Figure 7). Additionally, the total BSS follows a similar trend in seasonal variations as the wave-induced BSS, acting as an additional impact on the tidal currents in mobilizing seabed sediments.

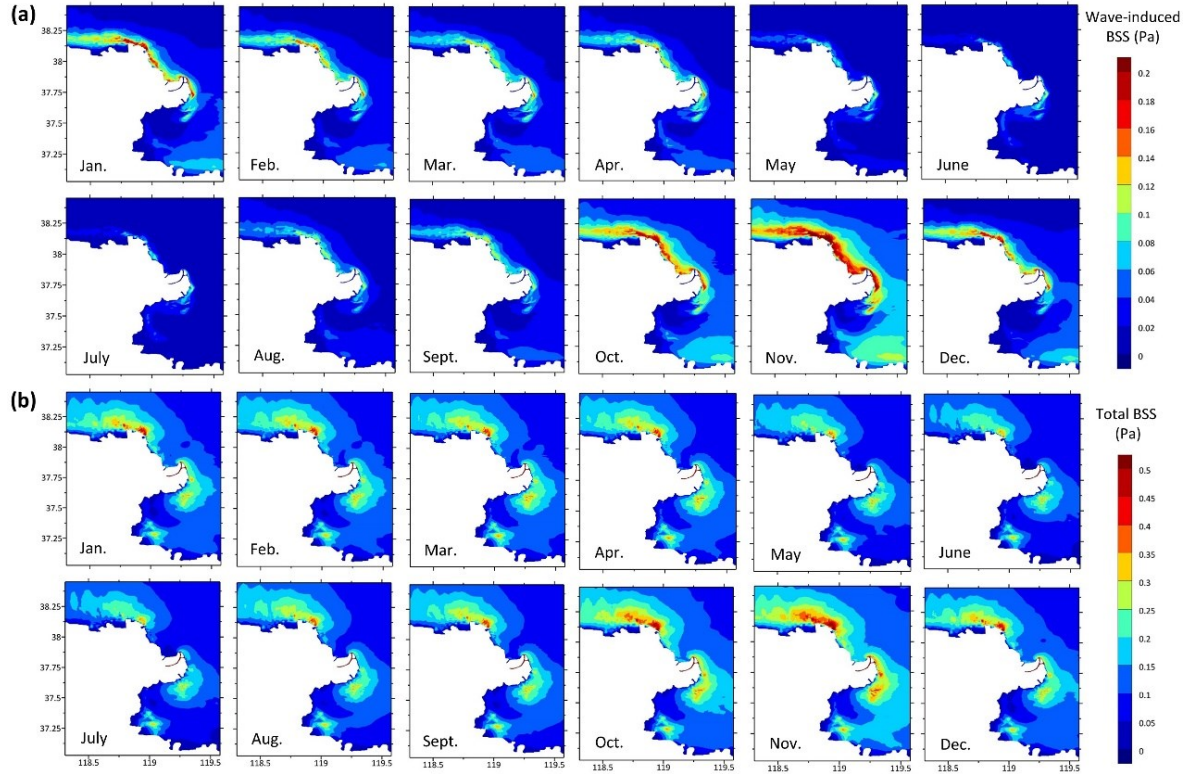


Figure 9. Monthly variability of distributions in (a) wave-induced and (b) total BSS off the YRD during 2015-2020.

4.3. Relationship between BSS and SSC

Considerable attention has been given to studying the relationship between wave heights and the spatial distribution of SSC in the coastal waters of the YRD (Li et al., 2022; Zhao et al., 2022; Jin et al., 2023). It is worth mentioning that the accuracy of wave forcing results obtained from large-scale global models may be limited, as they typically do not account for morphological changes in coastal and estuarine regions. Furthermore, previous studies have often placed less emphasis on the contribution of current-induced BSS, which is known to play a significant role in addition to wave forcing. Therefore, our objective is to compare the total BSS induced by waves

and tidal currents with the spatial distribution of SSC, utilizing the established coupled wave-current model.

The relationship between seasonal-scale total BSS and SSC at each year is depicted in [Figure 10](#). The findings reveal a close linear correlation between the distribution of BSS and fluctuations in SSC. Higher BSS and SSC levels are observed in winter compared to summer in Zones P1, P2, P3, and P5, where tidal currents and wave forcing have a dominant influence. In Zone P4, comparable SSC magnitudes are observed in summer and winter. But it should be noted that the SSC dynamics is attributed to direct high SSC delivery through upstream peak flow rather than sediment suspension in flood seasons.

