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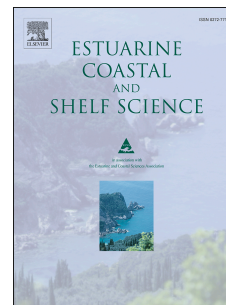


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Impacts of land reclamation on sediment transport and sedimentary environment in a macro-tidal estuary.

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Abstract:

During the past decades, extensive coastal areas have been reclaimed along the coastline of China, while the physical mechanisms of human pressures on estuarine-sedimentation are largely unknown. This study investigates the impacts of a land reclamation activity on estuarine sedimentation in the Yalu River Estuary (YE), China. For this purpose, we perform a multidisciplinary approach that combines rare earth element (REE) sediment records and numerical simulations. REE pattern of two sediment core samples from the main estuarine branch changed from diverse to homogenous after the early 1970s, which indicates that the estuarine sedimentary environment experienced dramatic change after the land reclamation activity completed in 1975. In order to explore physical drivers behind this change, hydro-sedimentary dynamics were simulated using Finite Volume Coastal Ocean Model (FVCOM) and an improved Track Marine Plastic Debris (TrackMPD) models. After the land reclamation, model results show that: (1) the degree of flood dominance decreased, and the tidal-choking effect was enhanced in the main branch. (2) The estuary became more well-mixed due to the stronger tidal current; (3) Suspended-sediment concentration (SSC),

26 especially SSC in the bottom layer was increased. (4) The landward sediment flux caused by
27 tidal pumping decreased significantly and the YE may turn into a sediment source instead of
28 a sink if more land is reclaimed in the future. Furthermore, sediments in the main branch
29 were likely from different sources before reclamation but became a homogenous mixture
30 afterwards. This study qualitatively demonstrates the human-induced impacts on estuarine
31 sedimentation using a multidisciplinary method.

32 **Key words:** Yalu River Estuary; FVCOM; sediment transport; particle tracking; numerical
33 simulation; land reclamation.

34 **1. Introduction**

35 Dynamics of suspended sediments affect the morphology, water clarity, light
36 attenuation, and the transport of nutrients and pollutants in an estuary (Byun and Wang, 2005;
37 Dyer, 1997). Thus, quantitative prediction of sediment transport in estuaries is required to
38 provide profound reference for coastal management. In a macro-tidal estuary, the transport of
39 suspended sediments is controlled by tidal dynamics and the erosion of seabed sediments is
40 mainly affected by the bottom tidal current velocity. The natural tidal dynamics in an estuary
41 can be altered by human activities such as mining, dredging, land reclamation and
42 construction of navigation channels and harbours. These human activities modify tidal
43 dynamics through changes of the bottom friction caused by the loss of tidal flats (Gao et al.,
44 2014; Song et al., 2013; Winterwerp et al., 2013), deepening the channel (Dijkstra et al.,
45 2019; Jalón-Rojas et al., 2018; Ralston et al., 2019; van Maren et al., 2015), narrowing the
46 width of waterway (Guo et al., 2017; Moore et al., 2009) and impacts of changing fluvial
47 discharge (Jalón-Rojas et al., 2018).

48 Such human-induced changes in tides consequently change the local sediment
49 transport, especially in a medium-scale estuary (Byun et al., 2004; Gao et al., 2014; Guo et
50 al., 2017). These changes of sediment transport occur in the sediment resuspension controlled

51 by tidal current (Li et al., 2014; Winterwerp et al., 2013), the sediment trapping or movement
52 of the estuarine turbidity maximum zone (TMZ) driven by tidal asymmetry (Jalón-Rojas et
53 al., 2015; Song and Wang, 2013) and the sedimentation rate for an estuary to maintain
54 morphological equilibrium (Moore et al., 2009; Williams et al., 2015). For example, in the
55 case of a large-scale human activity such as land reclamation, the suspended-sediment
56 concentration (SSC) was found to be increased greatly in the Ems Estuary (Van Maren et al.,
57 2016); the sediment accumulation rate became larger in the Nakdong Estuary (Williams et al.,
58 2015) and a stronger landward sediment flux was found in the Jiaozhou Bay after reclamation
59 (Gao et al., 2018).

60 Although recent progress has been made in human impacts on estuarine sediment
61 dynamics, the understanding of this topic in most areas remains vague and unconfirmed due
62 to the lack of historical observations. Elemental analysis from sediment records is an efficient
63 approach to identify the historical events in estuarine sedimentation. Of the various element
64 components in marine sediments, rare-earth elements (REE) contain valid information about
65 sediment provenance due to the stability of their fractionation during weathering and
66 diagenetic processes (Brito et al., 2018; Hathorne et al., 2014; Jung et al., 2012; Orani et al.,
67 2018). REE has been widely-used as a sediment provenance tracer, especially in a dynamic
68 system like the Yellow Sea (Li et al., 2014; Lim et al., 2014; Song et al., 2017; Song and
69 Choi, 2009). And recent studies have also used REE sediment records to investigate historical
70 changes in estuarine environments (Brito et al., 2018; Lim et al., 2014; Martins et al., 2012;
71 Shi et al., 2018; Shynu et al., 2013; Um et al., 2013).

72 In order to study the physical mechanisms behind the historical changes in estuarine
73 sedimentation, a high-resolution coastal ocean model is required. For determining the
74 sediment source-sink relationships in estuaries with limited historical observation,
75 Lagrangian tracking models for sediment particles can be an optimal tool. However, there are

76 only a few studies using this tool (Lane, 2005; Liubartseva et al., 2018; Souza and Lane,
77 2013) to track movements of suspended sediment particles, while studies considering the
78 resuspension process of sediments in 3D tracking are even rarer (Lackey and Macdonald,
79 2007).

80 This study takes the Yalu River Estuary (YE, border of China, Fig. 1) as an example
81 to study the human impacts on estuarine sedimentation, using REE sediment records together
82 with two numerical models. The YE forms a typical medium-scale, macro-tidal estuarine
83 environment. Previous studies have examined the local characteristics of sediment grain size,
84 ^{210}Pb and ^{137}Cs profiles and heavy-metal in the YE (Chen et al., 2013; Cheng et al., 2019;
85 Gao et al., 2009, 2012, 2003; Liu et al., 2013; Liu, 2016). Characteristics of the REE
86 chemistry in surface sediments in the YE has also been investigated (Liu et al., 2015).
87 However, such analysis must be extended to in-depth sediment samples to explore the
88 historical variation of REE. In terms of the sediment dynamics in the YE, Yu et al. (2014)
89 developed a two-dimensional simplified model to explore the mechanism of turbidity-
90 maxima formation but their results were based on idealized condition; certain details in the
91 three-dimensional (3D) coastal dynamics in this area still remain unknown.

92 Therefore, this study aims to: (1) reveal historical variation of REE sediment records
93 under anthropogenic influence in the YE; (2) explore the 3D structure of hydrodynamics and
94 sediment transport in this area to discuss the impacts of land reclamation; and (3) track the
95 transport of fine-grained sediments in the YE to investigate the potential changes in sources
96 for bottom sediments.

97 This study facilitates a more comprehensive understanding of the relevant physical
98 mechanisms of human-induced impacts on estuarine sedimentary environment. Furthermore,
99 an improved 3D particle resuspension and tracking model is proposed in this study, by which
100 we suggest a novel approach to determine the sediment sources in a coastal area.

2. Study area

2.1 Study area

The Yalu River is the largest river flowing into the Northern Yellow Sea (NYS) and contains much terrigenous material. The average annual freshwater and sediment discharge of the river are $2.67 \times 10^{10} \text{ m}^3$ and $1.59 \times 10^6 \text{ T}$, respectively (Cheng et al., 2016). Materials deposited in the YE and neighbouring area contributes to the bottom sediments in the Yellow Sea (Chen et al., 2013; Shi et al., 2018). The YE can be divided into two branches with three waterways: the West Branch on the west side of Chouduan Island contains the West River and the East Branch consists of the Middle and East rivers with Jiangxin Shoal in the middle (Fig. 1). The underlying tidal ridge system (Fig. 2a) in the YE has an area of $4,000 \text{ km}^2$, extending from the river entrance to the 40m isobaths (Gao et al., 2012), and is associated with parallel tidal ridge areas in the Western Korean Bay (Gao et al., 2016). Governed by that massive tidal ridge, the direction of the flood current in the YE is north-east, that of the ebb current is west-south. Previous study revealed that the sediment source in the YE were a mixture of materials from different regions (fluvial and neritic materials) and the parent rock type of surface sediments in the YE were mainly sedimentary rock and granite (Liu et al., 2015, 2013).

The YE is a macro-tidal estuary, with a mean tidal range of 4.5 m at the entrance (Cheng et al., 2016). The estuary is dominated by regular semi-diurnal tide outside the entrance and irregular semi-diurnal tide with a tidal-river reach of 54 km inside the entrance (Yu et al., 2014). The suspended sediment distribution in the YE is mainly controlled by tides, and there is a TMZ driven by tidal pumping in the lower estuary (Gao et al., 2004; Yu et al., 2014). Due to its strong estuarine hydrodynamics, YE is well-mixed for most of the time except during wet seasons, when there is an extremely large river flow (Cheng et al., 2016; Yu et al., 2014). According to field measurements during 1994, 1996 and 2009, the salinity in

126 the YRE is well-mixed with no obvious vertical stratification (Cheng et al., 2016; Gao et al.,
127 2004; Yu et al., 2014). Maximum salinity in the upper estuary was around 15 psu during high
128 slacks. Winds and wave action in this area are relatively weak, as the average significant
129 wave height outside the estuary is only 0.5 m (Yu et al., 2014) and the annual mean wind
130 speed is 3.2 m/s (Cheng et al., 2016).

131 **2.2 Reclamation of main islands in the YE**

132 The original Chouduan Island was separated from the Xin Island before 1970, divided
133 in the middle by Yingmen channel (Fig. 2b). The total area of the original Chouduan Island
134 and Xin Island was only 27.5 km² according to a joint measurement by the Chinese and
135 North Korean governments in 1956. In order to obtain more farmland, the major water
136 channel between the two islands, Yingmen Channel, was blocked by the North Korea in 1967
137 (Cheng, 2007). After that, the water flowing irregularly between the islands was gradually
138 diverted into the main water channel (the current Middle River). The lack of water between
139 the islands uncovered the tidal flats below. Thus, the area of exposed flats increased
140 significantly surrounding the Chouduan Island. Starting with this exposing island surface, a
141 massive land reclamation around Chouduan Island was begun by the North Korean
142 government in 1970. After the completion of the land reclamation in 1975, the Chouduan
143 Island was connected to the Xin Island and expanded to a much larger total area of 80 km²
144 (Fig. 2c).

145 **3. Methods**

146 **3.1 Field measurements**

147 **3.1.1 Sediment-samples collection**

148 Two sediment cores (K1 and K12) were collected in August 2014 in the YE (Fig. 1).
149 K1 (124°20'25"E, 39°48,15"N) is located in the shallow sea area of the YE. K12

150 (124°19'4"E,39°50'20"N) is located in the lower estuary, at the southern edge of the TMZ
151 observed by previous studies (Gao et al., 2004; Yu et al., 2014). The gravity corers were 4m-
152 long PVC tubes with an inner diameter of 85 mm and an outer diameter of 90 mm. The core
153 samples were collected by pushing the corers into the bottom sediments with the help of
154 laboratory technicians. Sampling was carried out during low slack water, when the water
155 depth was less than 1 m. The major lithologic characteristic of the two samples is clayey silt,
156 with a clay content of 20%–40%. The core samples were then divided into sub-samples at 4–
157 6 cm interval for REE detection, radioactive chronology testing and grain size analysis.

158 Surface sediment samples were collected from four sections around the YE using
159 clamshell-type samplers (Fig. 1). Forty surface sediment samples from the Middle and West
160 waterways and adjacent area (Sections A, B, C and E in Fig.1) were collected from June to
161 August 2006; eleven surface sediment samples were collected from the tidal flats outside the
162 entrance in July 2010 (Section D). These surface samples have been analyzed by Liu et al.
163 (2015), and here we use sectionally averaged REE concentrations of these samples as
164 additional information to our core samples.

165 **3.1.2 Hydrodynamics data collection**

166 A field survey for hydrodynamic observations was conducted in the YE during the
167 wet season (August) of 2009. Water level, turbidity, current velocity and direction were
168 measured at a ship-based anchor station Y03 (124° 16' 43" E, 39° 50' 22" N) over a
169 continuous 25h period during spring tide (8–9 August) and neap tide (14–15 August). Same
170 properties were also measured at station Y02 (124°18' 10" E, 39°55' 12" N; Fig. 1)
171 during spring tide (7–8 August) and neap tide (13–14 August). The current and water level
172 were measured by Acoustic Doppler Current Profilers (ADCP) with a frequency of 1200 kHz
173 and a current-speed resolution of 0.001 m/s. The receivers of the ADCPs were placed 0.1 m
174 below the water surface, facing downward, with a bin-layer depth of 0.25 m. Turbidity data

175 were observed using a multi-parameters water quality probe YSI6600. The measured
176 turbidity was converted into SSC according to in situ filtered water samples collected hourly
177 (Cheng et al., 2016).

178 **3.2 Sediment records of REE**

179 **3.2.1 REE concentrations**

180 The divided sub-samples (Section 3.1.1) were first air dried at room temperature
181 (27 °C), then ground using an agate mortar. The ground materials were filtered through a
182 nylon sieve with a diameter of 0.107 mm to eliminate the effect of size differences on the
183 REE measurements. In order to remove the bulk component (e.g. authigenic carbonate,
184 apatite and Fe-Mn oxides) in the sediment samples, the filtered samples were ignited at a
185 temperature of 450°C, acid pickled using HCl, and then dissolved in a mixed acid of HF and
186 HNO₃. Finally, the dissolved sample solutions were transferred into polyethylene test tubes,
187 and the REE concentrations was then determined using inductively coupled plasma mass
188 spectrometry (ICP-MS). To ensure the accuracy of the testing, repeat samples were tested
189 concurrently with the standard samples. For all 14 elements, the relative errors and the
190 differences between the repeat samples and standard samples were less than 6% and 7.7%,
191 respectively, indicating the satisfactory data reliability.

192 **3.2.2 Grain size analysis and chronology of sediment records**

193 The ²¹⁰Pb and ¹³⁷Cs radioactive decay curves of sediment cores K1 and K12 were
194 tested in the State Key Laboratory of Lake Science and Environment, Nanjing Institute of
195 Geography & Limnology, Chinese Academy of Sciences, based on γ -ray spectrum analysis
196 (Cheng et al., 2019). The ²¹⁰Pb_{ex}-based sedimentation rates were estimated using the Constant
197 Initial Concentration (CIC) mode (Appleby, 1997; Szmytkiewicz and Zalewska, 2014) and
198 the ¹³⁷Cs-based sedimentation rates calculated according to the key time markers of ¹³⁷Cs in
199 the YE (more details can be found in Cheng et al., 2019). For core K1, the ²¹⁰Pb_{ex}-based

200 sedimentation rate was 1.80cm/yr and the ^{137}Cs -based sedimentation rate of K1 1.61 cm/yr.
 201 The $^{210}\text{Pb}_{\text{ex}}$ -based and ^{137}Cs -based sedimentation rates for K12 were 1.80 cm/yr and 1.88
 202 cm/yr, respectively. As the sedimentation rates from each core found using the two different
 203 methods were similar, this study used the ^{137}Cs -based sedimentation rates to determine the
 204 age of every layer in the two cores.