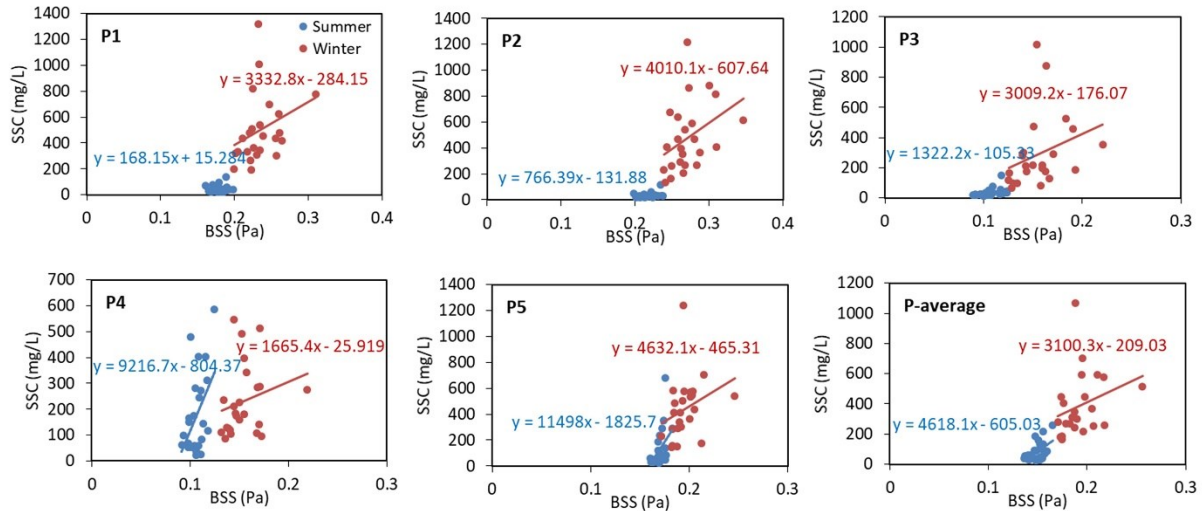


Figure 10. Relationship between BSS and SSC in Zones P1-P5, and their deltaic scale relationship (P-average).

The time series variations of averaged SSC and BSS in the study area at the annual scale are illustrated in [Figure 11](#). The SSC demonstrates pronounced annual fluctuations, and are strongly correlated with the annual variability of wave-induced and total BSS. In terms of annual coastal hydrodynamics and wave forcing, the wave-induced BSS generally exhibits less intensity

compared to the current-induced BSS. However, it displays a higher degree of variability due to the influence of wind. The varying trend of total BSS is more closely associated with wave-induced BSS and exhibits significant variations at the annual scale.

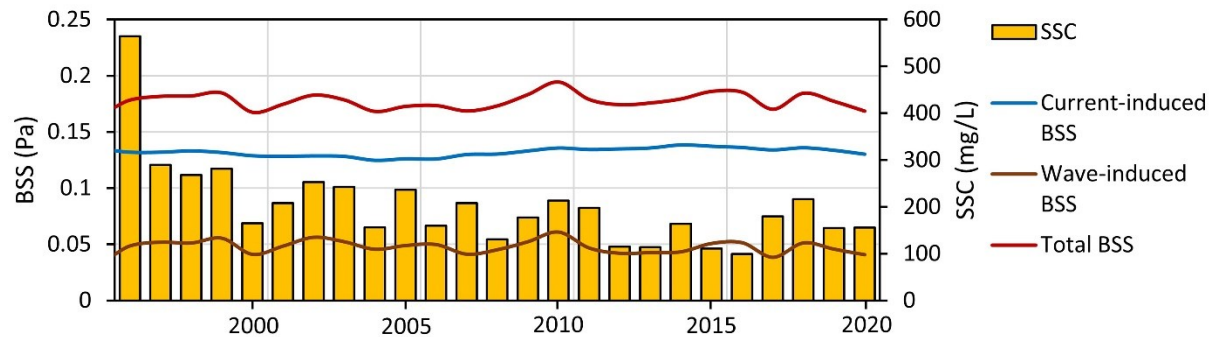


Figure 11. Time series of SSC, and calculated current- and wave-induced BSS, and total BSS in the coastal waters of the YRD during 1996-2020.

4.4. Contributions of currents and waves to sediment resuspension

In order to further quantify the influence of spatial-temporal variations in waves and currents on sediment resuspension, an analysis of current- and wave-induced BSS is conducted at both seasonal and interannual timescales, as illustrated in Figure 12, Table 2, and Table S1. The findings reveal that the total BSS is highest in Zones P1 and P2, followed by Zone P5, while Zones P3 and P4 exhibit the lowest values. The contributions of waves are most pronounced within the 5-meter depth contour in Zone P2, P3, and the northern vicinity of Zone P4, accounting for over 70% of the total BSS. In Zone P1, waves and currents contribute comparably, each accounting for approximately 50% of the total BSS, whereas in Zone P5, waves account for about 30% (Figure 12a). It is estimated that the wave impact on sediment resuspension in Zones P1-P5 has reached 27%-30% since 1996 (Table S1).

From a temporal perspective, a decrease in wave impact is observed, accompanied by a slight increase in current influence at the delta scale, which can be attributed to variations in wind patterns and morphological changes (Table 2). This trend is particularly noticeable in the northern and northeastern coastal waters of the delta, where wave impact dominates. Consequently, the contribution ratio of waves to sediment resuspension decreases in these areas. Seasonal variations are also noted, with the BSS induced by waves being twice as significant in winter compared to summer (Figure 12b & c, Table S1).

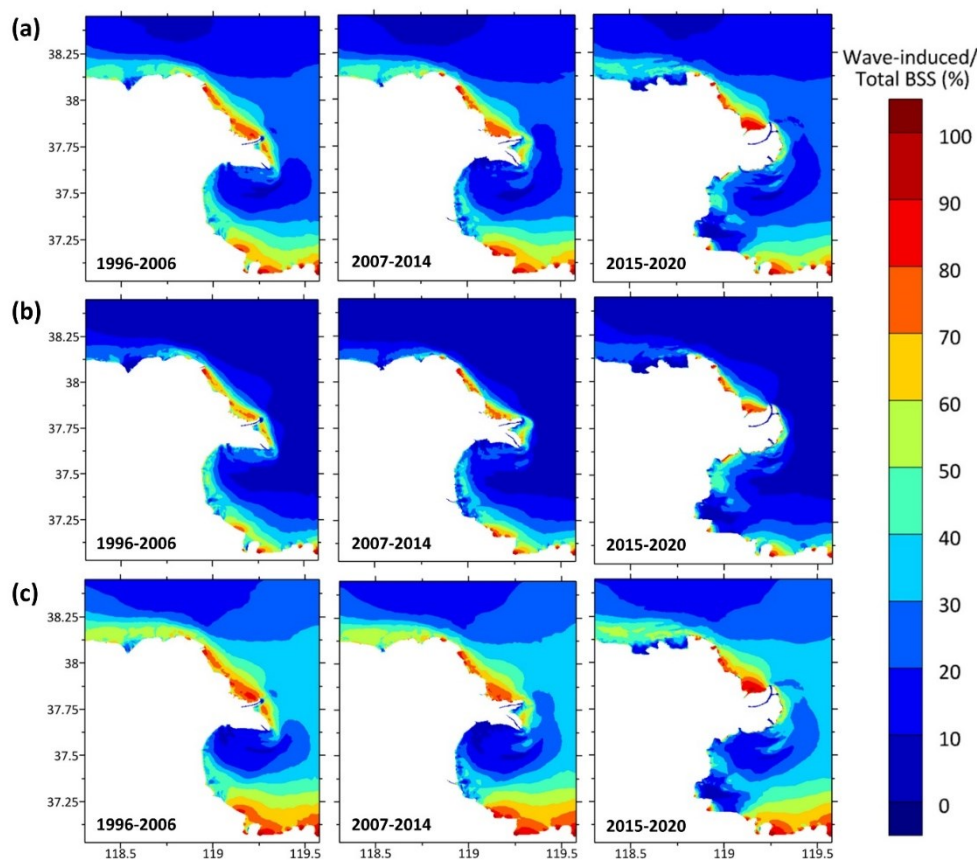


Figure 12. Ratio of wave-induced BSS to the total BSS in the three periods in (a) annual-averaged, (b) summer and (c) winter, with detailed information in Table 2 and Table S2.