205 A laser particle size analyzer BT-9300HT was used to measure sediment grain size in
 206 the cores. Sediment samples were first put into water and allowed to sit for 24 hours, then
 207 10–20 ml of $(\text{NaPO}_3)_6$ dispersant at a concentration of 0.05 mol/L were added. Determination
 208 of particle grain size was then conducted using the Collias equal-moment formula (Collias,
 209 1943).

210 3.2.3 REE elemental analysis

211 The REE enrichment values in the YE samples were normalized by corresponding
 212 values from the North American Shale Composite (NASC); this reveals the fractionation
 213 patterns of the REE during sedimentation (Hannigan et al., 2010; Um et al., 2013). Sectional-
 214 averaged REE concentrations from surface sediment samples in the YE and that of the
 215 reference samples are shown in Table 1.

216 Some characteristic coefficients of REE, known as fractionation factors, are widely-
 217 used to demonstrate the fractionation properties among elements. NASC-based normalized
 218 REE concentrations were used to calculate the REE fractionation factors $\delta\text{Eu}_{\text{NASC}}$, $\delta\text{Ce}_{\text{NASC}}$,
 219 $(\text{La}/\text{Sm})_{\text{NASC}}$, $(\text{Gd}/\text{Yb})_{\text{NASC}}$ and $(\text{La}/\text{Yb})_{\text{NASC}}$ in this study.

220 The Eu and Ce anomalies (δEu and δCe) are given in terms of the relevant
 221 concentrations as (Leybourne and Johannesson, 2008):

$$222 \quad \delta\text{Eu} = (\text{Eu}_N) / \sqrt{(\text{Sm}_N \text{Gd}_N)}, \quad (1)$$

$$223 \quad \delta\text{Ce} = (\text{Ce}_N) / \sqrt{(\text{La}_N \text{Pr}_N)}, \quad (2)$$

224 where N denotes the normalization method (using the NASC sample here). The anomaly level

225 of Ce and Eu can be estimated according to the closeness of the values to 1 (no anomaly).

226 This study focuses on the lanthanides of REEs from La to Lu and can be divided into
227 two groups: light REE (La, Ce, Pr, Nd, Sm and Eu) and heavy REE (Gd, Tb, Dy, Ho, Er, Tm,
228 Yb and Lu). $(La/Yb)_N$ indicates the fractionation property between the light REE (LREE)
229 and heavy REE (HREE): the larger the ratio, the higher the relative enrichment level of the
230 LREE. $(La/Sm)_N$ indicates the internal fractionation property in the LREEs: the larger the
231 ratio, the more obvious the fractionation is. $(Gd/Yb)_N$ indicates the internal fractionation
232 property in the HREEs: the larger the ratio, the more obvious the fractionation is.

233 **3.3 Numerical simulations**

234 **3.3.1 FVCOM model**

235 *Hydrodynamic simulation*

236 A 3D hydrodynamic model, the Finite Volume Coastal Ocean Model (FVCOM)
237 (Chen et al., 2003) was used to explore the hydrodynamic changes in the YE after the land
238 reclamation.

239 FVCOM adopts an unstructured, triangular grid to depict land boundaries with
240 wet/dry treatments (Ge et al., 2012), which provides an accurate simulation of the irregular
241 coastline and massive tidal flats in the YE region. The Mellor and Yamada level 2.5 (MY-2.5)
242 (Mellor and Yamada, 1982) and Smagorinsky turbulent closure schemes (Smagorinsky, 1963)
243 are used in this model for vertical and horizontal mixing, respectively. The governing
244 equations including momentum, continuity, temperature, salinity and density are given in
245 Chen et al (2013).

246 *Sediment simulation*

247 The UNSW-Sed sediment module which considers the effect of sediment
248 stratification in the bottom boundary layer (BBL) has been coupled with the hydrodynamics

249 model to obtain further accuracy. Following the sediment model developed in Wang (2002),
 250 sediment transport in UNSW-Sed for FVCOM in a sigma coordinate system can be described
 251 by:

$$\begin{aligned}
 252 \quad & \frac{\partial}{\partial t}(CD) + \frac{\partial}{\partial x}(CuD) + \frac{\partial}{\partial y}(CvD) + \frac{\partial}{\partial \sigma}[C(w + w_s)] \\
 253 \quad & = \frac{\partial}{\partial x}\left(HA_{\square} \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(HA_{\square} \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial \sigma}\left(\frac{K_{\square}}{D} \frac{\partial C}{\partial \sigma}\right) , \\
 254 \quad & (3)
 \end{aligned}$$

255 where t and D represent time and water depth, C is the SSC and w_s is the particle settling
 256 velocity, which is not affected by the transformation from a Cartesian coordinate system to
 257 the sigma-coordinate system. A_{\square} and K_{\square} are horizontal and vertical turbulent eddy
 258 viscosities, respectively.

259 With the contribution of the re-suspended sediments in nepheloid layer, the density of
 260 sea water can be expressed as:

$$\begin{aligned}
 261 \quad & \rho = \rho_w + \left(1 - \frac{\rho_w}{\rho_s}\right)C , \\
 262 \quad & (4) \text{ where } \rho_w \text{ is the density of clear seawater, and } \rho_s \text{ the sediment density.}
 \end{aligned}$$

263 The flux Richardson number was introduced into the bottom friction coefficient C_d to
 264 consider the effects of the sediment-induced BBL in the model (Wang, 2002):

$$\begin{aligned}
 265 \quad & C_d = \left[\frac{1}{\kappa/(1+AR_f)} \ln \frac{(H+z_b)}{z_0}\right]^{-2} , \\
 266 \quad & (5)
 \end{aligned}$$

267 where $\kappa = 0.4$ is the von Kármán constant; and R_f is the flux Richardson number, indicating
 268 the vertical density stratification in the Mellor-Yamada Level 2 approximation. A is an
 269 empirical constant ranging from 6.8 to 14.7, independent of flow state and R_f ; A was set to
 270 different values in previous studies (Glenn and Grant, 1987; Soulsby and Dyer, 1981; Wang,
 271 2002). z_0 and z_b are the bottom roughness and the thickness of the near-bottom layer.

272 According to Ariathurai and Krone (1977), the vertical sediment flux at the bottom
 273 caused by erosion/deposition processes, E_b , can be expressed as:

$$274 \quad E_b = \begin{cases} E_0 \left(\frac{|\tau_b|}{\tau_c} - 1 \right), & \text{if } |\tau_b| > \tau_c \\ C_b w_s \left(\frac{|\tau_b|}{\tau_c} - 1 \right), & \text{if } |\tau_b| < \tau_c \end{cases}$$

275 (6)

276 where E_0 is the erosion coefficient (E_0 and w_s are positive here), τ_b the bottom shear stress, τ_c
 277 the critical stress for resuspension and deposition, and C_b is the suspended-sediment
 278 concentration in the bottom layer. Erosion happens when E_b is positive.

279 3.3.2 Three-dimensional particle resuspension and tracking model

280 *Track Marine Plastic Debris (TrackMPD)*

281 A 3D Lagrangian particle-tracking model, TrackMPD, was adopted in this study to
 282 investigate the potential sediment source in the YE. TrackMPD is a newly developed
 283 transport model which simulates the behavior of marine plastic debris, but it can be also used
 284 for the transport of suspended sediments. TrackMPD considers processes such as advection,
 285 dispersion, windage, sinking, settling, beaching and re-floating of independent particles
 286 (Jalón-Rojas et al., 2019). The horizontal position (X) of a particle at time $t + \Delta t$ in
 287 TrackMPD can be expressed as:

$$288 \quad X(t + \Delta t) = X(t) + U\Delta t + R\sqrt{2K_h\Delta t}, \quad (7)$$

289 where $U = (u, v)$ and K_h are horizontal current vector and diffusion coefficient, respectively.
 290 i and j denote unit vectors in the zonal (x) and meridional (y) directions, respectively. R is a
 291 random number (from -1 to 1) generated at each time step with an average and standard
 292 deviation from 0 to 1, generated at each time step. $X(t)$ is the original horizontal location of
 293 the particle at time t . $U\Delta t$ is the advective displacement and $R\sqrt{2K_h\Delta t}$ is the random
 294 displacement due to horizontal turbulent diffusion.

295 The vertical position (Z) at time $t + \Delta t$ is computed as follows:

$$296 \quad Z(t + \Delta t) = Z(t) + w(t)\Delta t, \quad (8)$$

$$297 \quad w(t) = w(t) - w_s(t) + \frac{R\sqrt{2K_z\Delta t}}{\Delta t}, \quad (9)$$

298 where w , w_s and K_z are the vertical velocity, settling velocity and vertical diffusion
 299 coefficient, respectively. $Z(t)$ is the original vertical location of the particle at time t . Two
 300 diffusion coefficients (K_h and K_z) were used in this model: the final term on the right-hand
 301 side in Eqs. (7), (9) is from stochastic motion during turbulent diffusion.

302 TrackMPD can be easily adapted to different ocean models. Jalón-Rojas et al. (2019)
 303 used hydrodynamic results in curvilinear grid from the Princeton Ocean Model (POM) as
 304 inputs for TrackMPD. Here, we adopted FVCOM results for TrackMPD for the first time by
 305 interpolating the unstructured-grid data into rectangular grids. Moreover, instead of using a
 306 constant vertical turbulent eddy viscosity (K_z), a time-dependent K_z calculated by FVCOM at
 307 every node which was then incorporated into TrackMPD for further accuracy.

308 ***Resuspension of deposited particles***

309 It has always been challenging to reproduce the resuspension of particles in a
 310 Lagrangian particle-tracking model. In this study, a resuspension module is added to
 311 TrackMPD. A tracking particle is resuspended from the seabed when the bottom shear stress
 312 at its sink location is larger than the critical erosion stress. Bedload transport for a particle is
 313 not considered in this model. The movement of this particle on resuspension is controlled by
 314 both sediment settling under gravity and vertical turbulence in the BBL (Ji, 2006).
 315 Accordingly, when a deposited particle meets the criteria for resuspension (Eq. 10), the
 316 logical of resuspension variable is true (equals 1) and it is placed at the bottom sigma level;
 317 its vertical location after resuspension is determined by w_s and K_z as in Eqs. (8) and (9).
 318 Correspondingly, the particle will deposit and stay at the bottom when the relating bottom
 319 shear stress is smaller than the critical value.

$$Resuspension = \begin{cases} 1, & \text{if } |\tau_b| > \tau_c \\ 0, & \text{if } |\tau_b| < \tau_c \end{cases}$$

(10)

3.3.3 Model configuration and validation

Hydrodynamic-sediment model

The simulation domain (Fig. 3) in this study covered the entire YE area, together with part of the NYS. Two experiments with different coastlines, in 1956 (Fig. 3a) and 2011 (Fig. 3b), were designed to simulate the hydrodynamic and sediment-transport conditions before and after the land reclamation, respectively. Simulation meshes were built using the Surface-water Modeling System (SMS), based on coastline and bathymetry data extracted from sea charts from the Navigation Guarantee Department of the Chinese Navy Headquarters in 2011 and coastline in 1956 (Fig. 2b). Maximum and minimum grid sizes of the meshes were 3000 m at the open boundary and 150 m near shore. A uniformed sigma-stretched coordinate system with 20 vertical layers was applied in this model to study the barotropic hydrodynamics in the YE.

Previous studies in similar systems have concluded that the changes in the water depth after land reclamation had a limited effect on the hydrodynamics compared to the changes in coastline (Gao et al., 2014; Guo et al., 2017). In order to eliminate errors generated in the numerical calculations and to isolate the impacts of the land reclamation, the same bathymetry and initial boundary conditions in 2011 were used for Experiments 1 and 2 (pre-reclamation and post-reclamation). Experiment 3 was designed for model validation using the same mesh as in Experiment 2 but with the boundary conditions in 2009 according to period of the field trip (Section 3.1.2).

As mentioned in Section 2.1, the hydrodynamics in the YE region are dominated by tides; therefore, tidal elevation is adopted as the open boundary condition to drive the model.

344 The tidal elevations at the open boundary were calculated based on selected tidal components
345 including four diurnal (K_1 , Q_1 , P_1 , Q_1), four semidiurnal (M_2 , S_2 , N_2 , K_2), three shallow-water
346 (M_4 , MS_4 , MN_4) and two long-period components (M_f , M_m). The Harmonic constants for all
347 tidal components were retrieved from the global tidal model TPXO 7.2.

348 Given that river discharge also impacts the estuarine dynamics, a constant river
349 discharge of $700 \text{ m}^3/\text{s}$ with a suspended-sediment flux of $0.1 \text{ kg}/\text{m}^3/\text{s}$ from the river (typical
350 value for the Yalu River during the wet season) at 1h interval was used as another boundary
351 forcing in this model. According to field observations, the YE is well-mixed for most of the
352 time as a consequence of the limited water depth and strong tidal action (Cheng et al., 2016;
353 Yu et al., 2014). Therefore, only the barotropic effects of the freshwater input are considered
354 in this model. The initial conditions for sea temperature and salinity in this model used the
355 typical values in the YE during wet season of 25°C and 33 psu, respectively. The influence of
356 wind and wave action in this area is weak and transient, as discussed in Section 2.1.1;
357 therefore, wind and wave forcing were not considered in the model.

358 The sediment module set for all experiments considers only cohesive sediments, as
359 most suspended sediments are cohesive and are easily transported in an estuary (Brenon and
360 Hir, 1999). Due to the lack of observations for sediment parameters in the YE, the erosion
361 rate and critical shear stress were assumed to be constant over the estuary, with different
362 values tested to best fit the general pattern of the observation data. The mean grain size of
363 sediments in the YE is about 0.06 mm (Cheng et al., 2019) and the mean SSC in the estuary
364 is beneath the threshold for flocculation (Yu et al., 2014). Thus, the settling velocity was
365 estimated to be constant at $1.25 \times 10^{-4} \text{ m/s}$ according to Chakraborti and Kaur (2014) and Van
366 Rijn and Kroon (1993). Other values of key model parameters are shown in Table 2.

367 Experiments 1 and 2 ran for 92 days from 01 May 2011 to 31 July 2011, Experiment 3

368 for 62 days from 1 July 2009 to 31 August 2009. All experiments have run for 15 days to
369 warm up.

370 *Particle resuspension and tracking model*

371 Two scenarios (pre- and post-reclamation) were designed for TrackMPD in the YE to
372 reproduce the transport of suspended sediment particles before and after the land reclamation.
373 Using forward tracking to determine their subsequent movement, particles were released
374 every hour from five potential source areas (dark-blue points in Fig. 2a). RN, LR, WK, WR
375 and SW (Fig. 2a) indicate five potential sediment source which represent fluvial sediments
376 from the river load (RN), local resuspended sediments from the East Branch (LR), sediments
377 transported from the Western Korean Bay (WK), sediments transported from the West Branch
378 (WR) and sediments from the shallow waters in the Northern Yellow Sea (SW). These five
379 source areas were located around the estuarine main branch and covered particles from
380 almost all directions.

381 Particles were released from the near-bottom layer over an area of 0.048 km^2 for each
382 release area. A total number of 7,560 particles was released under different tidal conditions
383 (seven days from UTC 0000 22 May 2011 to UTC 0000 28 May 2011), and all particles were
384 tracked for 14 days after release.

385 The hydrodynamic inputs (u , v , w , water elevation, bottom shear stress and vertical
386 eddy viscosity) for the two scenarios were from FVCOM simulations (Experiments 1 and 2 in
387 previous section). Settling velocity and critical shear stress for resuspension were set to be the
388 same as for the FVCOM sediment model (Table 2). A particle touches the lateral boundary
389 will beach at its final location; a particle sinks at the bottom will be resuspended into the
390 water column when the bottom stress at its sinking location meets Equation (10).

391 **Model validation**

392 Figure 4 shows the comparison between the water-level observations at 1h intervals
393 from the Yalu Park Hydrology Station and that from the model at the north boundary point of
394 the study domain during June 2011. The hydrology station is located upstream in the river (64
395 km from the estuary entrance, Fig. 1), 15 km north of the model northern boundary.
396 According to the comparison in Fig. 4, modelled surface elevation agreed reasonably well
397 with the measurements. The slight difference between the two timeseries for the surface
398 elevation around 500 h is acceptable, considering the effects of river flow and the spatial
399 separation between the two sites. Table 3 shows comparison of amplitudes and phases
400 between modelled and observed surface elevation for main tidal constituents. According to
401 these harmonic constants of tidal analysis in Table 3, M_2 appeared to be the predominant tidal
402 constituent in the YE, indicating the estuary is dominant by semidiurnal tides. The average
403 discrepancy in amplitude and phase were 0.05m and 11.4° , demonstrating solid agreement
404 between modelled and observed water level.

405 The model results of Experiment 3 were further validated against the measurements
406 from the field trip in August 2009. Figure 5(a) shows good agreement between the modelled
407 and measured water elevations during spring and neap tides at Stations Y02 and Y03 (Fig. 1).
408 Figures 5(b, c) show good agreement in the streamwise current speed and current direction,
409 with mean correlation coefficients between model results and measurements of 0.87 and 0.85
410 (Table 4), respectively. Validation of SSC is shown in Fig. 5(d), indicating the model has
411 captured the magnitude and fluctuations over time of the observed SSC. The differences
412 between the measured and modelled SSC at Y02 may be related to freshwater input. While
413 we used the monthly-averaged river flow as model input due to the lack the high-frequency
414 measurements, the real river flow can vary largely during the wet season. The lower SSC
415 observed at Y02 can be the result of the dilution by the instantaneous freshwater discharge as

416 the field trip was conducted in August. Simulation of the SSC has always been challenging
 417 due to the uncertainty in setting the local parameters (e.g. settling velocity and critical bottom
 418 stress; Song and Wang, 2013; Xing et al., 2012). The simulated SSC in this study is already
 419 more accurate than in the previous study in the YE (Yu et al., 2014). Although the model did
 420 not capture the precise values of SSC, it reproduced its first-order variation and is therefore
 421 suitable for studying the changes in sediment transport after land reclamation.

422 3.3.4 Data post-processing

423 *Decomposition method for the suspended-sediment flux*

424 In order to quantitatively understand the change in sediment transport after the land
 425 reclamation, the suspended sediment flux was decomposed using the mass-transport flux
 426 formulation of Dyer (1997). By neglecting high-frequency turbulence, the tidally and sigma-
 427 averaged suspended-sediment flux can be quantified as:

$$\begin{aligned}
 428 \quad \langle T \rangle &= \frac{1}{T} \int_0^T \int_0^1 hUC \, d\sigma dt = h_0 \bar{U}_0 \bar{C}_0 + \bar{C}_0 \langle h_t \bar{U}_t \rangle + \bar{U}_0 \langle h_t \bar{C}_t \rangle + h_0 \langle \bar{U}_t \bar{C}_t \rangle + \\
 429 \quad &\langle h_t \bar{U}_t \bar{C}_t \rangle + h_0 \langle \bar{U}_d \bar{C}_d \rangle + \langle \bar{h}_t \bar{U}_d \bar{C}_d \rangle = T1 + T2 + T3 + T4 + T5 + T6 + T7 \quad , \\
 430 \quad (11)
 \end{aligned}$$

431 where U and C are the velocity (m/s) and SSC (mg/L), respectively, both functions of depth
 432 and tidal phase; h is the water depth (m), a function of time, and T is the tidal period (h).
 433 Subscript 0 denotes tidally averaged value; t denotes deviation from tidally averaged value; d
 434 deviation from the corresponding depth-averaged value; overbar denotes depth-averaged and
 435 angle brackets tidally averaged.

436 The decomposition terms T_1 to T_7 represent the different contributions of the various
 437 physical processes affecting sediment transport (Dyer, 1997): T_1 is the flux induced by the
 438 residual flow of water (Eulerian residual velocity); T_2 the Stokes drift caused by the tides; T_3
 439 to T_5 are tidal pumping terms produced by tidal phase differences, with T_3 the correlation

440 term between the tidal level and SSC, T_4 mainly a consequence of lags between sediment
 441 erosion and maximum tidal current and T_5 gives the third-order correlation between tidal
 442 levels, velocities, and SSC, which characterizes tidal trapping. T_6 and T_7 arise from vertical
 443 circulation effects.

444 *Tidal asymmetry*

445 The skewness γ_{M_2/M_4} was used in this study to investigate the change in tidal
 446 asymmetry after land reclamation. γ_{M_2/M_4} is calculated using the harmonic-analysis results
 447 of the modelled sea surface elevation for 1 lunar month, according to Song et al. (2011):

$$448 \quad \gamma_{M_2/M_4} = \frac{\frac{3}{2}a_{M_2}^2 a_{M_4} \cdot \sin(2\varphi_{M_2} - \varphi_{M_4})}{\left[\frac{1}{2}(a_{M_2}^2 + a_{M_4}^2)\right]^{\frac{3}{2}}},$$

449 (12)

450 where a_{M_2} and a_{M_4} are the amplitudes of the M_2 and M_4 tidal constituents, respectively;
 451 φ_{M_2} and φ_{M_4} are the corresponding phases.

452 **4. Results**

453 **4.1 Historical variations of REE sediment records in the YE**

454 **4.1.1 Profiles of REE fractionation factors**

455 REE fractionation factors including ΣREE , $\Sigma\text{LREE}/\Sigma\text{HREE}$, $(\text{La}/\text{Sm})_{\text{NASC}}$,
 456 $(\text{Gd}/\text{Yb})_{\text{NASC}}$, $(\text{La}/\text{Yb})_{\text{NASC}}$, $\delta\text{Ce}_{\text{NASC}}$ and $\delta\text{Eu}_{\text{NASC}}$ (Sections 3.2.3 and 3.2.4) were calculated in
 457 this study as indicators of historical changes in sedimentation in the YE. Figure 6 shows the
 458 vertical profiles of REE fractionation factors for cores K1 and K12, together with the
 459 corresponding ages derived from chronology results (Cheng et al., 2019). For most profiles,
 460 there was an obvious turning point at the layer corresponding to the year 1975.

461 For K1, ΣREE (Fig. 6a) ranged from 180 $\mu\text{g}/\text{g}$ to 286 $\mu\text{g}/\text{g}$, with a mean value of 227

462 $\mu\text{g/g}$. $\Sigma\text{LREE}/\Sigma\text{HREE}$ (Fig. 6b) ranged from 12.0 to 15.4, with a mean value of 12.5. ΣREE
463 was significantly larger than the average before 1975, then decreased to and remained at the
464 average in the years after. A similar trend was found in the ratio $\Sigma\text{LREE}/\Sigma\text{HREE}$, with higher
465 values before 1975 and lower values after. For K12, ΣREE ranged from 147 $\mu\text{g/g}$ to 238 $\mu\text{g/g}$,
466 with a mean value of 202 $\mu\text{g/g}$ (slightly lower than that of K1). $\Sigma\text{LREE}/\Sigma\text{HREE}$ ranged from
467 10.4 to 13.5, with a mean value of 12.0. In contrast to K1, ΣREE in K12 was smaller than the
468 average before 1975, then increased to the average, close to that of K1, after 1975.
469 $\Sigma\text{LREE}/\Sigma\text{HREE}$ in K12 showed an increasing trend before 1975 and came close to the K1
470 value after 1975.

471 $\delta\text{Ce}_{\text{NASC}}$ of K1 (Fig. 6f) ranged from 0.78 to 0.86, with a mean value of 0.82
472 (relatively close to 1). There was also an obvious inflection around 1975, with $\delta\text{Ce}_{\text{NASC}}$ larger
473 than the average before the inflection and smaller after. $\delta\text{Eu}_{\text{NASC}}$ of K1 (Fig. 6g) was between
474 0.48 and 0.82, with a mean value of 0.63. The inflection around 1975 layer was also evident
475 in $\delta\text{Eu}_{\text{NASC}}$ of K1 but with an opposite trend (values were larger after 1975).

476 $\delta\text{Ce}_{\text{NASC}}$ of K12 ranged from 0.76 to 0.83 with a mean value of 0.80. The 1975
477 inflexion was also distinctive in $\delta\text{Ce}_{\text{NASC}}$ of K12. In contrast to that of K1, $\delta\text{Ce}_{\text{NASC}}$ of K12
478 was smaller than average value before 1975, and became larger after. $\delta\text{Eu}_{\text{NASC}}$ of K12 ranged
479 from 0.52 to 0.95, with a mean value of 0.69. The 1975 inflection was again evident in $\delta\text{Eu}_{\text{NASC}}$
480 of K12, with large values before 1975 and small values after.

481 For the internal fractionation pattern of HREE: $(\text{Gd}/\text{Yb})_{\text{NASC}}$ (Fig. 6c) of K1 and K12
482 ranged from 1.19 to 1.56, and 1.05 to 1.40 with mean values of 1.37 and 1.28, respectively.
483 $(\text{Gd}/\text{Yb})_{\text{NASC}}$ of K1 was generally larger before 1975 than after, while $(\text{Gd}/\text{Yb})_{\text{NASC}}$ of K12
484 decreased slightly after 1975.

485 $(\text{La}/\text{Sm})_{\text{NASC}}$ (Fig. 6d) demonstrates the internal fractionation pattern of LREE:
486 $(\text{La}/\text{Sm})_{\text{NASC}}$ of K1 ranged from 1.35 to 1.47, with a mean value of 1.41. $(\text{La}/\text{Sm})_{\text{NASC}}$ of K12

487 was between 1.26 and 1.41, with a mean value of 1.33. Pre- and post-1975 change in
488 $(La/Sm)_{NASC}$ was not marked as in the other profiles. For $(La/Yb)_{NASC}$ (Fig. 6e), which
489 reveals fractionation-pattern differences between LREE and HREE: $(La/Yb)_{NASC}$ of K1 was
490 from 1.9 to 2.7, with a mean value of 2.3 before 1975, falling below the average after 1975.
491 $(La/Yb)_{NASC}$ of K12 was between 1.52 and 2.24, with a mean value of 1.98.

492 For most fractionation factors, the differences between K1 and K12 were large before
493 1975 but became smaller after that. Accordingly, the sediment cores in this study were
494 divided into two sections (upper and lower) using the 1975 sedimentation layer as the split
495 line.

496 **4.1.2 Normalized REE fractionation curves**

497 The averaged correlation coefficient between mean grain size and ΣREE ,
498 $\Sigma LREE/\Sigma HREE$, $(La/Yb)_{NASC}$, $(La/Sm)_{NASC}$ and $(Gd/Yb)_{NASC}$ over all layers from K1 and
499 K12 was 0.1512, indicating that the granularity effect was not significant in these results.

500 In order to eliminate the potential effects of other factors on REE fractionation, we
501 also compared the geometric shapes of the normalized REE patterns instead of the abundance
502 of the REE. The REE concentrations of representative sedimentation layers from cores K1
503 and K12, together with those of surficial sediments of five sections (Fig.1), were normalized
504 by values from the NASC (Table 1).

505 The NASC-normalized REE curves (Figs. 7a, b) of K1 and K12 had a stronger
506 enrichment in LREE comparing to other surface samples. Samples after 1975 in K12 showed
507 a clear larger deficit in Eu than before 1975. Conversely, samples after 1975 in K1 have a
508 smaller Eu deficit than before 1975. Section E showed a distinct curve with significant
509 depletion in Dy, implying REE upstream area may originated from a different source
510 compared to other samples around the estuary. Previous study also showed that the sediments
511 originated from basaltic lava platform in the Yalu River headstream were restrained in the

512 upper reach of the river after the reservoir construction (Liu et al., 2015), which may explain
513 the distinct fractionation pattern of Section E.

514 The fractionation patterns of the YE samples were still belong to a same group,
515 indicating a predominant common parent rock type for this area. However, obvious
516 differences can be found before and after 1975 in K1 and K12. As the sediment source in the
517 YE were a mixture of materials from terrigenous sources (fluvial inputs) and neritic sources
518 carried by ocean currents (Liu et al., 2013), the significant changes in the REE patterns may
519 reflect the changes in the composition of this mixture (e.g., the proportion of fluvial and
520 neritic inputs).

521 **4.1.3 Spatial distribution of REE sedimentation**

522 The chart of ΣREE versus $\Sigma\text{LREE}/\text{HREE}$ was used here to identify the differences in
523 REE sedimentation between K1 and K12 and to compare the sediment property at these two
524 sites with surface sediments from surrounding areas.

525 The patch of sedimentation units (scatter points in Fig. 8) at K1 before 1975 was
526 distinct from other samples around the estuary. These sedimentation units were characterized
527 by prominently higher ΣREE and $\Sigma\text{LREE}/\text{HREE}$, suggesting a unique sediment supply
528 contributed to sediments at K1 before 1975. This particular sediment source before 1975 no
529 longer affected K1 afterwards. After 1975, the patch of sediment units in K1 moved to an
530 area with a center point corresponding to a total REE of 220 $\mu\text{g}/\text{g}$ and a $\Sigma\text{LREE}/\text{HREE}$
531 around 13. Compared to the surface samples from five sections around the YE, deposits in K1
532 after 1975 were more similar to the samples from the LP muddy coast (Section C).

533 According to Fig. 8(b), the patch of sedimentation units at K12 also moved to a
534 similar area as those of K1 after 1975. The change of REE at K12 was not as prominent as
535 K1, but a distinct change can still be identified: sediment in K12 before 1975 had a more
536 complex feature, whereas units after 1975 were more concentrated. In summary, although the

537 sediments of K1 and K12 were different before 1975, they became similar after 1975.

538 It is noteworthy that the slight similarity in the REE property after 1975 between the
539 two cores and Section C does not necessarily indicate sediments of K1 and K12 were from
540 Section C after 1975. It only implied that the post-1975 deposits at K1, K12 and Section C
541 may have a common sediment input.

542 To further analyze the homogeneity of the deposits at K1 and K12, the Discrimination
543 Function (DF) index was calculated in this study. DF has been widely used in REE studies to
544 evaluate the difference between two samples (Jung et al., 2012; Yang et al., 2019). The DF
545 index is given by:

$$546 \quad DF = |C_1/C_2 - 1|, \quad (13)$$

547 where C_1 is an REE parameter from one sample and C_2 the same REE factor from a
548 different sample.