Table 2. Averaged current- and wave-induced BSS (Pa) during three periods

		P1	P2	P3	P4	P5	P-average
1996-2006	Currents	0.160	0.192	0.086	0.086	0.155	0.129
	Waves	0.056	0.065	0.058	0.047	0.038	0.050
	Total	0.213	0.254	0.143	0.131	0.190	0.177
2007-2014	Currents	0.172	0.198	0.084	0.094	0.156	0.134
	Waves	0.054	0.057	0.050	0.046	0.038	0.047
	Total	0.223	0.251	0.133	0.138	0.190	0.179
2007-2014	Currents	0.158	0.196	0.081	0.102	0.154	0.134
	Waves	0.049	0.056	0.053	0.042	0.039	0.046
	Total	0.204	0.250	0.133	0.143	0.190	0.179

5. Discussions

5.1. Driving factors of SSC at different timescales

Quantifying wave- and current- induced BSS and resultant sediment resuspension are a primary aspect of this study. The results have revealed that the distribution of total BSS, induced by combinations of tidal currents and waves, is closely correlated with the spatial variations in SSC distribution and its dynamics at both seasonal and annual timescales, as indicated in [Figure 10](#) and [Figure 11](#).

Over interannual and longer timescales, the sediment grain size and morphology of the subaqueous YRD display significant spatial variations ([Figure S3](#)). These variations can play a crucial role in determining the critical BSS and influencing the processes of seabed sediment resuspension and mobilization. To assess sediment mobilization and seabed erosion potential in the context of changing sediment properties and subaqueous morphology, the sediment

411 mobilization frequency index (MFI) is introduced, which is based on calculating the frequency of
412 sediment mobilization by comparing total BSS with the critical BSS values on an hourly basis.

413 [Figure 13](#) and [Table 3](#) presents a comparison of interannual-scale averaged MFI at the
414 coastal waters of YRD, indicating MFI variations under total BSS during the three periods from
415 1996 to 2020. The results show the existence of three high MFI zones. The two high MFI zones
416 are in the abandoned in DKH and QSG lobes, which experience strong tidal current forcing and
417 additional impact from waves throughout the year, and the one occurs in the active Q8 river mouth,
418 which has transformed into a high BSS zone due to its direct role as a pathway for riverine sediment
419 input since the latest engineered diversion in 1996.

420 The seabed sediment mobility is influenced by changing wave and current forcing, as well
421 as variations in critical BSS. It is observed that the total BSS fluctuates at the annual timescale
422 ([Figure 11](#)), while on the interannual timescale, the total BSS levels are relatively similar ([Table](#)
423 [2](#)), and it relies more on the changing sediment properties and related τ_{cr} on seabed. In Zones P1-
424 P3, the seabed sediments follow generally coarsening trends, resulting in a decreasing trend in
425 FMI. In Zone P4, the sediment mobility increases, mainly as the result of the combined effects of
426 river flow and tide dynamics under changing morphology and sedimentary environments. In Zone
427 P5, the sediment mobility follows a decreasing trend from 1996-2006 to 2007-2014, and increases
428 during 2015-2020, primarily because that the seabed sediment significantly coarsens during initial
429 channel migration in the abandoned delta lobe and then becomes finer ([Figure S3](#)), which induces
430 changes in critical bed shear stress and sediment resuspension processes. Overall, the averaged
431 sediment mobility under combined BSS induced by currents and waves are accordance with SSC
432 distributions and variations at interannual scales, which implies that the variations in critical BSS,

associated with the median grain size, is the essential driver of sediment resuspension in the coastal waters.