549 In general, the closer the DF index is to zero, the more similar the sedimentary
550 features of the two samples are. REE fractionation factor $\Sigma LREE/\Sigma HREE$ was used to
551 calculate the DF between K1 and K12 for corresponding layers (Fig. 9). The DF curve clearly
552 shows that the deposits in K1 and K12 became more homogeneous after 1975, with a larger
553 DF index, near 0.3, before 1975 and values smaller than 0.1 after 1975.

554 In conclusion, multiple indicators demonstrated there was a dramatic change in the
555 sedimentation process around 1975 in K1 and K12. These REE sediment records indicated
556 that the properties of sediments in these two cores became homogeneous after 1975. This
557 homogeneity may be an indicator for concurrent sedimentary succession in the YE.

558 Unlike natural evolution, human activities can rapidly change the estuarine
559 morphology. Previous studies have shown that a change in coastline can alter the
560 hydrodynamics and sediment transport (Byun and Wang, 2005; Gao et al., 2014; Guo et al.,
561 2017; Li et al., 2014). And the dramatic change in 1975 in REE properties in the YE here is

562 hypothesized as a consequence of the contemporaneous human-induced changes. In
563 particular, it can be related to the substantial increase of the area of Chouduan Island during
564 the 1970s due to the land reclamation and blocking of the lateral water arms.

565 These activities generated a narrower estuarine entrance which almost certainly
566 changed the hydrodynamics around the East Branch and thus the changes in the
567 sedimentation process. To verify this hypothesis, numerical models for this area were
568 established in this study to simulate the hydrodynamics condition before and after that
569 reclamation.

570 **4.2 Variations of hydrodynamic-sedimentary dynamics in** 571 **the YE**

572 **4.2.1 Changes in hydrodynamics post-reclamation**

573 Figure 10 presents the model depth-averaged current field for Experiments 1 (pre-
574 reclamation) and 2 (post-reclamation) for flood and ebb during spring and neap tides. The
575 tidal current in the YE generally flowed in the northeast-southwest direction, both pre and
576 post land reclamation. After land reclamation, the magnitude of the tidal current in the East
577 Branch area during spring tide increased by 0.08 m/s for both flood and ebb (Figs. 10a-d). It
578 decreased by 0.4 m/s in a small area to the south of Chouduan Island (Fig. 1) at flood time
579 due to the effects of the prominent headland (Figs. 10a, b). Although not as evident as for the
580 spring tide, the current speed during neap tide also increased slightly by 0.03 m/s after land
581 reclamation (Figs. 10e-h).

582 In all simulations, the maximum flood current was larger than the maximum ebb
583 current, showing a significant tidal asymmetry in this area with strong flood dominance. The
584 skewness γ_{M_2/M_4} (Section 3.3.4) in the estuarine area was positive in both experiments,
585 indicating the YE was a flood-dominance system both pre- and post-reclamation (Figs. 11a,

586 b). However, γ_{M_2/M_4} around the East Branch decreased from 0.5 to 0.47 in Experiment 2
587 (Fig. 11c), suggesting that the strength of flood dominance in this area was weakened post-
588 reclamation.

589 **4.2.2 Changes in suspended sediment distribution post-reclamation**

590 Figure 12 shows the modelled depth-averaged SSC before and after land reclamation
591 at different tidal phases (flood time, high water, ebb time and low water) during spring and
592 neap tides. The SSC during spring tide was higher than during neap, with maximum values at
593 flood and ebb, and minimum values at slack water, in accordance with previous studies
594 (Cheng et al., 2016; Yu et al., 2014). A TMZ occurred in the seaward part of the East Branch,
595 coinciding with its location in previous observations (Gao et al., 2004; Yu et al., 2014).
596 Controlled by the tidal excursion, this TMZ moved landward during flood phase and seaward
597 during ebb. The position of the TMZ did not change significantly after land reclamation, but
598 its area and strengthen slightly increased. The magnitude of SSC in the East Branch increased
599 by 140 mg/L after land reclamation, as expected from the enhanced bottom shear stress due
600 to the stronger tidal currents.

601 Figure 13 shows the model horizontal distributions of tidally averaged SSC in the
602 surface and bottom layers and their changes pre- and post-reclamation. The horizontal SSC
603 distributions were similar in the YE for the two experiments. However, the SSC in the surface
604 layer in the East Branch was about one third that in the bottom layer, and the difference
605 became more significant after land reclamation. The horizontal gradient of SSC between the
606 inner and outer estuary also became larger post-reclamation.

607 **5 Discussion**

608 In Section 4, we found that REE pattern at K1 and K12 has changed from diverse to
609 homogenous after 1975. Hydrodynamics and the distribution of SSC in the YE also changed
610 greatly because of the concurrent land reclamation. Thus, this section aims to: (1) provide a

611 physical explanation to that dramatic change in estuarine sedimentation; and (2) determine
612 the sediment source (terrigenous or neritic inputs) of the estuary before and after the land
613 reclamation.

614 **5.1 Effects of tidal-choking on mixing process**

615 Tidal-choking is a phenomenon in which the tidal amplitude is damped and the phase
616 delayed when tides propagate through a long, narrow channel (Byun et al., 2004; Guo et al.,
617 2017; Stigebrandt, 1980). It is a geometric feature that often occurs in macro-tidal areas with
618 shallow water (Byun and Wang, 2005). According to model results in Fig. 14, the tidal-
619 choking effect was enhanced in the main branch of YE due to the land reclamation. A slight
620 drop in the M_2 amplitude, 2 cm, occurred in the East Branch after reclamation according to
621 the harmonic analysis of tidal elevation (Fig. 14a); the phase of M_2 was also delayed by 2°
622 (Fig. 14b). This drop in amplitude together with the delayed phase of M_2 in this area indicates
623 the system was more choked after reclamation.

624 Due to the Bernoulli Equation, the reduced water level accelerates the water flow
625 through a choked channel (Stigebrandt, 1980). This change in tidal current was also found in
626 the YE (Fig. 14c). After land reclamation, major axis of vertically averaged M_2 tidal current
627 increased by over 0.1 m/s due to the enhanced tidal-choking. Previous studies also found
628 stronger tidal-choking can generate a stronger current in choked channel: for example, tidal
629 current in the Mokpo Coastal Zone was larger due to the enhanced tidal-choking (Byun et al.,
630 2004); current in the Yangshan Harbour channel was increased as a consequence of stronger
631 tidal choking after narrowing (Guo et al., 2017); and the removal of tidal flats in the Jiaozhou
632 Bay and less mangroves in the Darwin Harbour resulted in a decreased current speed due to
633 reduced tidal choking (Gao et al., 2014; Li et al., 2012).

634 The intensity of turbulent mixing is described using vertical and horizontal turbulent
635 eddy viscosities. The enhanced tidal-choking effect leads to stronger mixing processes in the

636 East Branch: both vertical and horizontal eddy viscosities were increased post-reclamation
637 (Figs.14d, e). This provides an explanation to the dramatic change in the REE sedimentation
638 around 1975: the larger vertical mixing hindered the settling of suspended particles in the
639 water column, enhanced the mixing of the different sediments (from multiple sources) before
640 they deposit to the seabed, resulting in a more homogeneous local deposits on the seabed (as
641 discussed in Section 4.1). The slightly larger post-reclamation horizontal mixing caused a
642 stronger horizontal dispersion of sediments in the water, which also contributed to the
643 homogeneity of sediments in the East Branch.

644 **5.2 Variations of suspended sediment transport**

645 In order to understand the transport of suspended sediments between the estuary and
646 surrounding shallow waters, the profiles of SSC and net suspended-sediment transport across
647 the estuary entrance line (Fig. 1) was shown in Fig. 15. For both experiments, larger SSC
648 were found at bottom in the west side of the entrance, near the Middle River (Fig. 15a). This
649 bottom patch of higher SSC became larger post-reclamation in Experiment 2. The net
650 sediment flux was seaward at the western end of the cross-section and landward at the eastern
651 part. The overall direction of the net sediment flux was landward. However, this landward
652 flux was reduced post-reclamation, especially near the Middle River (Fig. 15f).

653 The sediment flux across the entrance indicated that the estuary experienced erosion
654 on its west side and siltation on the east. However, the intensity of erosion increased
655 significantly across the whole entrance after land reclamation. Estuaries tend to be a sink for
656 cohesive, fine sediments, especially those with weak dynamic environments (Cundy et al.,
657 2003). But in a macro-tidal estuary like the YE, sediments can be easily remobilized by
658 strong currents. Therefore, dramatic changes in tidal dynamics may induce a “sink-to-source”
659 transformation of the YE. The reduced landward sediment flux in the YE implies that the
660 estuary may experience more erosion instead of siltation and shift from a sediment sink to a

661 source if more land is reclaimed in the future.

662 To investigate further the main physical mechanisms driving this change, the net
663 sediment flux was decomposed using Eq. (11). Figure 16a displays the decomposed sediment
664 flux at sites K1 and K12 (Fig.1) in Experiments 1 and 2. Tidal pumping (terms T_3 , T_4 and T_5)
665 was the dominant mechanism for sediment transport at these two sites, following by sediment
666 flux generated by Eulerian-residual current (T_1). As the estuary was vertically well-mixed,
667 sediment flux induced by vertical circulation (T_6 and T_7) at the two sites was negligible in
668 both scenarios.

669 The direction of sediment transport was consistently landward at K1 and K12 (Fig.
670 16b). However, the dominant landward contribution from tidal pumping decreased
671 significantly post-reclamation, consistent with the seaward advective sediment flux slightly
672 increased. Tidal pumping effect decreased because of the reduced flood dominance (Section
673 4.2.1, Fig. 11). And the seaward flux (the Lagrangian flux in Fig. 16b) was enhanced due to
674 the larger seaward residual currents (river flows concentrated more in the main branch post-
675 reclamation whereas they can be transported through the lateral Yingmen Channel before). As
676 a consequence of these changes, the total landward transport of sediments at these sites
677 decreased by more than 50% after land reclamation.

678 Previous studies proposed that the YE is a sink for sediments, with resuspended
679 sediments moving landward at the entrance line (Gao et al., 2004, 2003; Liu et al., 2013).
680 Results from the sediment model in this study confirmed this hypothesis. However, although
681 general tendency of SSC transport has always been landward, the degree of this landward
682 transport decreased significantly after the land reclamation as discussed in this section.

683 **5.3 Changes in sediment sources**

684 As discussed in Section 4.1, the property of deposits at the two sites (K1 and K12 in

685 Fig. 1) changed significantly and became similar after 1975. To investigate this change in
686 sediments in the East Branch area post-reclamation, particle resuspension and tracking
687 simulations were conducted using TrackMPD (Section 3.3.3). Fig. 17 shows the trajectories
688 of these simulated particles.

689 Fluvial particles released upstream (RN in Fig. 17) could be transported through the
690 Yingmen Channel and West River before reclamation but distributed mainly in the East
691 Branch afterwards. The fluvial particles therefore contributed significantly more to the
692 estuarine deposits after reclamation, corresponding to the increased seaward sediment flux
693 discussed in Section 5.2.

694 A similar pattern was also found in particles from the middle region of the East
695 Branch (representing local resuspended particles; LR in Fig. 17). Due to the stronger mixing
696 post-reclamation, the trajectories of the LR particles were more spread out.

697 The particles released from shallow water in the NYS (SW in Fig. 17) did not show
698 any obvious change in their trajectories. These particles did reach further north to the inner
699 estuary after reclamation, but still had a relatively low probability of being transported to K1
700 and K12. A previous study using indicative minerals for provenance tracking treated this
701 particular shallow-water area as a sediment source (termed “neritic sediments” in their study),
702 together with the fluvial source (Liu et al., 2013). According to our model results, there was a
703 tendency for these particles to accumulate around the Xin Island before reclamation.
704 However, they were more distributed in the shallow water away from the estuary afterwards.

705 Pre-reclamation, particles released from WR can be washed away into the NYS,
706 whereas it generally remained around WR post-reclamation. Additionally, particles from the
707 fluvial area (RN) reached WR before reclamation but no longer transported to this area
708 afterwards. These results suggested the sediment source of WR changed from fluvial
709 materials to local deposits after land reclamation. The reason for this phenomenon is that the

710 West Channel (WR in Fig.17) was transformed from a main water outlet into an abandoned
711 tidal waterway over a relatively short time. After reclamation, the WR area received only a
712 very small amount of river discharge and turned into a gulf-like environment. Thus, deposits
713 here were mainly from local resuspended sediments controlled by tides. Before the expansion
714 of the islands in the early 1970s, the bulk of these local sediments were from fluvial input. A
715 previous study also found that the deposits in the West Channel were old fluvial materials
716 (Liu et al., 2013). This would provide an explanation to why the sediments in the East Branch
717 at K1 and K12 after reclamation had similar REE properties to the surface sediments from the
718 Liaodong muddy coast (Section C in Fig.1, which is near WR).

719 In terms of particles released from Western Korean Bay (WK in Fig.17), the
720 trajectories of these particles covered a larger part of the estuary before reclamation but were
721 restricted to a smaller area afterwards.

722 Several conclusions can be drawn from these particle-tracking results. **(1)** Before
723 reclamation, site K1 mainly received particles from the Western Korean Bay region; particles
724 from other areas did not reach K1. Sediments at K12 were multiple sources, which contained
725 mainly fluvial materials (from RN), partly local resuspended particles from the East Branch
726 (LR) and a small amount of neritic sediments (SW). **(2)** After reclamation, the bulk of the
727 sediments at both K1 and K12 were derived predominantly from two sources: fluvial input
728 (from RN); and local resuspended sediments from main-branch deposits (LR).

729 These conclusions help to explain the REE results in Section 4.1: bulk of the deposits
730 at K1 had a distinct REE property before reclamation, suggesting a single sediment input
731 from the Western Korean Bay. At K12 before reclamation, sediments had diverse REE
732 properties, corresponding to the multiple sediment sources implied by the particle-tracking
733 results. After land reclamation, deposits at both K1 and K12 became similar to those from
734 Section C (the WR area; Fig. 2a) because they have a more common composition (with

735 sediments from RN and LR).

736 Essentially, after land reclamation, the estuarine main branch (the East Branch)
737 received more materials from fluvial inputs due to the increased seaward flux caused by
738 reduced flood dominance; the deposits became more homogeneous, with a common
739 composition that contains more fluvial and local resuspended sediments as a result of
740 stronger mixing; particles from the Western Korean Bay no longer transported to the inner
741 estuary.

742 **6 Conclusion**

743 This study firstly examined the historical variations in rare-earth element (REE)
744 sedimentation in the Yalu River Estuary (YE). The REE records in two cores (K1 and K12)
745 demonstrated there was a dramatic change in sedimentation in the YE around the year 1975.
746 Results indicated that sediment property in the main branch has changed from diverse to
747 homogenous after 1975.

748 Then a 3D hydrodynamic-sediment model was established in the YE for the first time
749 to explore the structure of the estuarine dynamics pre- and post-reclamation. Model results
750 showed that the local hydrodynamics changed significantly after the land reclamation: (1) the
751 magnitude of the tidal currents during both spring and neap tide increased; (2) the degree of
752 the flood dominance in the main branch was reduced; (3) tidal-choking in the estuary was
753 found to be enhanced; and (4) the intensity of turbulent mixing became stronger.

754 The varying hydrodynamics led to changes in sediment transport post-reclamation:
755 (1) the SSC in the main branch of YE increased greatly by 140 mg/L; (2) the difference
756 between surface and bottom SSC also increased; (3) there was a larger horizontal SSC
757 gradient between the inner and outer estuary; (4) although the net suspended sediment flux
758 remained landward, this landward transport has been weakened after reclamation; and (5) the
759 dominant landward sediment flux caused by tidal pumping decreased significantly, with a

760 slightly increase in the seaward Lagrangian flux. These changes in sediment transport showed
761 that erosion in the estuary was enhanced after the reclamation, which may change the estuary
762 from a sediment sink to a source if the reclamation continues.

763 Simulations from a newly developed Lagrangian 3-D particle resuspension and
764 tracking model demonstrated that the sediment source of the estuary altered after reclamation
765 as well: (1) site K1 at the mouth of the estuary received more sediment particles from the
766 Western Korean Bay before the reclamation, whereas K12 received particles from multiple
767 areas; (2) the source area of sediments at the two sites and in the East Branch area became
768 similar post-reclamation, with most particles from the river and local resuspension. These
769 results presented an explanation to the previous results found in the REE sediment records:
770 the main branch of the estuary received more fluvial sediments after 1975 due to the stronger
771 seaward flux caused by the reduced flood dominance; and sediments at K1 and K12 showed
772 homogeneity after 1975, with a common composition as a result of the stronger mixing.

773 Results from this study demonstrates the possibility of a “source-sink” shift in a
774 medium-scale estuary after a large-scale land reclamation. This study also contributes to a
775 better understanding of the link between changes in sediment source and their relationship
776 with suspended-sediment transport. Furthermore, this study gives an approach to future study
777 of a medium-to-long term estuarine sedimentation process by combining numerical
778 simulations and geochemical results of sedimentology.

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790 **Competing interest**

791 The authors declare no competing interest.

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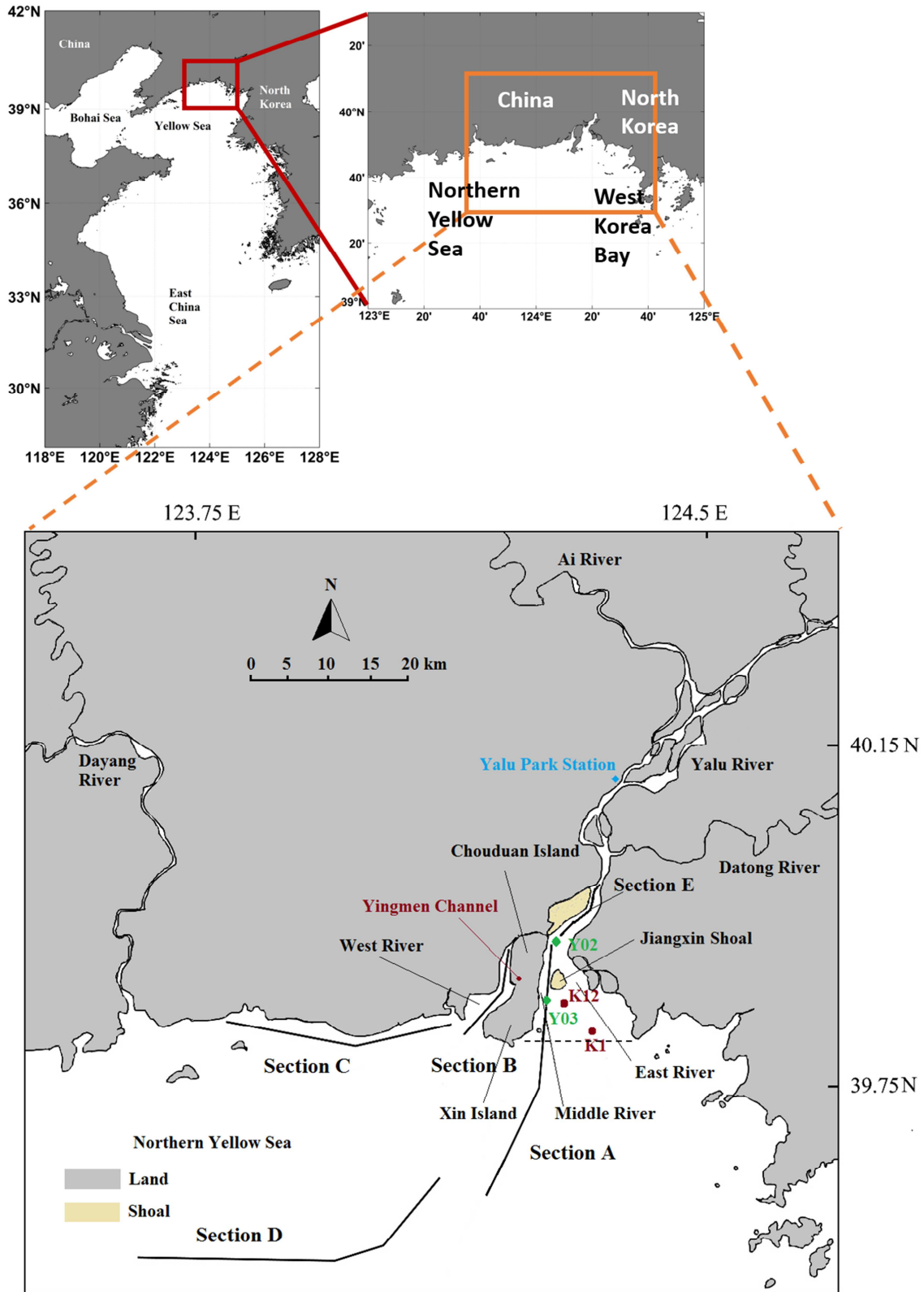
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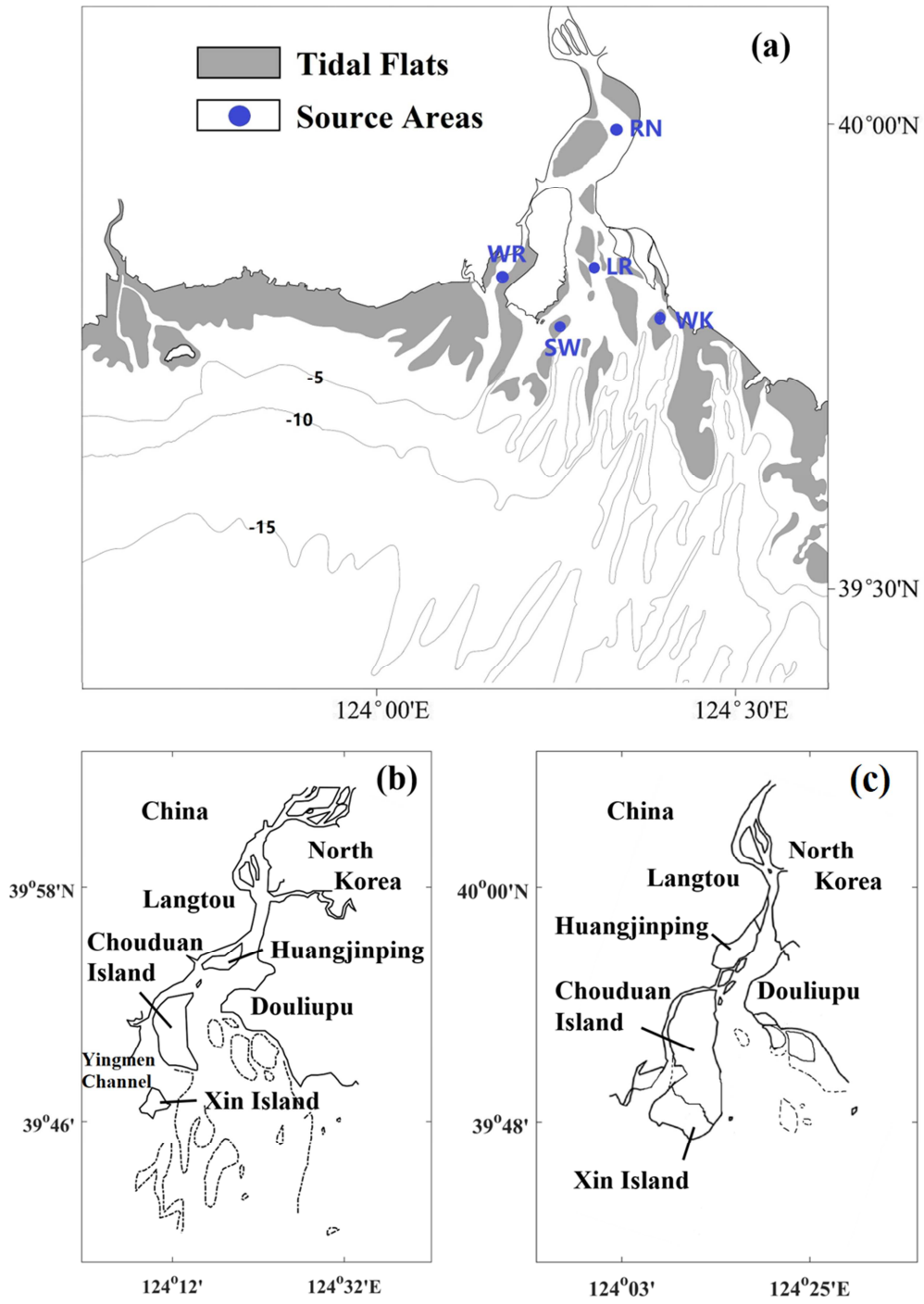
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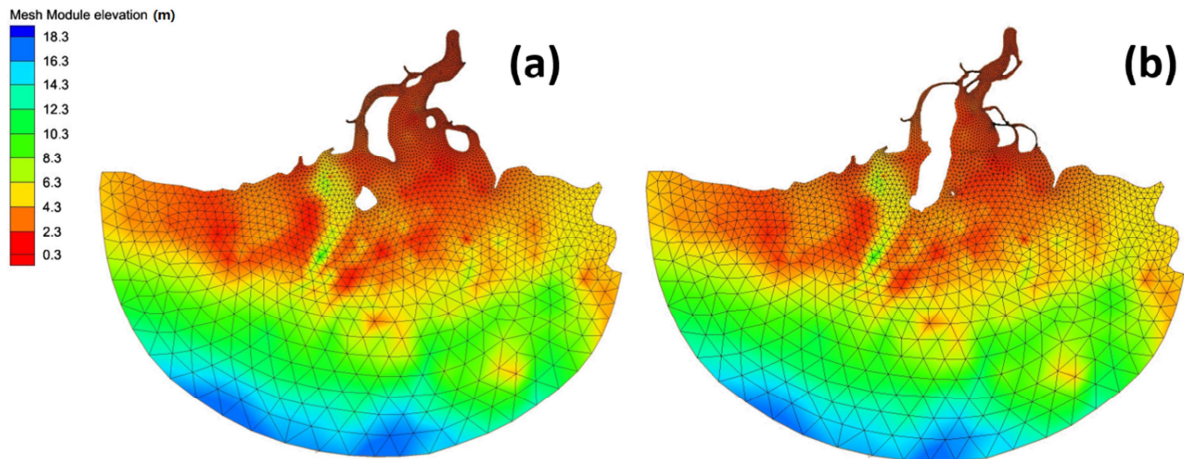
1018 **Figure 1.** Location of sampling sites around the YE and its surrounding shelf region. K1 and
1019 K12 indicate the core-sample collecting sites. Y02 and Y03 are the current-measurement
1020 sites. Yalu Park Station is the upstream hydrology station. The black dashed line shows the
1021 estuarine entrance line. Sections A, B contain surface sampling sites along the Middle River
1022 and West River, respectively. Section C contains sampling sites from the muddy coast along
1023 the Liaodong Peninsula (LP). Section D contains sites in the adjacent shallow waters outside
1024 the estuary entrance. Section E contains sites in the estuary, immediately downstream of the
1025 river.



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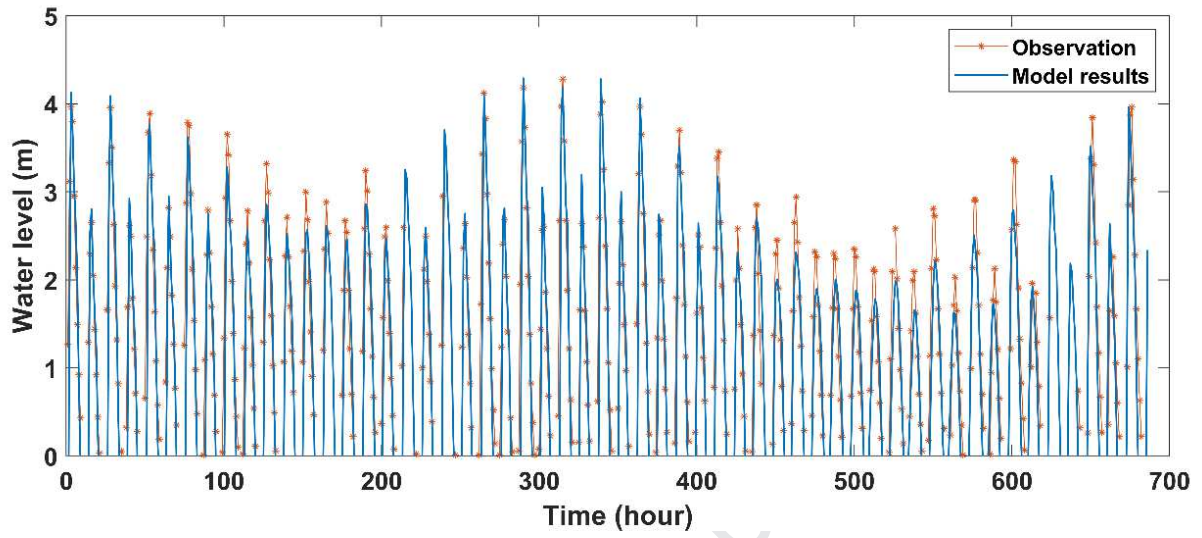
1027 **Figure 2. (a)** Bathymetry (black dash lines) and distribution of tidal flats (in grey) in the YE
1028 (modified from Liu et al., 2013). Points in dark blue show the potential source areas for the
1029 particle-tracking model: RN is a small area where the river flows into the estuary; WR a
1030 small area downstream of the West River; SW an area in shallow water near the entrance;
1031 WK stands for Western Korean Bay; LR is in the middle region of the estuary, with the
1032 sediment here from local resuspension in the main estuary branch. Coastline change of the
1033 YE: **(b)** coastline in 1956 **(c)** coastline in 1976 (modified from Gao et al. (2012) and Landsat
1034 image on 15 September 1976).