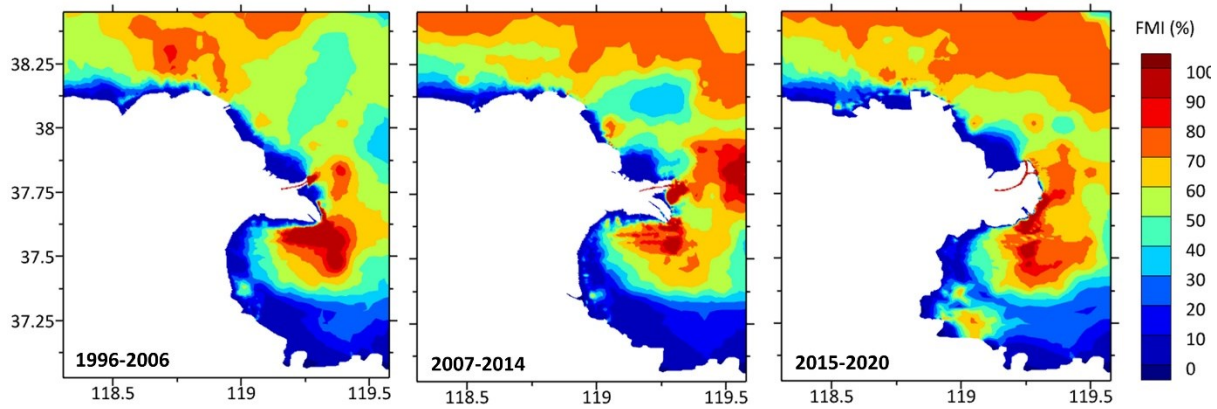


Figure 13. Sediment mobility assessment during the three periods.

Table 3. Sediment mobility (%) in different periods

	P1	P2	P3	P4	P5	P-average
1996-2006	57.2	63.0	42.3	49.5	73.8	57.7
2007-2014	51.2	59.0	42.6	53.2	67.5	55.6
2015-2020	48.1	61.8	37.7	58.3	71.6	56.6

5.2. Implications for delta erosion and accretion patterns

The morphological variability of subaqueous deltas depends on factors such as river input, sediment characteristics, and combined wave-current actions (Fagherazzi et al., 2015; Luan et al., 2016; Franz et al., 2017). While variations in river input can primarily influence the evolution of the active river mouth in the YRD (Wu et al., 2017; Jiang et al., 2017; Bi et al., 2021), the coastal currents and waves plays more significant role in shaping sediment dynamics and morphological changes of the delta with reduced river input in recent decades.

By collecting and comparing the bathymetric surveying datasets, the interannual delta-scale DEM (digital elevation model) and the erosion-accretion evolution of the subaqueous YRD

are calculated, as shown in [Figure 14](#). From 2000-2007 to 2007-2015, the morphological change patterns follows similar trends. There is rapid accretion in the active river mouth, with a vertical rate of 0.4 m/yr, which receives direct riverine sediment input. Whilst erosion occurs in the abandoned DKH and QSG delta lobes, with the erosion rate of 0.2 m/yr. After the mouth channel bifurcates and migrates from the east to the north in 2007, the deposition center and erosion center has switched locations.

Distributions of high BSS and sediment mobility zones indicate considerable potential for sediment resuspension, concentrated in northern abandoned delta, the active river mouth, and abandoned QSG lobe. They also coincide with high velocity zones ([Figure 7a and b](#)) for the efficient transport of suspended sediment, inducing the consistence with the active area of morphological changes, except for the Gudong littoral zone (Zone P3). Because the BSS and MFI reflect the potential for erosion and accretion and the frequency of sediment mobilization, rather than the actual quantities of erosion and accretion. Although the Gudong littoral zone is under engineering protection, the seabed still experienced severe erosion under increased BSS induced by strong waves during stormy weather conditions ([Fan et al., 2020; Sun et al., 2022; Cheng et al., 2023](#)).

Under the current condition of the single QSG channel discharging riverine water and sediment to the Bohai Sea, the morphological erosion-accretion evolution trends of the YRD are likely to continue. Although the Water-Sediment Regulation Scheme (WSRS), aiming at regulating the water and sediment discharge from catchment reservoirs, has effectively transported a substantial amount of river-derived sediment to the YRD ([Wang et al., 2022](#)), it cannot prevent the sinking of the entire delta due to the reduced sediment supply under relatively strong coastal hydrodynamics in recent decades ([Ji et al., 2018; Wu et al., 2023](#)). If the flow path follows the

alternative channel, e.g., Beicha channel in the west of the current river mouth, the erosion in the Gudong littoral zone may be reduced, but the delta-scale erosion and accretion patterns would remain relatively unchanged.