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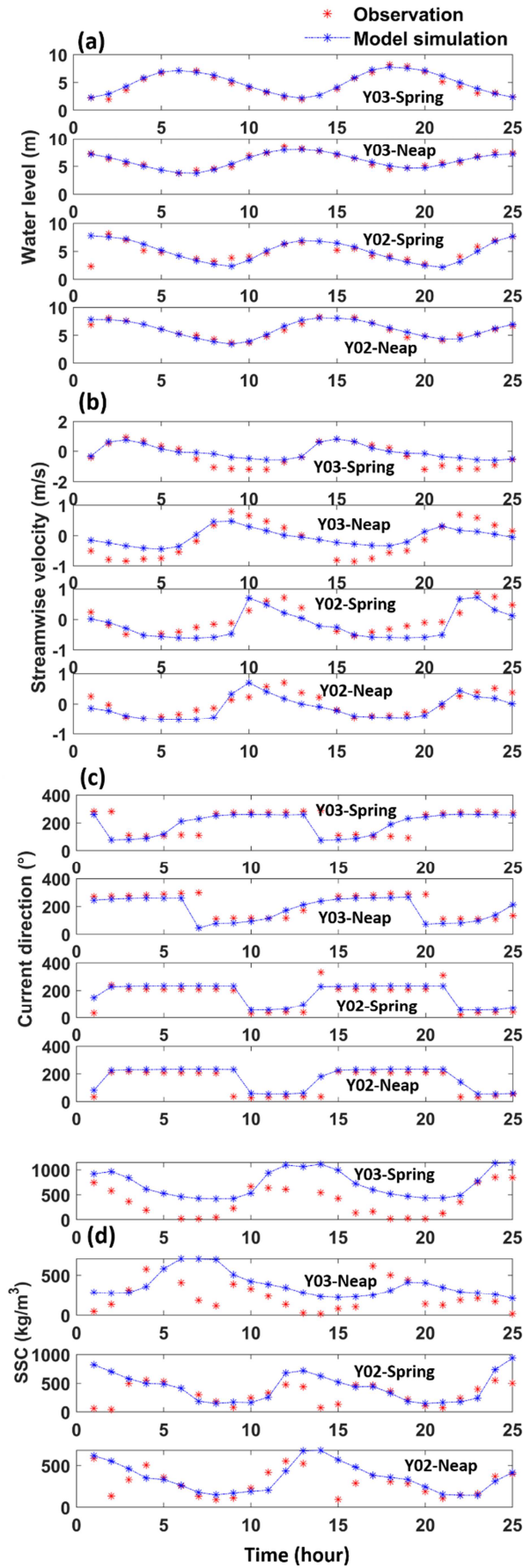
1037 **Figure 3.** Grids of the model domain for (a) 1956 (before land reclamation) and (b) 2011
1038 (after reclamation).



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1040 **Figure 4.** Comparison of the measured and modelled water elevation during June 2011.

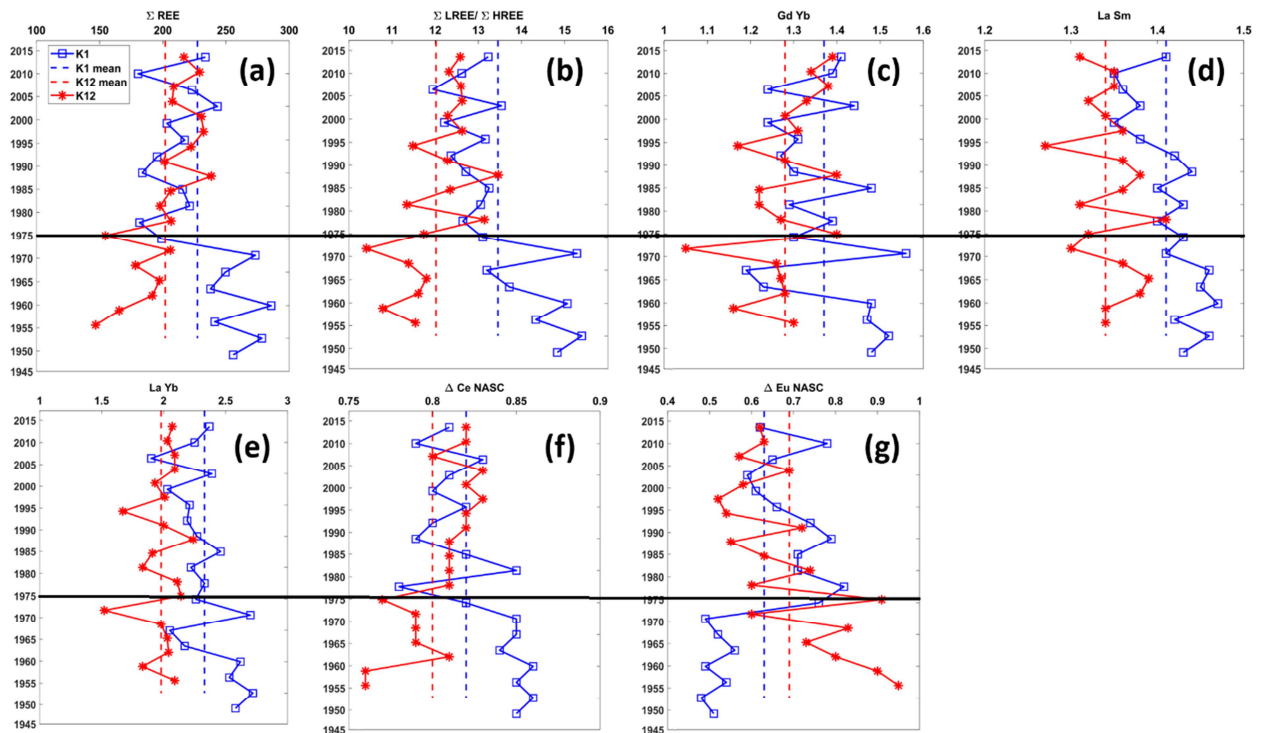
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1042 **Figure 5.** Comparison of depth-averaged: **(a)** water elevation; **(b)** streamwise velocity; **(c)**
 1043 current direction; and **(d)** suspended-sediment concentration between the FVCOM model
 1044 results and field observations in August 2009 at Stations Y02 and Y03 during spring and neap
 1045 tides.

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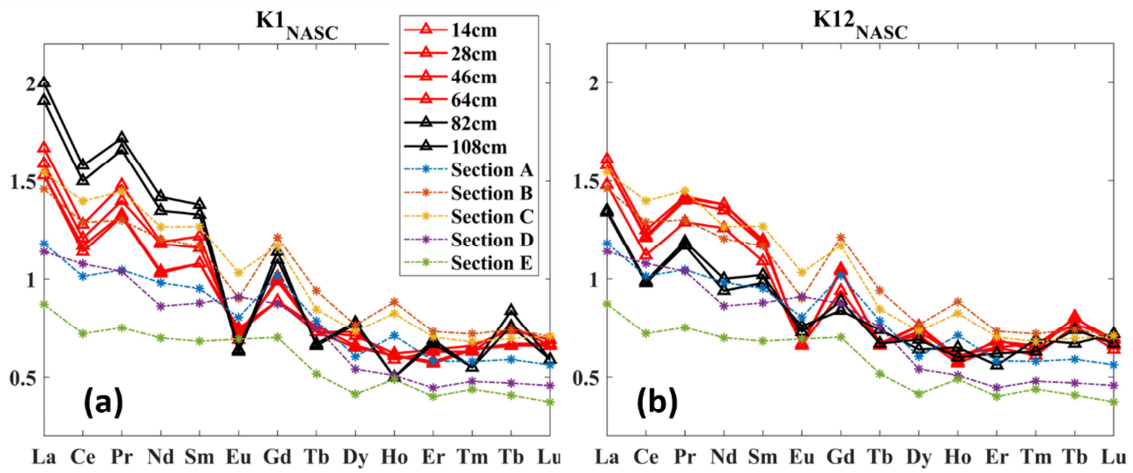
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1049 **Figure 6.** Profiles of **(a)** ΣREE , **(b)** $\Sigma\text{LREE}/\Sigma\text{HREE}$, **(c)** $(\text{Gd}/\text{Yb})_{\text{NASC}}$, **(d)** $(\text{La}/\text{Sm})_{\text{NASC}}$, **(e)**
 1050 $(\text{La}/\text{Yb})_{\text{NASC}}$, **(f)** $\delta\text{Ce}_{\text{NASC}}$ and **(g)** $\delta\text{Eu}_{\text{NASC}}$ in K1 and K12; dashed straight lines show the
 1051 average values.

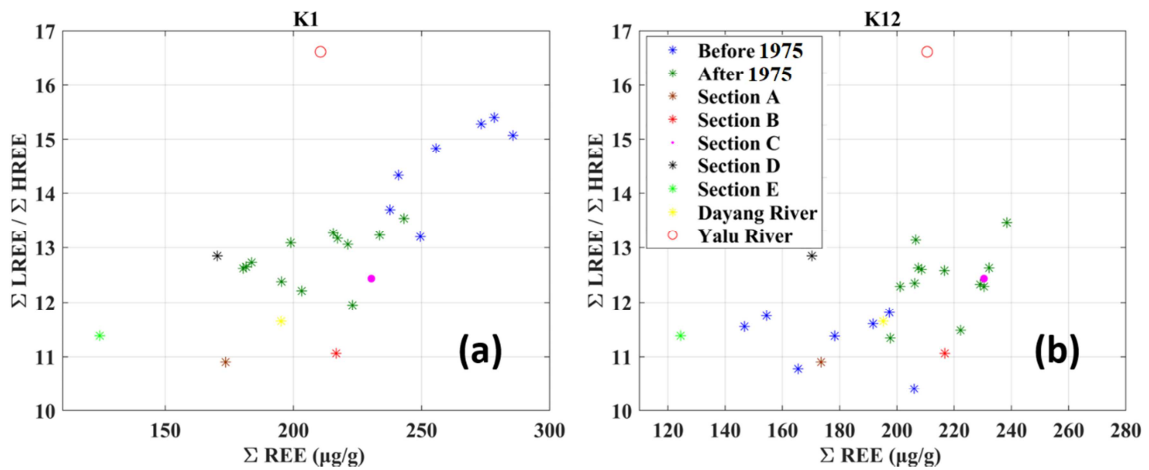
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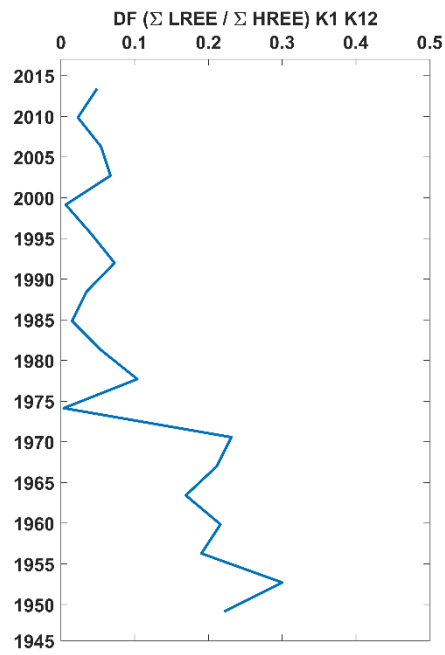
1054 **Figure 7.** NASC-normalized REE patterns of K1 (a), K12 (b) and surface samples from
 1055 surrounding shallow waters. Black and red lines represent layers pre- and post-1975,
 1056 respectively.

1057



1058

1059 **Figure 8.** Binary diagrams of $\Sigma\text{LREE}/\text{HREE}$ and ΣREE for K1 and K12.



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1061 **Figure 9.** Vertical profile of the DF based on $\Sigma\text{LREE}/\Sigma\text{HREE}$ between K1 and K12.