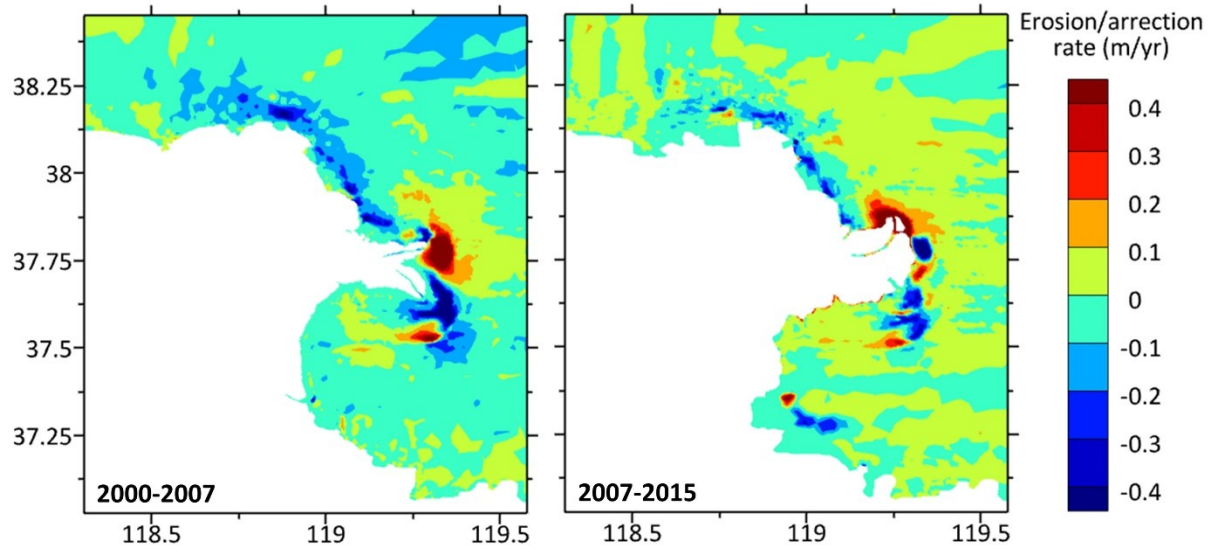


Figure 14. Erosion-accretion patterns of the subaqueous YRD.

5.3. Limitations of SSC retrieval and numerical model

The SSC retrieval algorithm used in this study is based on the work by [Li et al. \(2019\)](#), where the model achieved an RMSE < 55 mg/L with a relative percentage difference < 21% compared to in-situ SSC measurements. However, it is important to note that the accuracy of the SSC retrieval algorithm is also highly dependent on the selection and utilization of satellite imagery. In this study, a total of 541 images are used to retrieve SSC distributions at the YRD over a span of two decades. Due to the randomness of satellite image availability, some months have only 1-2 satellite images, which may not accurately reflect the monthly-averaged SSC distributions. Nonetheless, the observed SSC dynamics follows a general decreasing trend and exhibits annual fluctuations since the mouth channel diversion to Q8, which aligns with similar

findings in other studies (Zhou et al., 2017; Zhao et al., 2022; Jin et al., 2023; Li et al., 2023; Yu et al., 2023).

The coupled wave-current model based on the TELEMAC suite is used in this study to investigate the distributions of waves and currents in the coastal waters of YRD over the past decades. The coupling time step for wave-current interactions was set at 5 minutes to capture the wave-induced currents and the impact of currents on waves. Figure 15 illustrates the mean difference in current magnitude and wave climate between the coupled and decoupled modes. Figure 15a shows that tidal currents can be either reduced or enhanced primarily due to the angle between currents and wind wave directions. When compared to the coupled wave-current model runs, current velocities are reduced in the northern abandoned YRD by approximately 0.02 m/s, and are enhanced by 0.02-0.06 m/s along the coastline at the active delta lobe. In comparison, wave heights are often underestimated by 0.04 m when the model does not consider wave-current interactions (Figure 15b).

The seasonal stratification and vertical mixing in coastal waters, in addition to current and wave forcing, play a role in the dynamics of SSC (Wilson and Heath, 2019; Xie et al., 2022; Du et al., 2023). However, our model does not consider a three-dimensional mode due to computational costs. Since the water depths in the YRD are relatively shallow, the depth-averaged mode can effectively capture the BSS induced by currents and waves (Santoro et al., 2017; Zhang et al., 2018; Coughlan et al., 2021). Additionally, our model assumed a constant flow discharge of 1500 m³/s instead of varying river discharge inputs. This is because the combinations of currents and waves are more widespread and influential than the limited river input, especially given the reduced terrestrial sediment supply in recent decades.