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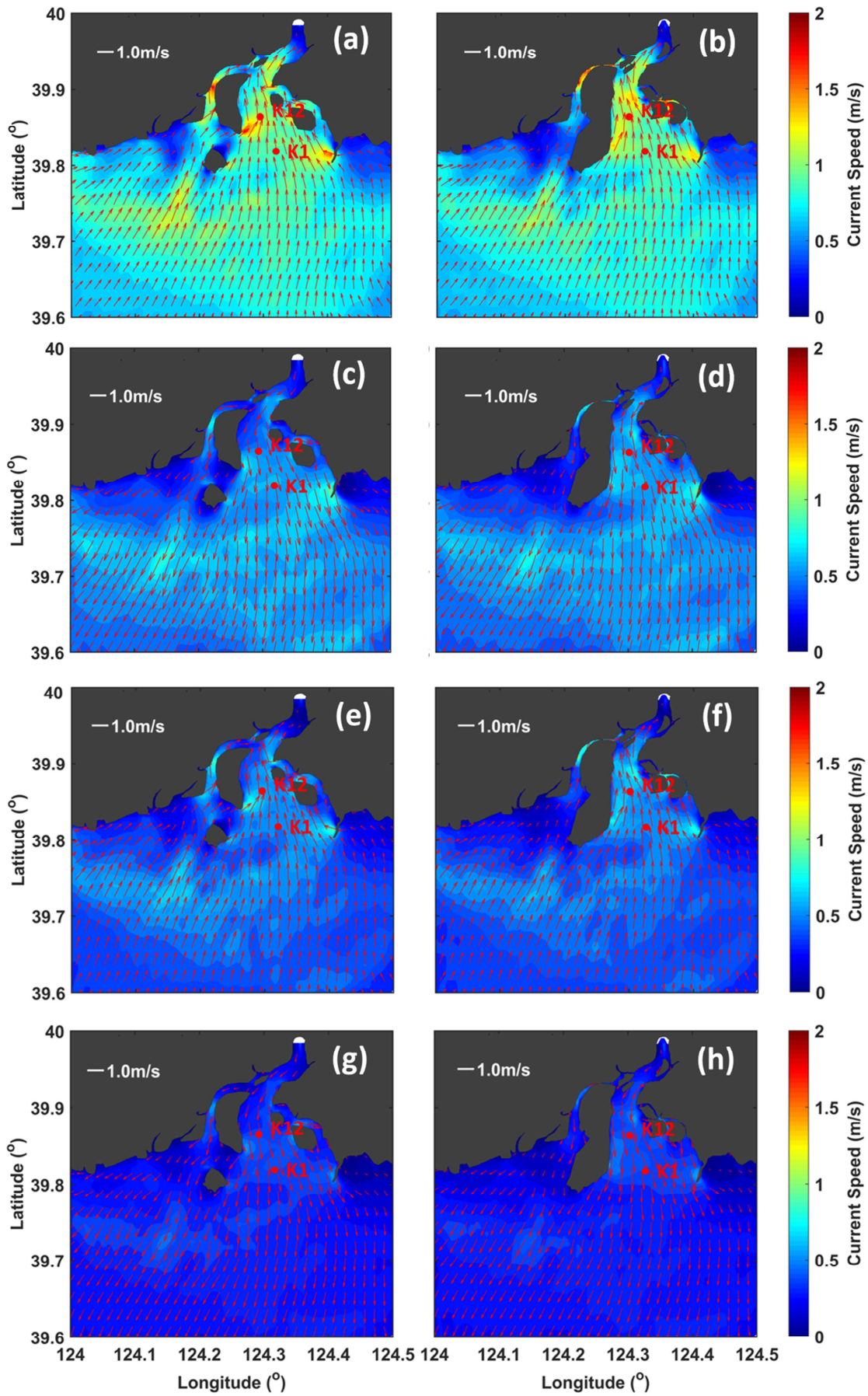
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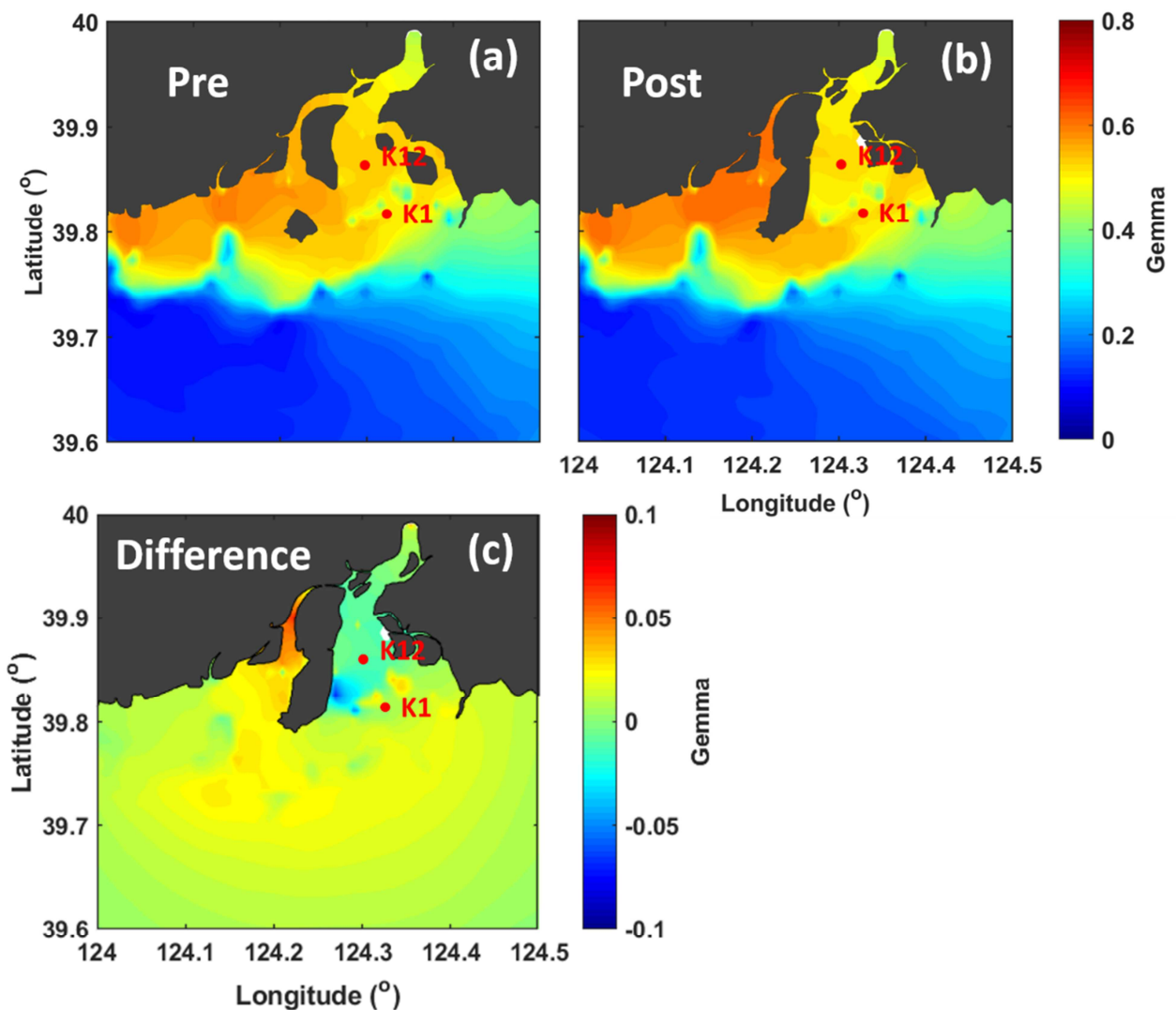
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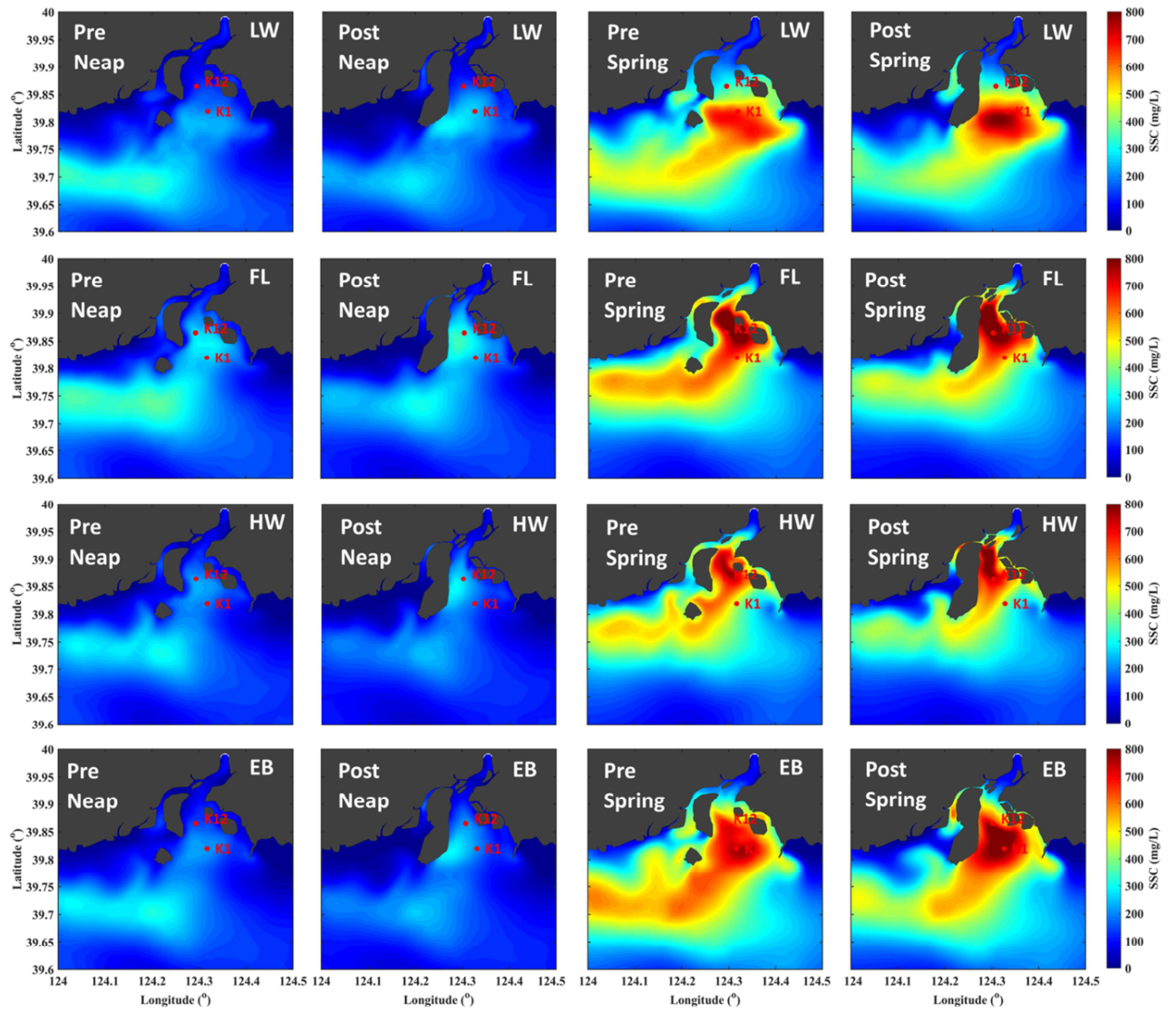
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1071 **Figure 10.** Model depth-averaged current field during spring tide at maximum flood time **(a)**
 1072 pre-reclamation (Experiment 1) and **(b)** post-reclamation (Experiment 2); **(c)** and **(d)** show
 1073 the corresponding current fields at maximum ebb time. **(e, f, g, h)** as for Figs. 10(a, b, c, d)
 1074 but during neap tide.
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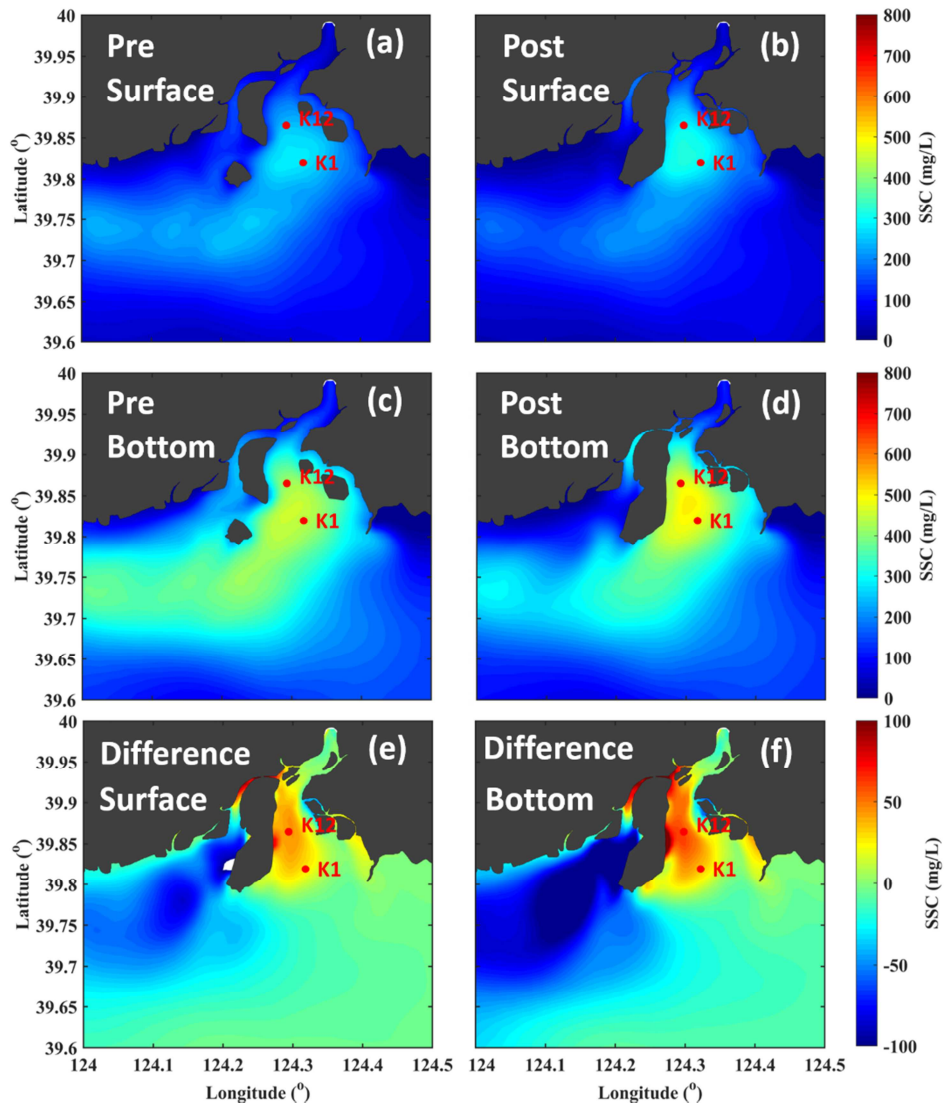


1077 **Figure 11.** Model tidal asymmetry skewness field **(a)** pre-reclamation (Experiment 1) and **(b)**
 1078 post-reclamation (Experiment 2); **(c)** difference in the tidal asymmetry skewness between the
 1079 two experiments (Experiment 2 – Experiment 1).
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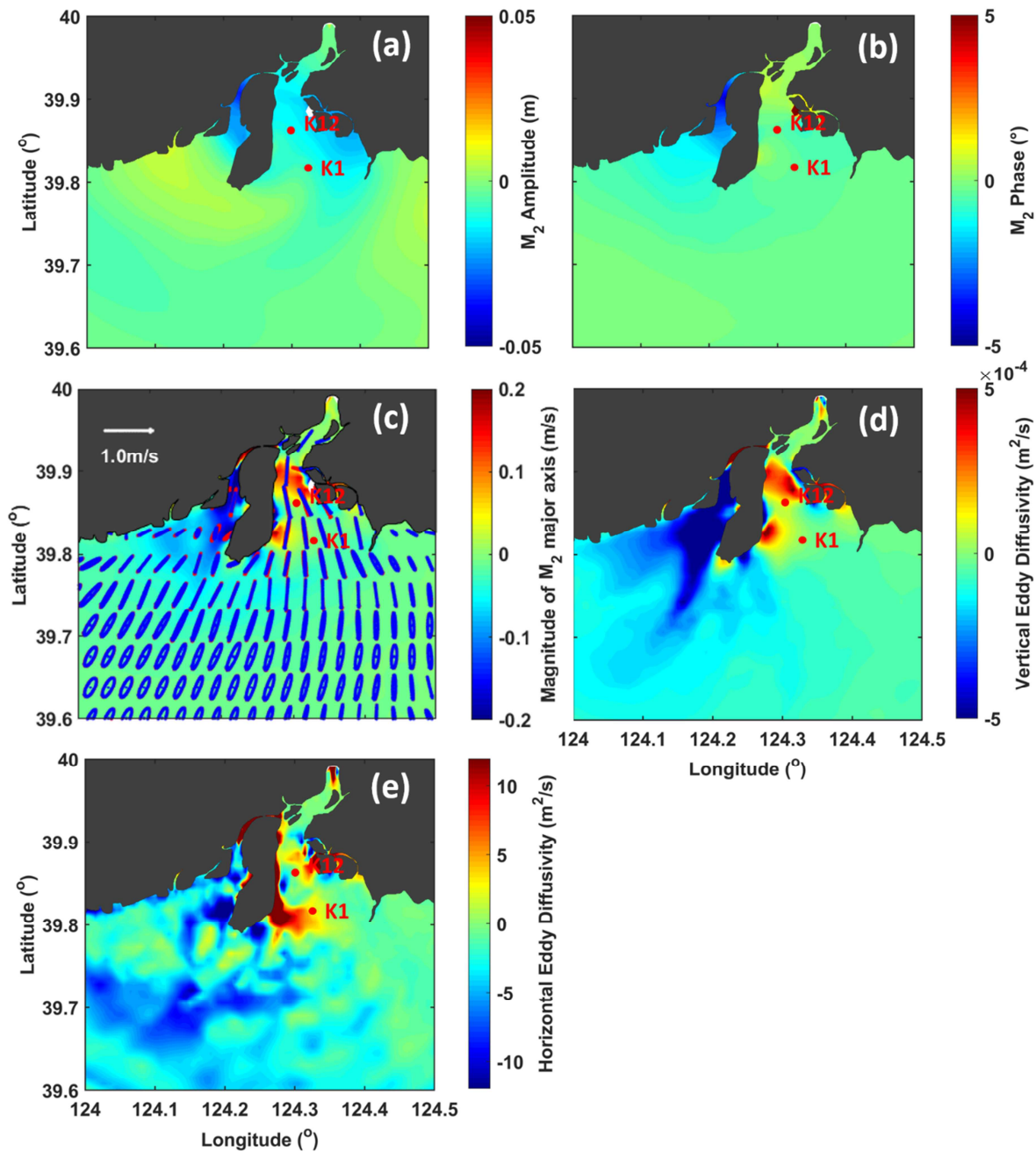
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1083 **Figure 12.** Model horizontal distribution of depth-averaged SSC (mg/L) for different tidal
 1084 phases (LW low water; FL flood; HW high water; EB ebb) pre-reclamation (the first and third
 1085 panels) and post-reclamation (the second and forth panels) during neap tide (left two panels)
 1086 and spring tide (right two panels).