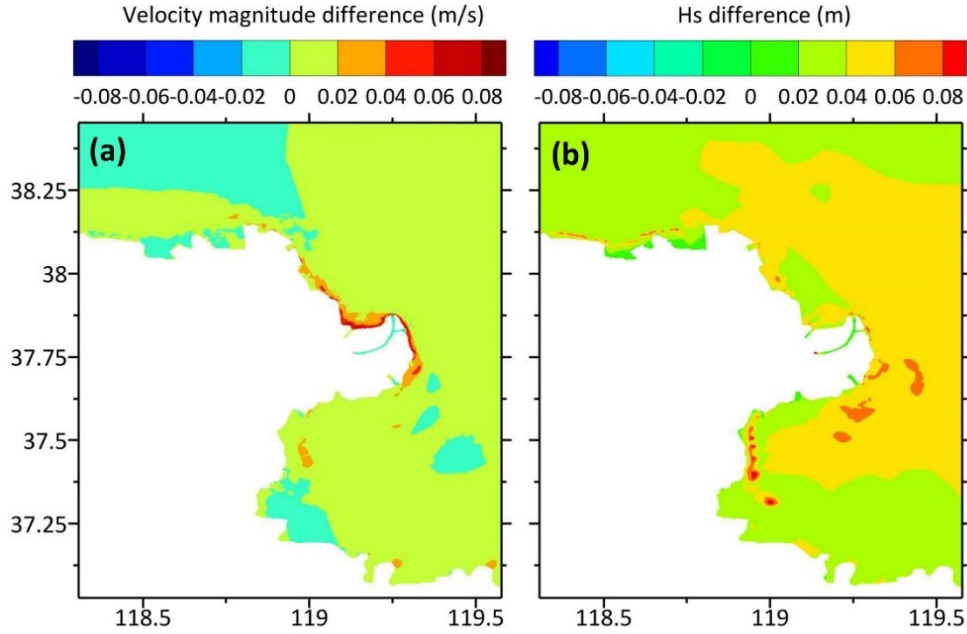


Figure 15. (a) Current velocities and (b) significant wave height difference compared with the coupled and decoupled TELEMAC2D and TOMOWAC modes.

5 Conclusions

In this study, validated remote sensing sediment retrieval algorithms with 541 satellite images and a numerical model based on the TELEMAC suite are applied to investigate the distributions of SSC and current-wave dynamics at the YRD over a two-decade period after the latest engineered diversion. The SSC retrieval results show that high turbidity zones appears in coastal waters of the northern abandoned DKH delta, the active river mouth and the abandoned QSG delta. On the interannual scale, the SSC distributions have shown a general decreasing trend in the coastal waters of YRD since 1996. At the intra-annual scale, the SSC is significantly higher in winter compared to summer.

The BSS induced by combined waves and currents is related to the distributions of SSC at multiple spatial-temporal scales. The BSS induced by wind waves is generally weaker compared

to currents, accounting for approximately 27%-30% of total BSS, but exhibits significant spatial-temporal variability. The contribution of wave-induced BSS is spatially stronger within 5-m depth contour in the engineering coasts, and less significant in the abandoned DKH and abandoned QSG delta lobes, and its contribution being overall decreasing during the past decades.

The strong correlations between SSC and sediment mobility distributions suggest that SSC is significantly influenced by local sediment resuspension processes. On interannual and longer timescales, the seabed sediment mobilization, influenced by currents and wave climate, may be more dependent on the seabed sediment grain size. The distributions of high BSS and sediment mobility zones are consistent with the high velocity zones and the active areas of erosion-accretion evolution, with net accretion observed in the active river mouth and erosion in the abandoned delta lobes.

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Data availability

Landsat images are downloaded from the U.S. Geological Survey's remote sensing image database (<https://earthexplorer.usgs.gov/>), with atmospherically correction in the ACOLITE software package (<http://odnature.naturalsciences.be/remsem/acolite/>). Varying wind velocities across the Bohai Sea are sourced from the ECMWF-ERA5 database (<https://cds.climate.copernicus.eu>). The coupled wave-current model are sourced from TELEMAC-MASCARET system (<https://www.opentelemac.org/>).

Appendix A. Supplementary data

Supporting information.

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