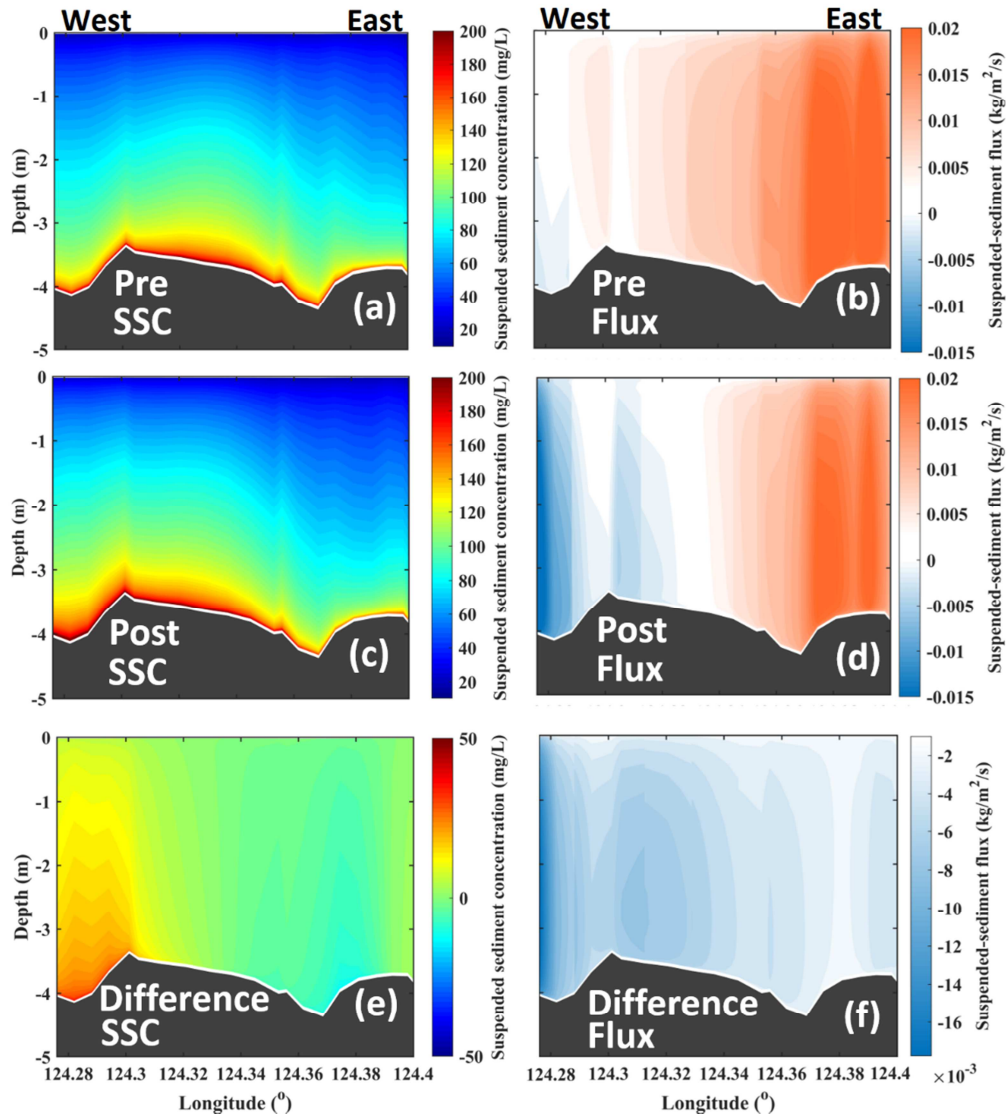
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1088 **Figure 13.** Model horizontal distributions of monthly averaged SSC in the surface layer **(a)**
 1089 pre-reclamation (Experiment 1) and **(b)** post-reclamation (Experiment 2); and in the bottom
 1090 layer **(c)** pre-reclamation and **(d)** post-reclamation. Difference in the SSC distributions
 1091 (Experiment 2 – Experiment 1) in the **(e)** surface layer and **(f)** bottom layer.



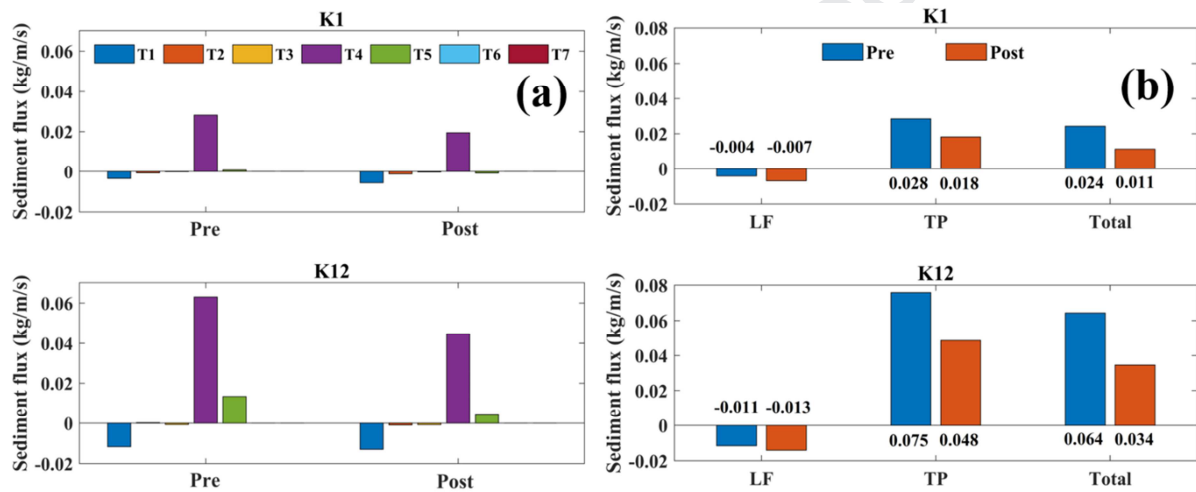
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1093 **Figure 14.** Changes (Experiment 2 – Experiment 1) in the: **(a)** M2 amplitude; **(b)** M2 phase;
 1094 **(c)** depth-averaged M2 major axis; **(d)** maximum monthly averaged vertical eddy viscosity;
 1095 and **(e)** maximum monthly averaged horizontal eddy viscosity. The red and black ellipses in
 1096 **(c)** are the M2 ellipses in Experiment 1 and Experiment 2, respectively.



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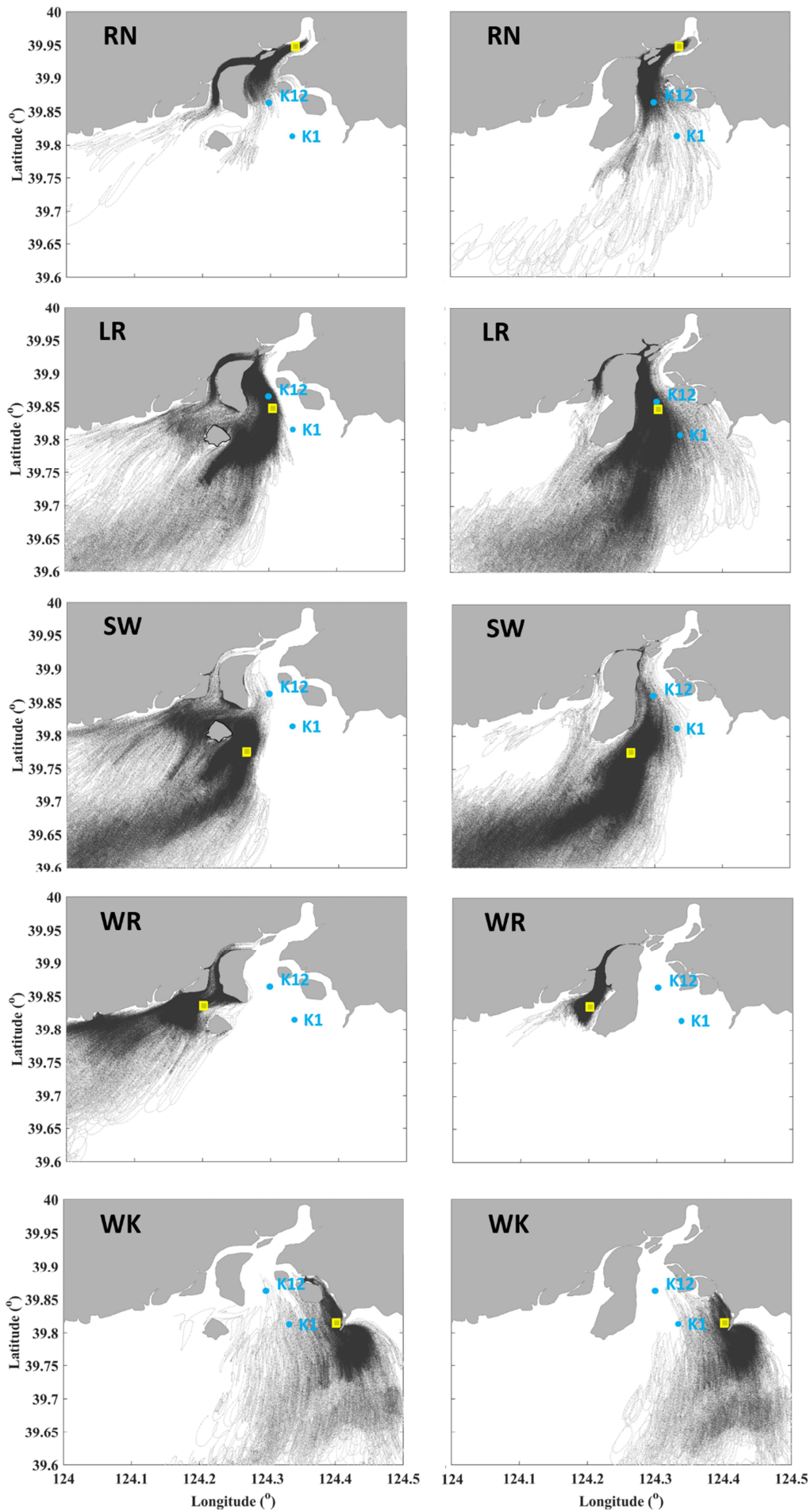
1098 **Figure 15.** Model monthly averaged SSC along Cross-section 1 (estuary entrance line, Fig.1)
 1099 **(a)** pre-reclamation (Experiment 1) and **(c)** post-reclamation (Experiment 2); **(b)** and **(d)** the
 1100 corresponding suspended-sediment fluxes. Positive and negative values represent landward
 1101 and seaward directions, respectively. The left- and right-hand sides of the figures correspond
 1102 respectively to the western and eastern ends of the cross-section. **(e)** shows the difference
 1103 between **(a)** and **(c)**: and **(f)** the difference between **(b)** and **(d)** (Experiment 2 –Experiment 1).
 1104 Western side of the cross-section is near the Middle River in Fig. 1 and eastern side is close to
 1105 the Western Korean Bay.



1106

1107 **Figure 16. (a)** Decomposition of the model monthly averaged sediment flux per unit width
1108 (kg/m/s) at K1 and K12 using Dyer's equation, Eq. (9) (Dyer, 1997). **(b)** As for Fig. 16a but
1109 with tidally averaged suspended sediment fluxes per unit width (kg/m/s). LF and TP denote
1110 the Lagrangian flux (T_1+T_2) and tidal pumping ($T_3+T_4+T_5$), respectively. Positive and
1111 negative values represent landward and seaward directions, respectively.

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1113 **Figure 17.** Particle-tracking results pre-reclamation (left-hand column) and post-reclamation
 1114 (right-hand column). Transparent grey lines mark the trajectories of the released particles;
 1115 yellow squares the source areas (release positions of the particles).

1116

1117 **Table 1.** Sectional-averaged REE concentrations ($\mu\text{g/g}$) in the YE and REE concentrations of
 1118 reference samples (NASC) obtained from Taylor and McLennan (1985).

REE ($\mu\text{g/g}$)	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Location														
Section A	37.81	74.04	8.27	32.40	5.43	1.00	5.29	0.67	3.51	0.74	1.98	0.29	1.83	0.27
Section B	46.72	94.19	10.28	39.79	6.66	1.12	6.31	0.80	4.45	0.92	2.49	0.36	2.30	0.34
Section C	49.43	102.05	11.44	41.84	7.23	1.28	6.08	0.72	4.26	0.86	2.39	0.34	2.16	0.34
Section D	36.48	78.70	8.21	28.48	5.01	1.13	4.55	0.64	3.14	0.53	1.52	0.24	1.46	0.22
Section E	27.95	52.67	5.94	23.08	3.89	0.86	3.65	0.44	2.41	0.51	1.37	0.22	1.27	0.18
NASC	32	73	7.9	33	5.7	1.24	5.2	0.85	5.8	1.04	3.4	0.5	3.1	0.48

1119

1120 **Table 2.** Key parameters of the model configuration.

Model parameters	Value/method
Model external time step	1.0 s
Bottom friction coefficient	0.0025
Horizontal diffusion	Smagorinsky scheme
Vertical eddy viscosity	M-Y 2.5 turbulent closure
Settling velocity	1.25×10^{-4} m/s
Critical bottom stress for erosion	0.1 N/m^2
Critical bottom stress for deposition	0.08 N/m^2
Erosion rate	$5 \times 10^{-6} \text{ kg/m}^2/\text{s}$
Number of mesh nodes and elements	3363, 6138 (Experiment 1) 2988, 5348 (Experiments 2 & 3)

1121

1122 **Table 3.** Harmonic analysis of the measured and modelled tidal constituents; measurements
 1123 from the Yalu Park Hydrology Station.

Tidal Constituent	O_1		K_1		M_2	
	Amplitude (m)	Phase ($^\circ$)	Amplitude (m)	Phase ($^\circ$)	Amplitude (m)	Phase ($^\circ$)
Measured	0.26	105.04	0.40	327.42	1.35	50.79

Model	0.22	121.03	0.40	347.08	1.49	67.88
Discrepancy	0.04	15.99	0.0	19.66	0.14	17.09

Tidal Constituent	S_2		M_4		MS_4	
	Amplitude (m)	Phase (°)	Amplitude (m)	Phase (°)	Amplitude (m)	Phase (°)
Measured	0.49	26.18	0.35	49.33	0.34	90.14
Model	0.48	32.74	0.42	47.88	0.27	83.51
Discrepancy	0.01	6.56	0.07	2.55	0.07	6.63

1124

1125 **Table 4.** Correlation coefficient (R) between model results and observation data for different
 1126 variables.

	Station Y03 (spring tide)	Station Y03 (neap tide)	Station Y02 (spring tide)	Station Y02 (neap tide)
Water elevation	0.84	0.97	0.95	0.89
Streamwise velocity	0.90	0.88	0.83	0.85
Current direction	0.91	0.75	0.86	0.86
SSC	0.81	0.50	0.51	0.57

1127

Highlights in “Impacts of land reclamation on sediment transport and sedimentary environment in a macro-tidal estuary.”:

- According to model results from a 3D hydrodynamic-sediment coastal model, flood dominance in a medium-scale estuary decreased after a massive land reclamation.
- Tidal-choking effect was enhanced in the main branch after reclamation, with a decreased tidal range and stronger tidal currents, which resulted in stronger mixing processes.
- The landward sediment flux caused by tidal pumping decreased significantly after the reclamation.
- A newly improved Lagrangian 3D particle-tracking model with resuspension showed sediments in the main branch were likely from different sources before reclamation but were more homogeneous with a common composition of sediment sources afterwards.
- This study proposed a multidiscipline approach to determine the sediment sources in a coastal area.

Declaration of interests

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.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: