

**Local human activities overwhelm decreased sediment supply from the Changjiang River
Continued rapid accumulation in the Hangzhou Bay-Qiantang Estuary system**

Xie, Dongfeng; Pan, Cunhong; Wu, Xiuguang; Gao, Shu; Wang, Zheng Bing

DOI

[10.1016/j.margeo.2017.08.013](https://doi.org/10.1016/j.margeo.2017.08.013)

Publication date

2017

Document Version

Accepted author manuscript

Published in

Marine Geology

Citation (APA)

Xie, D., Pan, C., Wu, X., Gao, S., & Wang, Z. B. (2017). Local human activities overwhelm decreased sediment supply from the Changjiang River: Continued rapid accumulation in the Hangzhou Bay-Qiantang Estuary system. *Marine Geology*, 392, 66-77. <https://doi.org/10.1016/j.margeo.2017.08.013>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

1 **Local human activities overwhelm decreased sediment from the Changjiang**

2 **River: continued rapid accumulation in the Hangzhou Bay-Qiantang Estuary**

3 Dongfeng Xie^{a,*}, Cunhong Pan^a, Xiuguang Wu^a, Shu Gao^b, Zhengbing Wang^{c,d}

4 ^aZhejiang Institute of Hydraulics and Estuary, Hangzhou, China.

5 ^bState Key Laboratory for Estuarine and Coastal Research, East China Normal
6 University, Shanghai, China.

7 ^cFaculty of Civil Engineering and Geosciences, Delft University of Technology, The
8 Netherlands.

9 ^dDeltares, P.O. Box 177, 2600 MH Delft, The Netherlands

10 *Corresponding author at: Zhejiang Institute of Hydraulics and Estuary, No.50 East
11 Fengqi Road, Hangzhou, 310020, China.

12 E-mail address: dongfeng.xie@hotmail.com (D. Xie)

13

14 **Abstract:**

15 The aim of this contribution is to investigate the morphological responses of Hangzhou
16 Bay, China, located immediately south of the Changjiang Estuary, to the drastic
17 reduction of the sediment load from the Changjiang River and the large-scale coastal
18 embankment over past decades. The spatial patterns of deposition and erosion, sediment
19 volume changes, and the feedback with hydrodynamics and sediment transport were
20 analyzed, on the basis of historical bathymetric and hydrographic data. The results show
21 that the sedimentation rates in the bay have overall increased rather than decreased over
22 the past decades, despite bed erosion having occurred in the northern bay-mouth. This
23 reveals that the influence of the reduction in the Changjiang River sediment load on the

24 morphological evolution of Hangzhou Bay has to date been insignificant, mainly due to
25 the buffering effect of existing sediment in the outer Changjiang Estuary. The
26 morphological change is mainly related to the implementation process of the coastal
27 embankment. Sediment accumulation induced by progressive seaward coastal
28 embankment has resulted in seaward aggradation from the Qiantang Estuary towards
29 Hangzhou Bay. Analysis of the annually-averaged high and low tidal levels, and
30 durations of rising and falling tides reveals that flood dominance in the inner bay has
31 been increased, due to the coastal embankment and sediment accumulation. The ratio
32 between annually-averaged rising tide and falling tide durations have decreased from
33 0.85 to 0.63. The tidal prism at the interface between the inner and outer bay has
34 decreased by about 25% since 1980s, while the net landward sediment flux has been
35 intensified to a certain extent, which is responsible for the intensifying sedimentation in
36 the inner bay. The local human activities have overcome the decreased sediment from
37 the Changjiang River. Although the coastal embankment will cease in the near future,
38 the morphological response to human activities is expected to continue on for a longer
39 time.

40 **Keywords:** *Morphology; Sediment transport; Tidal asymmetry; Sediment load;*
41 *Hangzhou Bay; Changjiang Estuary.*

42

43 **1. Introduction**

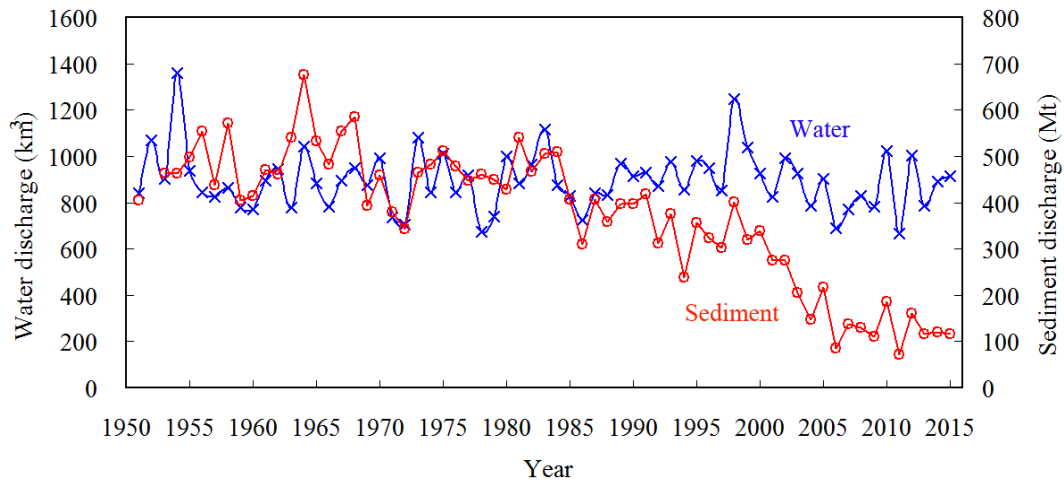
44 Estuaries are defined as semi-enclosed coastal bodies of water which have free
45 connection with the open sea (Fairbridge, 1980). They are unique ecosystems and are
46 often located in densely populated areas (e.g. Kennedy, 1984; Dyer, 1997; Trenhaile,
47 1997; Wang et al., 2015). River discharge, tidal currents, waves and sediment supply

48 are generally the major natural factors controlling the morphological evolution of
49 estuarine environments. On the other hand, morphodynamic development of an estuary
50 is also influenced by human activities such as flood protection, navigation channel
51 dredging, land reclamation, dam construction, or sand extraction. Such human activities
52 frequently cause substantial changes in the configuration of estuaries, their
53 hydrodynamic regime, sediment transport, deposition and erosion patterns (e.g. Van der
54 Wal et al., 2002; Blott et al., 2006; Wang et al., 2002, 2015; Winterwerp and Wang,
55 2013). In many cases the effects of human activities have exceeded changes induced by
56 natural forcing factors. From the coastal management point of view, it is of major
57 importance to understand the processes and mechanisms of morphological responses to
58 human activities and to predict the trends of their future evolution.

59

60 Worldwide, the transport rate of river-borne sediments into most estuaries has
61 apparently decreased in recent decades (Syvitski et al., 2005; Milliman and Farnsworth,
62 2011). With the sediment supply reduction, rapid changes have taken place, among
63 them sediment transport adjustments, coastal retreat, slowdown of accumulation, and
64 even onset of erosion (e.g. Milliman, 1997; Syvitski et al., 2005; Yang et al., 2005,
65 2011; Gao and Wang, 2008). The Changjiang River is one of the largest rivers in the
66 world, ranking 3rd in length (6,400 km), 5th in runoff ($925 \text{ km}^3/\text{y}$) and 4th in sediment
67 load (486 Mt/y) (Eisma, 1998). In the last 30 years, and especially since 2003 when the
68 Three Gorges Dam was constructed and operated, the sediment load at the Datong
69 measuring station located about 640 km upstream of the Changjiang River mouth (the
70 approximate limit of tidal penetration), has decreased drastically from more than 450
71 Mt/y before the 1980s to less than 150 Mt/y, in some dry years (e.g. 2006 and 2011)

72 falling below 100 Mt (Fig. 1). As a result, the subaqueous delta of the Changjiang
 73 Estuary (CE) has switched from deposition to erosion, and the progradation rates of the
 74 fringing tidal flats have slowed down and locally even turned to degradation (Gao and
 75 Wang, 2008; Yang et al., 2011; Wang et al., 2015).



76
 77 Fig. 1. Temporal variations of annual water and sediment discharges measured at the
 78 Datong gauging station located at the tidal limit 640 km upstream from the Changjiang
 79 River mouth (data from the Changjiang River Hydraulic Engineering Committee).

80
 81 The Hangzhou Bay, located immediately south of the CE, is one of the largest
 82 embayment along the coast of the East China Sea, covering an area of about 4,800 km²
 83 (Fig. 2). Hangzhou Bay is typical funnel-shaped embayment and dominated by tidal
 84 currents. The west of Hangzhou Bay, from Ganpu to Zakou, is the Qiantang Estuary
 85 (QE), which is controlled by the combination of river discharge and tides (cf. Fig. 2).
 86 Hangzhou Bay is an area of extensive material exchange with the Changjiang Estuary,
 87 on one hand, and the Qiantang Estuary, on the other (e.g. Chen et al., 1990; Han et al.,
 88 2003).

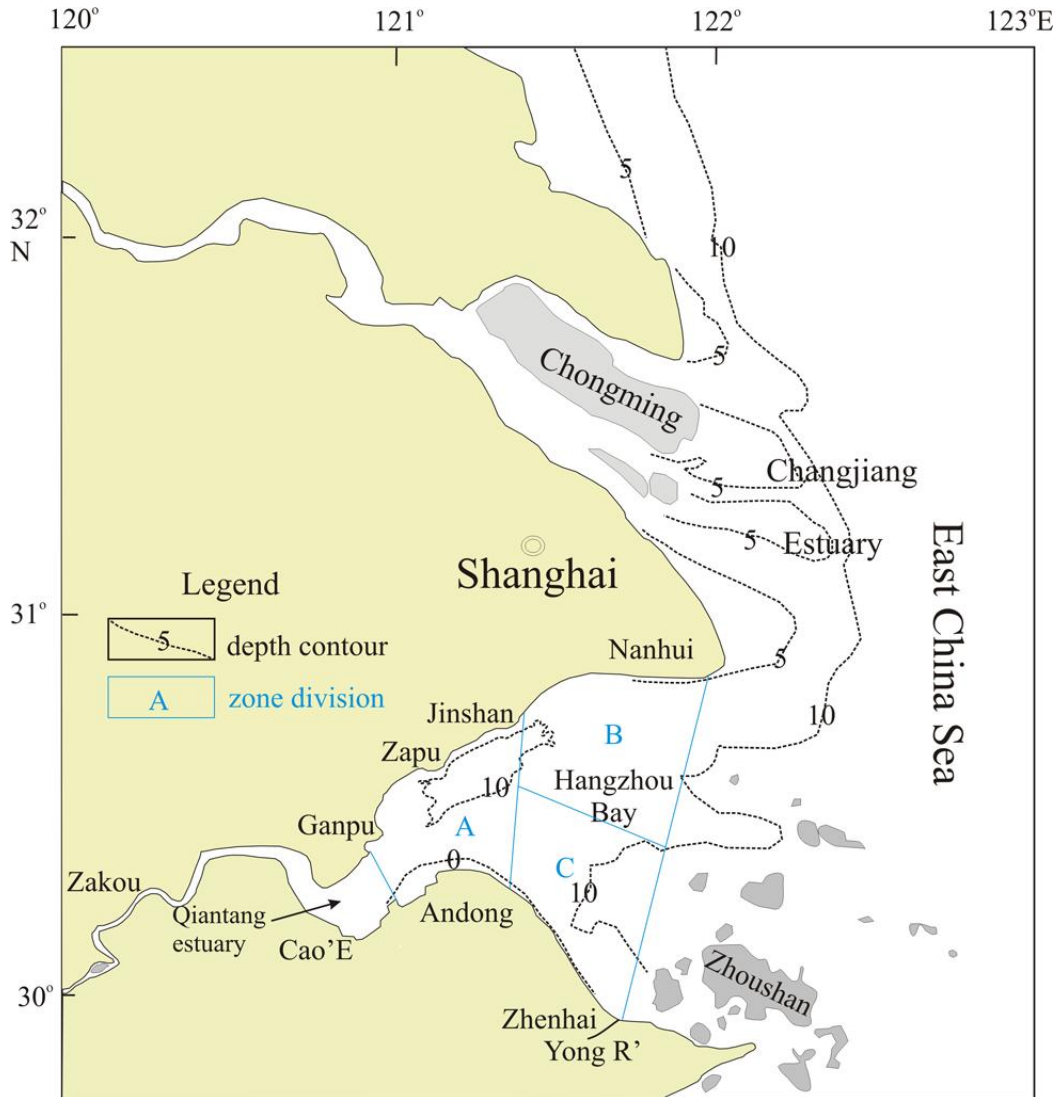


Fig. 2. Locations in Hangzhou Bay referred to in the text. The dashed lines depict water depths. The definitions of the three zones referred to in the statistics of Tables 1 are also given.

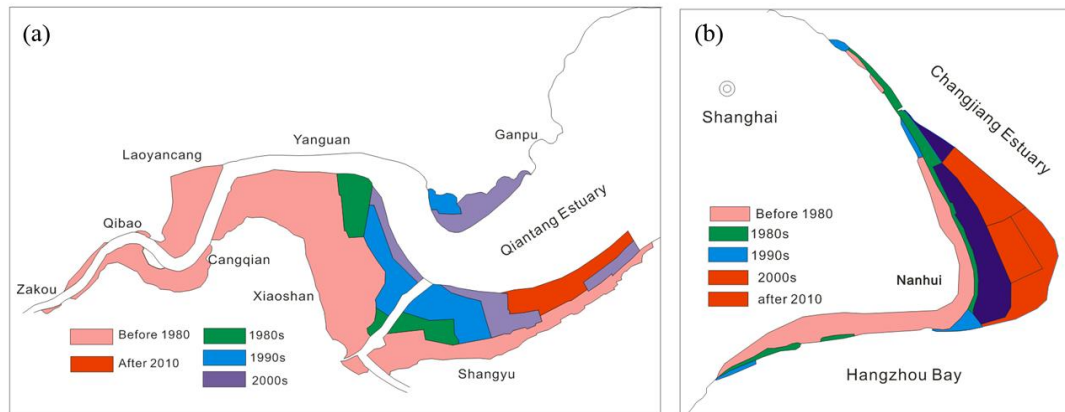
The recent drastic reduction of sediment discharge from the Changjiang River and its effect on the morphological evolution of Hangzhou Bay have been a matter of great concern to marine scientists, coastal engineers and the regional management. In recent years, the northern bay mouth has evolved from an accumulating area to an eroding area,

98 and thought to be related to reduction of sediment discharge from Changjiang River (e.g.
99 Dai et al., 2014). However, little quantitative work has been done on the large-scale
100 morphological response in Hangzhou Bay to such sediment reduction, in particular, on
101 assessing whether the sediment input into Hangzhou Bay has decreased by taking the
102 sediment exchange with the QE into account.

103

104 On the other hand, a large-scale coastal embankment program has been implemented in
105 the QE since the 1960s (Fig. 3), aiming at improving flood protection and navigation (Li
106 and Dai, 1986; Han et al., 2003; Pan et al., 2010). So far, more than 1000 km² of tidal
107 flats have been reclaimed, substantially changing the configuration of the estuary. Li
108 and Dai (1986) reported that sedimentation in the QE before the 1980s was mainly
109 caused by the reduction of the tidal prism. They predicted qualitatively that, with the
110 downstream constriction of the QE, accumulation would shift seaward and thereby
111 cause the tidal prism to decrease further. Yu and Cao (2006) documented that
112 sedimentation in the QE from the 1960s to 2000 amounted to about 250×10^6 m³. The
113 morphological response of the Hangzhou Bay to the embankments is expected to be
114 slower than that of the QE. Recently, Yu et al. (2012) modeled the formation of the
115 large longitudinal sand bar in the QE which elongated 130 km upward of Zapu and
116 occupied the whole QE, using an idealized long-term 2-D model. Their model results
117 showed the sandbar would shift seawards with the increasing convergence of the estuary,
118 and erosion would occur first at the mouth area with the sediment supply decreasing at
119 the sea side. However, their model results were not fully verified due to the lack of
120 detailed information on the temporal evolution of the QE. Although numerous human
121 activities take place concurrently in estuaries, morphologic responses have often been

122 observed to be slow (Wang et al., 2015). To capture the morphological evolution of the
 123 Hangzhou Bay, it is therefore necessary to base investigations on more and updated
 124 data.



125
 126 Fig. 3. Coastal embankment in the Qiantang Estuary (a) and land reclamations in front
 127 of the Nanhui flat bordering the Changjiang Estuary (b).

128
 129 Short-term changes on more local scales can often be satisfactorily predicted using the
 130 so-called ‘bottom-up’ models, which are based on hydrodynamic models and other
 131 process-based computer models, but they have limited capabilities for the prediction of
 132 longer-term geomorphological evolution (e.g. Whitehouse, 2002; Townend and
 133 Whitehead, 2003). Hence, so-called ‘top-down’ models, which are based on historical
 134 trend analysis, are more frequently used (e.g. Wang et al., 2002; Van der Wal et al.,
 135 2002; Lane, 2004; Blott et al., 2006; Yang et al., 2011).

136
 137 In this study, several detailed bathymetries of the Hangzhou Bay since 1959, long-term
 138 time series of channel volume data of the QE, as well as hydrographic data from
 139 representative stations have been compiled. On the basis of these data, deposition-

erosion patterns, sedimentation rates for different time intervals, and feedback between hydrodynamics and morphological evolution have been reconstructed. In accordance, the aims of the present study are to clarify whether the sediment supply to the Hangzhou Bay has decreased since the drastic reduction in sediment discharge by the Changjiang River, and to investigate whether any morphological responses are evident in the Hangzhou Bay in response to the large-scale coastal embankments in the region.

2. Regional setting

The Hangzhou Bay is normally defined as the reach downstream of Ganpu to the Nanhui-Zhenhai section at the bay mouth (Fig. 2). It is a typical funnel-shaped embayment. The width at the mouth is about 98.5 km and decreases gradually to about 20 km some 100 km up-estuary. The total area of Hangzhou Bay amounts to about 4,800 km². The hydrodynamics and sediment transport are mainly controlled by tidal currents in the bay. Upstream of the Hangzhou Bay, between the cities of Ganpu and Zakou, is the 108 km long QE, which is controlled by the combination of river discharges and tides.

The Hangzhou Bay can be divided into an outer and an inner part. The outer part from the mouth to Jinshan covers an area of 3,000 km² (about 2/3 of the bay) is characterized by a flat seabed with an average water depth of 8~10 m and incorporates numerous scattered islands (Fig. 2). Upstream from Jinshan, the inner Hangzhou Bay covers an area of 1,800 km² (about 1/3 of the bay). Between Zapu and the Qibao-Cangqian section, the QE is occupied by a 130 km long, elongated subaqueous sandbar (Chien et al., 1964; Han et al., 2003; Yu et al., 2012). Following the northern shoreline of the

164 middle part of the bay is a large, 60 km long and up to 50 m deep tidal channel, whereas
165 the southern shore is lined by extensive tidal flats. As a whole, the morphology is
166 characterized by sediment accumulation in the south and erosion in the north.

167

168 Runoff and sediment load of the Qiantang River are about $30 \text{ km}^3/\text{y}$ and 3.40 Mt/y ,
169 respectively (Han et al., 2003). Runoff and sediment load of the Changjiang River are
170 $925 \text{ km}^3/\text{y}$ and 486 Mt/y , respectively, being ranked 5th and 4th in the world (Eisma,
171 1998). After the water and sediment enter the sea, one part is dispersed southward into
172 the Hangzhou Bay due to the Changjiang secondary plume, representing the main
173 sediment input to the Hangzhou Bay and the Qiantang Estuary (Su and Wang, 1989;
174 Chen et al., 1990). With the sediment input from Changjiang Estuary, the average
175 accumulation rate in the Hangzhou Bay used to be 1.15 cm/y (Xue, 1995). Despite the
176 fact that the discharge of the Changjiang River has hardly changed over the last few
177 decades, the sediment load has decreased continually since the 1980s, especially from
178 2003 onward when the Three Gorges Dam was constructed and operated (Fig. 1).

179

180 The semidiurnal tide is the main driving force behind the horizontal water flow in the
181 Hangzhou Bay, with the M_2 constituent being the dominant tidal component (ECCHE,
182 1992). The tidal range is 2~4 m at the northern bay mouth, increasing upstream to reach
183 a maximum at Ganpu with 4~6 m. At the southern mouth, the tidal range is only 1~2 m
184 due to the sheltering effect of the Zhoushan archipelago. The deformation of the tidal
185 wave is gradually enhanced upstream due to the progressive constriction of the estuary
186 and the shoaling bathymetry along the large sandbar. This eventually evolves into be the
187 world-famous, Qiantang tidal bore, with the maximum bore height over 3 m and the

188 maximum current velocity up to 5 m/s (Chen et al., 1990; Han et al., 2003; Pan and
189 Huang, 2010). In Hangzhou Bay tidal currents are strong, reaching maximum velocities
190 up to 3 m/s. The northern part is dominated by flood currents, whereas the southern part
191 is dominated by ebb currents. In correspondence, the residual flow and sediment
192 transport directions over one tidal cycle is landward in the north and seaward in the
193 south (Su and Wang, 1989; Xie et al., 2009).

194

195 Sediment in the Hangzhou Bay and the Qiantang Estuary is predominantly composed of
196 well sorted fine-grained non-cohesive silt, with the grain sized between 20 and 40 μm ,
197 and transported in suspension (Fig. 4). Suspended sediments in the Hangzhou Bay are
198 vertically well-mixed. Suspended sediment concentration (SSC) in the bay is
199 characterized by three regions of high values separated by two of low values. Average
200 SSCs at the upstream end of the large sandbar, on the southern tidal flat and the
201 northeastern mouth region are 3.4~4.4, 1.2~3.2 and 1.0~2.6 kg/m^3 , respectively,
202 whereas in the southeastern bay and in the northern tidal channels the SSCs are less than
203 1.0 kg/m^3 , respectively (Fig. 5). In the QE, the SSC can be more than 10 kg/m^3 at the
204 tidal bore arrival (Chen et al., 1990; Pan and Huang, 2010; Tu and Fan, 2017). Wind
205 generated waves in the bay reach heights of 0.2~0.5 m (ECCHE, 1992).

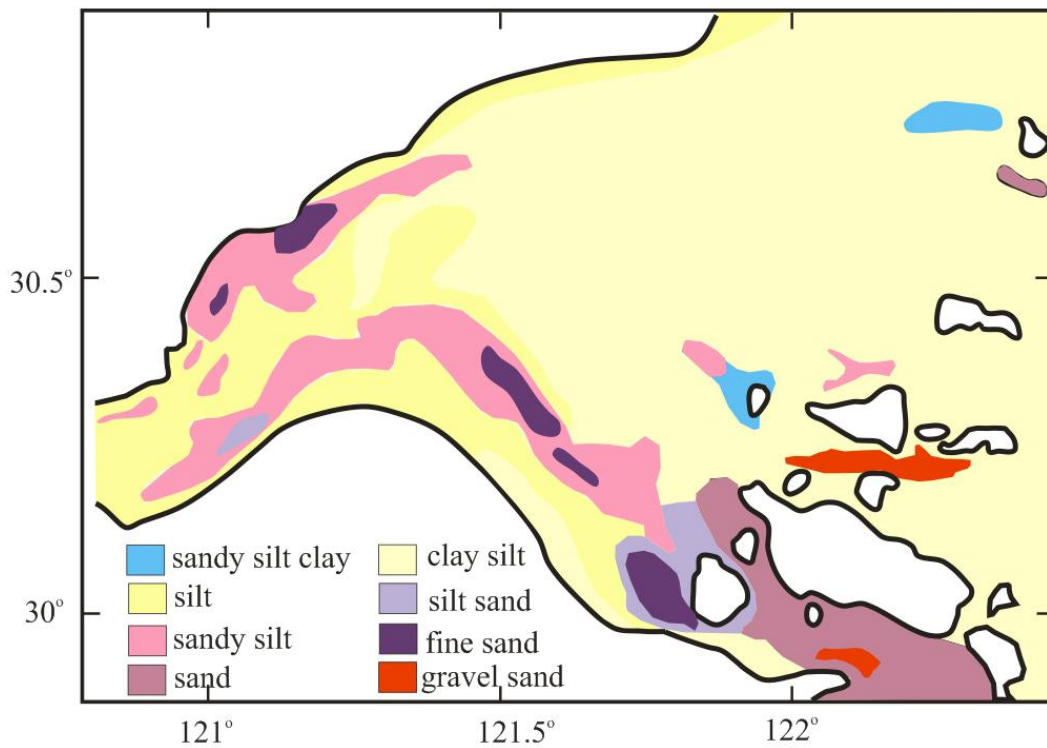


Fig. 4. Surface sediment grain size in Hangzhou Bay (from Xie et al., 2009).

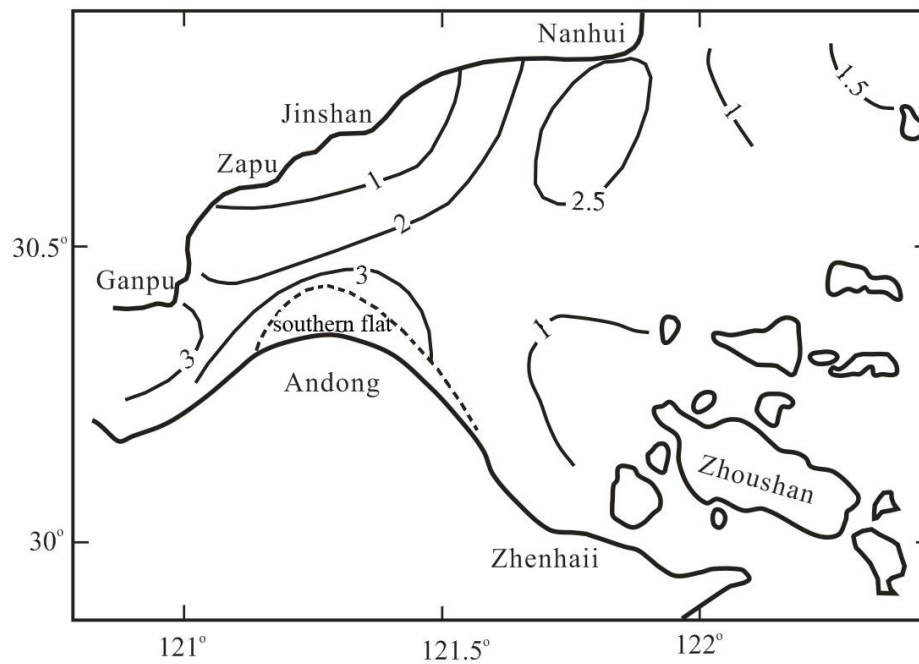


Fig. 5. Suspended sediment concentration distribution during spring tide in the Hangzhou Bay (modified from Han et al., 2003).

211

212 **3. Materials and methods**

213 **3.1 Collection and analysis of bathymetric data**

214 Due to the strong hydrodynamics and the easily erodible bed, the bed level of the QE
215 changes drastically on seasonal and inter-annual scales. Maximum vertical bed changes
216 can be up to 5 m in a single year (e.g. Chien et al., 1964; Han et al., 2003). Owing to the
217 importance of the morphology for flood protection, navigation, salt water intrusion, etc.,
218 there are relatively good historical bathymetric time series available for this reach. In
219 this study, the river channel volumes below mean high-tide level in the QE and the
220 inner bay in the month of April of each year since 1980 were collected to quantify the
221 sediment volume changes.

222

223 Available large-scale charts of the Hangzhou Bay mostly only cover the outer
224 Hangzhou Bay or the northern mouth. In this study, detailed and large-scale bathymetric
225 data in the Hangzhou Bay in 1959, 2003, 2010 and 2014, were collected from Zhejiang
226 Surveying Institute of Estuary and Coast (ZSIEC). These data cover the entire bay from
227 the mouth to the Ganpu section. The Odom Hydrotrac echo-sounder was used for the
228 2003, 2010, 2014 data. The vertical error is 0.1 m, and a global positioning system
229 (GPS) by Trimble was used that gave the positioning error within 1 m. The bathymetric
230 tidal corrections used tidal levels recorded at gauging stations within the area of
231 bathymetric data. Bathymetry in 1959 was surveyed by line echo-sounder, with the
232 vertical error less than 1% for water depths greater than 5m. The positioning errors for
233 the 1959 data were 50 m. The accuracy and quality of the bathymetric data depend on
234 the number and density of elevation points along the traverselines used in the

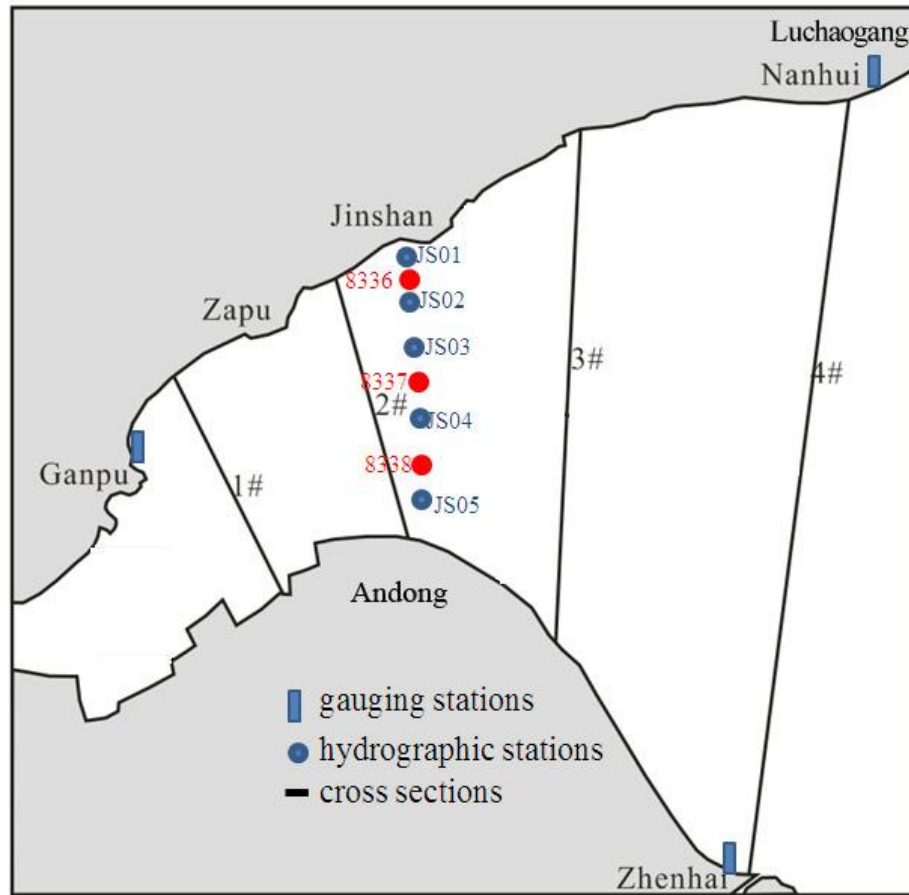
235 bathymetry construction. For the latest three depth measurements, the scales of the
236 maps are 1:50,000 at most area, but 1:10,000 locally, including the tidal flats; for the
237 1959 data, the scale is 1:100,000. These data allowed a detailed analysis of sediment
238 volume changes in the whole bay. As the sediment load from the Changjiang River
239 decreased drastically from 2003 onward, it was possible to determine the bed evolution
240 characteristics of the Hangzhou Bay before and after this date.

241

242 The bed elevation in 1959 was mapped with respect to the theoretically lowest
243 astronomical tidal datum at Wusong, whereas the subsequent surveys were with respect
244 to the Chinese National Vertical Datum of 1985. In a first step the bathymetry maps
245 were digitized using ArcGis10.2 software and then normalized to the theoretically
246 lowest astronomical tidal datum at Wusong. Thereafter, the digitized data were
247 transferred from their original projections onto the Beijing 54 coordinates, the
248 bathymetric data being gridded at 100×100 m resolution using the Surfer software
249 package, making use of the kriging interpolation technique (Burrough and McDonnell,
250 1998), which is appropriate for sparse datasets and has been widely used in previous
251 studies (e.g. Van der Wal and Pye, 2002; Blott, et al., 2006). Subsequently, digital
252 elevation models (DEM) for each digitized bathymetric chart were generated. Spatial
253 deposition and erosion patterns and associated sediment volume changes were
254 calculated by subtraction of the DEMs of different years. The bed level of the reclaimed
255 areas is assumed to be the local average high-tide level, in accordance with the practice
256 of the reclamation procedure. For sediment volume calculations, the bay was divided
257 into three major zones (Fig. 2): the inner Hangzhou Bay upstream of Jinshan (Zone A),
258 the outer, flood-dominated northern Hangzhou Bay where material exchange takes
259 place with the Changjiang Estuary (Zone B), and the outer, ebb-dominated southern

260 Hangzhou Bay (Zone C). The area of each zone approximately corresponds to 1/3 of the
 261 Hangzhou Bay. In addition, for each bathymetric chart, the water depths along four
 262 transects were extracted for detailed analysis (Fig. 6).

263



264

265 Fig. 6. The cross-sections illustrated in Fig. 8 and the hydrographic stations of 1983 (red
 266 cycles) and 2015 (blue cycles).

267

268 3.2 Collection and analysis of hydrographic data

269 Tide levels in the outer Hangzhou Bay and the Changjiang Estuary changed little over
 270 the past few decades (Liu et al., 2016), whereas the high-tide level in the inner

271 Hangzhou Bay increased to a certain extent (Han et al., 2003). Hence, time series of
272 tidal elevation at the Ganpu gauging station since 1950s were collected from Zhejiang
273 Hydrographic Office to determine the annually-averaged tidal elevation and duration
274 changes of rising and falling tides and to analyze the non-linear interaction between
275 hydrodynamics and the morphological evolution over the last decades.

276

277 Synchronous hydrographic data along the Jinshan transect, measured in January 1983
278 and January 2015 was collected. The Jinshan transect is the interface between the inner
279 and outer Hangzhou Bay. The cruise in January 1983 was conducted during the
280 Zhejiang Coast Survey, including 4 hydrographic stations restricted to intermediate
281 tides. At all stations, tidal level, water depth, flow velocity, and SSC were recorded. The
282 flow velocities were recorded by Ekman current meters, and SSCs were determined by
283 taking water samples, which were subsequently filtered through pre-weighed paper
284 filters that were weighed after being oven-dried. All water samples, as well as current
285 measurements, were taken at 1 and 5 m below the water surface and at 1 m above the
286 bottom. The cruise in 2015 included 5 hydrographic stations, including spring,
287 intermediate and neap tide. During the cruise in 2015, the measurements at all stations
288 covered at least a full tidal cycle (25 h). During spring tide the measurements were
289 conducted for 36 h. Flow velocities were recorded by means of an acoustic Doppler
290 current profiler (ADCP) and SSCs were measured hourly at the surface, 0.2H, 0.4H,
291 0.6H, 0.8H and the bottom, respectively, using an optical backscatter sensor (OBS),
292 where H is the water depth. Meanwhile, the synchronous tide-level data were collected
293 from several tidal gauging stations including Ganpu, Luchaogang and Zhenhai, etc. (Fig.
294 6).

295

296 Water and sediment fluxes were calculated for various tides of each cruise, with water
297 fluxes being the product of the cross-sectional area and mean velocity, and sediment
298 fluxes being the product of water fluxes and SSCs. The fluxes were calculated per layer
299 and then integrated over the vertical profiles for each tidal cycle by summing the hourly
300 data. For cross-sectional area determinations, the representative distance of each station
301 was defined as the sum of the half-distances between the station and its two neighboring
302 stations. If the station was near the coastline, then the shoreward distance was the
303 distance between the station and the coastline. Because the transects ended at the
304 southern and northern banks, the fluxes represent water and sediment entering or
305 leaving the upper Hangzhou Bay. To examine the tidal influences, the relationship
306 between flood-/ebb-averaged fluxes, i.e. the averaged fluxes over the flood and ebb
307 period, and tidal ranges of Luchaogang station were analyzed. The reason for choosing
308 the Luchaogang station is that it is located outside the bay where the tidal range is not
309 influenced by the morphological changes in the Hangzhou Bay, in contrast to the inner
310 Hangzhou Bay where the tidal range has increased, as will be illustrated later.

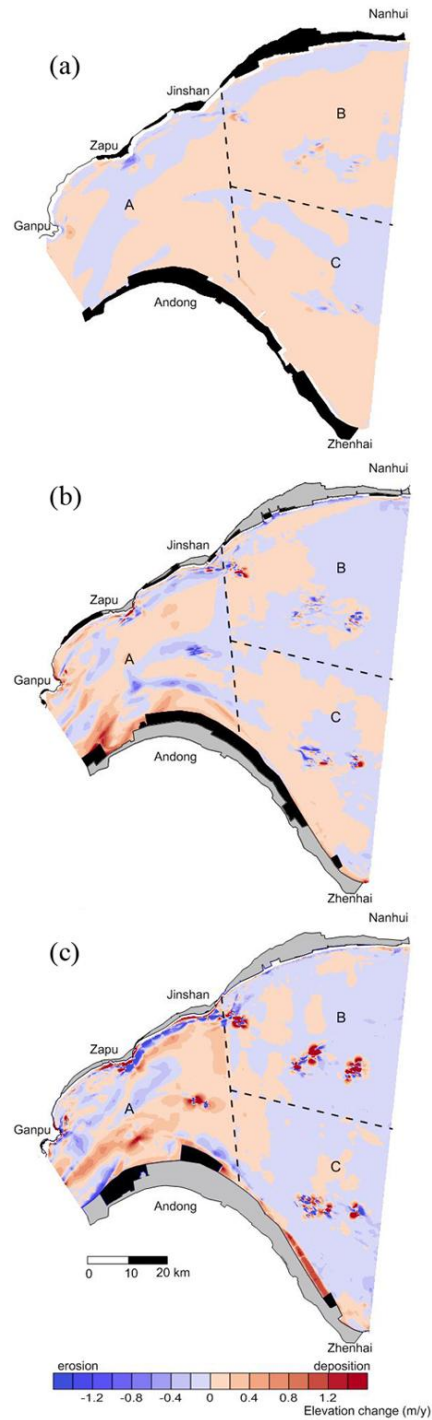
311

312 **4. Results**

313 **4.1 Morphological evolution of the Hangzhou Bay**

314 Figure 7 illustrates the rates of morphological change in the Hangzhou Bay over
315 successive periods. From 1959-2003, erosion mainly occurred in the northern channel,
316 while deposition occurred in other parts. This pattern is consistent with the earlier
317 reported historical evolution of the Hangzhou Bay that was characterized by “erosion in
318 the north and deposition in the south” (Cao et al., 1985; Han et al., 2003). These

319 changes were related to large-scale sediment transport induced by the propagation of the
 320 tidal wave under the influence of the Coriolis force (ECCHE, 1992). Sediment
 321 accumulation during this period was $5.2 \times 10^9 \text{ m}^3$ (Table 1). The sedimentation



322

Fig. 7. Rates of morphological change in Hangzhou Bay over successive periods: (a) 1959~2003; (b) 2003~2010; and (c) 2010~2014. The black areas denote land reclamation and the shading areas denote the original shoreline and the latest reclamation.

accumulations in the periods 2003~2010 and 2010~2014 were 1.1×10^9 and 0.6×10^9 m³, respectively. Correspondingly, the accumulation rates in the three periods were 2.4, 3.3 and 3.0 cm/y, which indicate a generally increasing accumulation trend. Xue (1995) studied volume changes in the Hangzhou Bay using charts of 1887, 1937 and 1987. His results show that the deposition rates in the Hangzhou Bay were 0.8 and 1.5 cm/y in the former and latter 50 years, respectively and the average was 1.15 cm/y for the 100 year period. This suggests that the sedimentation rates in the Hangzhou Bay increased gradually from 1887 to 2014.

All three zones (cf. Fig. 2) showed accumulation in the period 1959~2003. In Zone A (the inner bay) the rate was 2.4 cm/y, and those in zones B and C (the northern and southern parts of the outer bay), were 1.0 and 3.9 cm/y, respectively. In the periods 2003~2010 and 2010~2014, the accumulation rates in Zone A were 9.0 and 13.4 cm/y, revealing a 2.5- and 4.5-fold increase compared to the period 1959~2003. The sediment deposited in the subaqueous area of Zone A since 1959 amounted to 2.36×10^9 m³, indicating an average bed-level change of about 1.47 m. Zone B switched from accumulation to erosion in the latter two periods, the rates being -4.0 and -1.9 cm/y, respectively. Zone C maintained the accumulating trend from 2003 to 2010, but also switched to erosion from 2010 to 2014, the rates being 5.8 and -1.3 cm/y, respectively.

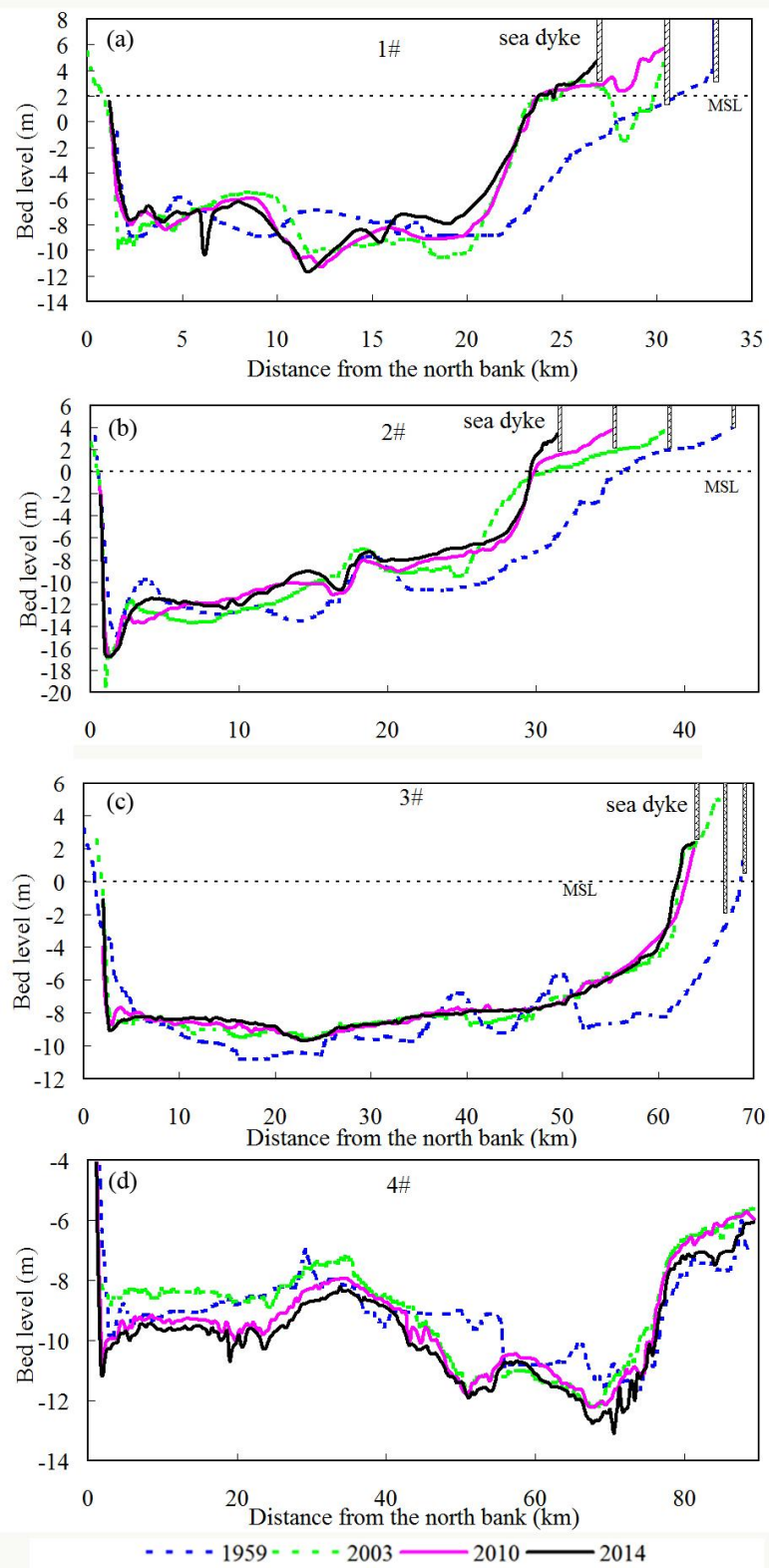
4.2 Changes in cross-sections

348 Cross-sections of the inner and outer parts of the bay illustrate the bed-level changes in
349 greater details (Fig. 8). Along cross-sections of the inner bay (1# and 2#), the overall
350 sedimentation can be observed, with the averaged elevations of the sea bed increasing
351 by around 1.5 m. Notable strong sedimentation occurred at the southern bank. The
352 shoreline in the south advanced by about 6 km and 12 km in cross-section 1 and 2#,
353 respectively, since 1959 due to embankment by dyke buildings. The southern flat above
354 mean sea level (MSL) advanced correspondingly and the slope above MSL steepened
355 gradually. Strong sedimentation occurred at the front of the flat (sub-tidal area below
356 MSL) from 1959 to 2003, with the maximum sedimentation of about 5m, indicating a
357 sedimentation rate of about 11 cm/y. The average slopes of the front area of 1 and 2#
358 increased from 1.2‰ to 2.5‰ and from 0.9‰ to 1.7‰, respectively. The steeper slope
359 was more or less maintained during 2003 and 2014. This is probably because the
360 development of the front area of the southern flat is constrained by the main channel of
361 the Hangzhou Bay (Chen et al., 1989). The erosion in the front of 2# between 2003 and
362 2010 is probably caused by the embankment enhancing the current in the adjacent area.

363

364 Along cross-section 3#, the southern channel-shoal system that existed in 1959
365 disappeared and the bed became smooth. From 1959~2003, the northern part accreted
366 vertically by about 1 m, and the southern shoreline advanced by about 5 km and
367 accreted by about 3.5 m, with the sedimentation rate being about 8 cm/y. After 2003 the
368 bed showed slight accumulation with a maximum of about 0.7 m.

369



370

371 Fig. 8. Bed level changes along the cross-sections depicted in Fig. 6.

372 Cross-section 4#, located at the bay mouth, showed accumulation in the northern and
373 southern parts, but erosion in the central part in the period from 1959~2003, on average
374 amounting to about 1 m. From 2003-2010 the most remarkable change was the up to 1
375 m erosion at the northern mouth. From 2010-2014 the whole section along the mouth
376 eroded about 0.4 m.

377

378 **4.3 Morphological evolution of the Hangzhou Bay-Qiantang Estuary system**

379 There are strong water and sediment exchanges between the Hangzhou Bay and the QE
380 (e.g. Chen et al., 1990; Han et al., 2003). In the last decades, the bed change in the QE
381 was characterized by continuous accumulation, which was mainly caused by artificial
382 coastal embankments since the 1960s, which resulted in constriction of the estuary (Li
383 and Dai, 1986; Han et al., 2003; Pan et al., 2010).

384

385 Figure 9 illustrates time series of channel volumes below the mean high-tide level of the
386 QE and the inner bay since 1980. Channel volume decreases indicate accumulation.
387 Before 1993, the volume in the QE was basically stable, fluctuating around an average
388 of about $4.1 \times 10^9 \text{ m}^3$. From 1993~2005, the volume continuously decreased with the rate
389 of $71 \times 10^6 \text{ m}^3/\text{y}$, and the accumulate rate being 10.2 cm/y. The fluctuation of volumes
390 between neighboring years should be attributed to the variation of the water discharge
391 from Qiantang River. The bed level change in the QE is sensitive to the river discharge
392 because the fine sediment in the estuary can be easily resuspended. The seabed of the
393 QE tends to be eroded during high flow season or years, and deposited during low flow
394 season or years (Chien et al., 1964; Han et al., 2003; Yu et al., 2012). After 2006, a new
395 relatively stable volume reached with an average channel volume of $3.0 \times 10^9 \text{ m}^3$. For the

inner bay, the bathymetric data was deficient before 1986. Since 1986, the volume decreased stepwise in two stages. From 1986~2005, the average volume change was about $74 \times 10^6 \text{ m}^3/\text{y}$, whereas since 2006 it doubled to about $150 \times 10^6 \text{ m}^3/\text{y}$ (Fig. 9). Correspondingly, the accumulation rates were 4.4 cm/y and 9.0 cm/y, respectively. It is interesting to note that the difference between the average volume changes before and after 2006 ($76 \times 10^6 \text{ m}^3$) was almost identical to that of the QE in the period from 1993~2005. This suggests that, when the morphological evolution of the QE was relatively stable, the location of sediment deposition moved seaward to the inner Hangzhou Bay. The total accumulation rate of the two areas together remained more or less constant.

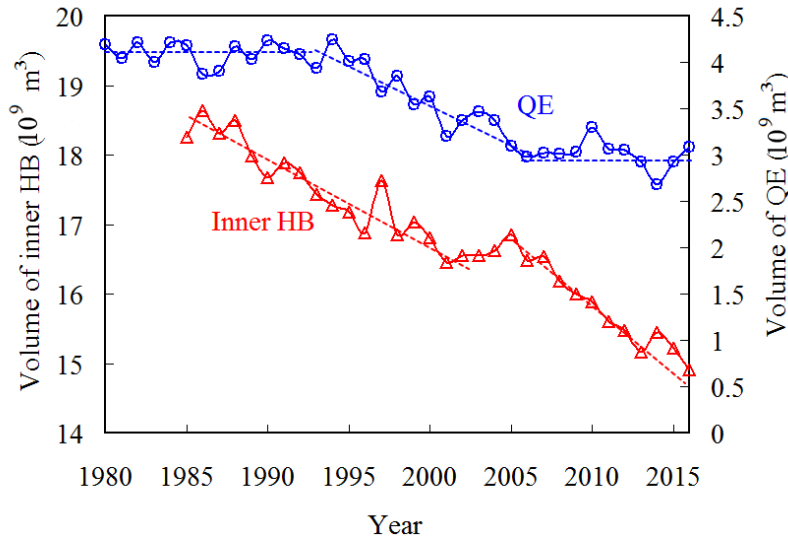


Fig. 9. Temporal changes in channel volumes below mean high-tide level in the Qiantang Estuary and the inner Hangzhou Bay (zone A in Fig.2).

Table 2 lists the channel volume changes of the QE and the Hangzhou Bay in the same periods. The accumulation rates were 6.4, 9.8 and 8.4 cm/y, from 1959~2003, 2003~2010 and 2010~2014, respectively. For the Hangzhou Bay-QE system, the

413 accumulation rates in the three periods were 2.9, 4.2 and 3.8 cm/y, respectively. It is
414 obvious that, although the sediment load from the Changjiang River drastically
415 decreased in recent years, the deposition rate in the system did not decrease but actually
416 increased to a certain extent.

417

418 **4.4 Feedback of morphological evolution on hydrodynamics**

419 Hydrodynamics, sediment transport and bed evolution generally interact in nonlinear
420 fashion (e.g. Dronkers, 1986; Hibma et al., 2003; Yu et al., 2012; Winterwerp and
421 Wang, 2013). The asymmetry of the tide is one of the controlling factors for residual
422 sediment transport and hence morphological evolution of estuaries and tidal basins (e.g.
423 Aubrey, 1986; Dronkers, 1986; Friedrichs and Aubrey, 1988; Wang et al., 2002). In
424 estuaries, the tide is flood-dominant if the flood duration is shorter than the ebb
425 duration, and ebb-dominant if the opposite is true (Wang et al., 2002).

426

427 Figure 10a and 8b illustrates the time series of annually averaged high- and low-tide
428 levels and the tidal ranges, respectively, at the Ganpu gauging station. Since the 1970s,
429 the high-tide level has increased gradually from around 4.7 m to 5.4 m, whereas the
430 low-tide level remained stable around -2.6 m up to 2000 before increasing gradually to -
431 2.4 m since then. In accordance, the annually-averaged tidal range increased by about
432 0.6 m since the 1970s. The increasing high-tide level is caused by the land boundary
433 changes due to the coastal embankment which enhanced the tidal wave reflection (Xie
434 et al., 2005). A good relationship exists between the embanked area and the annual high
435 level (Fig. 11). An addition factor for the high tidal level increase is the increasing

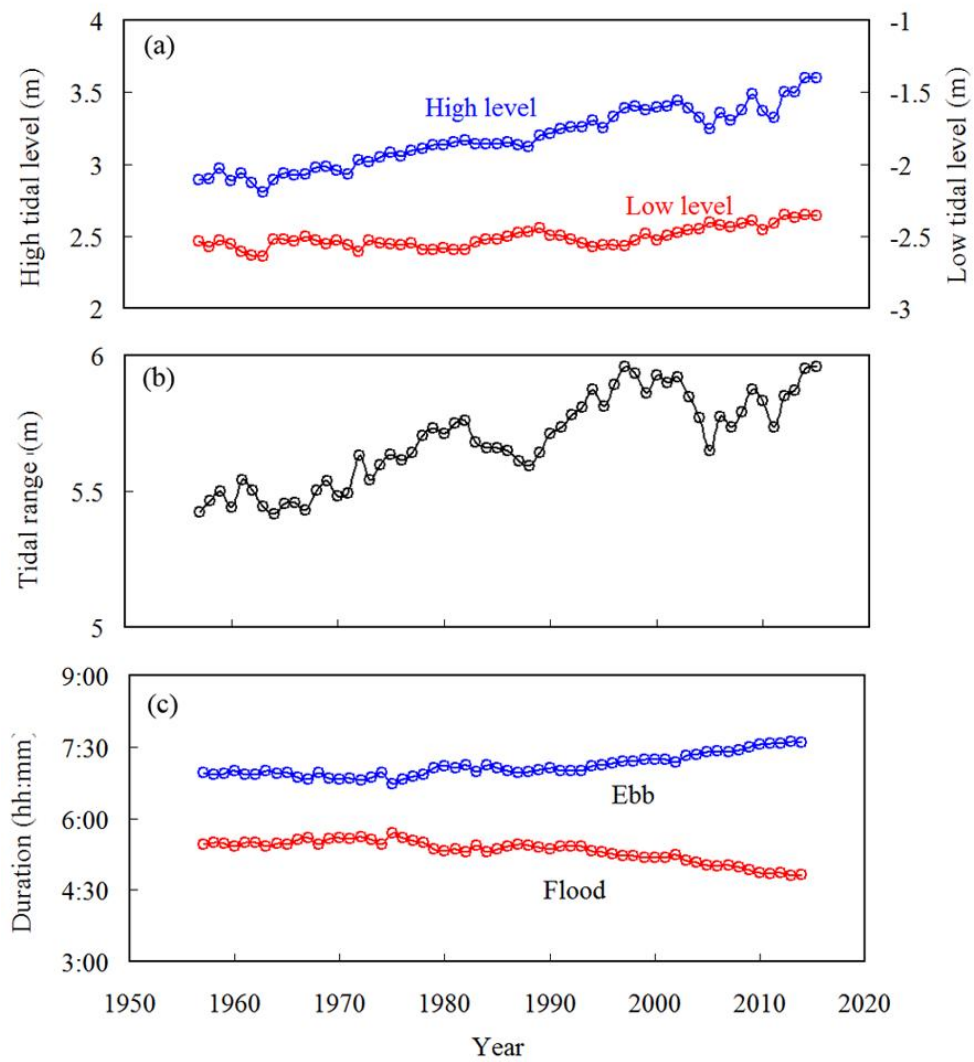
436 occurrence of storm surges in the Hangzhou Bay area (Liu et al., 2016). The change in
437 the low-tide level was mainly related to the changes in bed level (Han et al., 2003).

438

439 Figure 10c illustrates the annually-averaged flood and ebb durations based on the water
440 level data at the Ganpu station. As can be seen, the duration of the flood is shorter than
441 that of the ebb. Before 1980, the flood duration was around 5 h 30 min and the ebb
442 duration around 6 h 50 min, the ratio between the two being constant around 0.85. Since
443 1981, the duration of the flood became gradually shorter, whereas that of the ebb
444 became gradually longer. From 1981 to 2015, the change in duration of both flood and
445 ebb was about 40 minutes. Subsequently, the ratio between the two gradually decreased
446 to 0.63. This reveals that the flood dominance of the inner Hangzhou Bay became
447 enhanced due to coastal embankment and sediment accumulation.

448

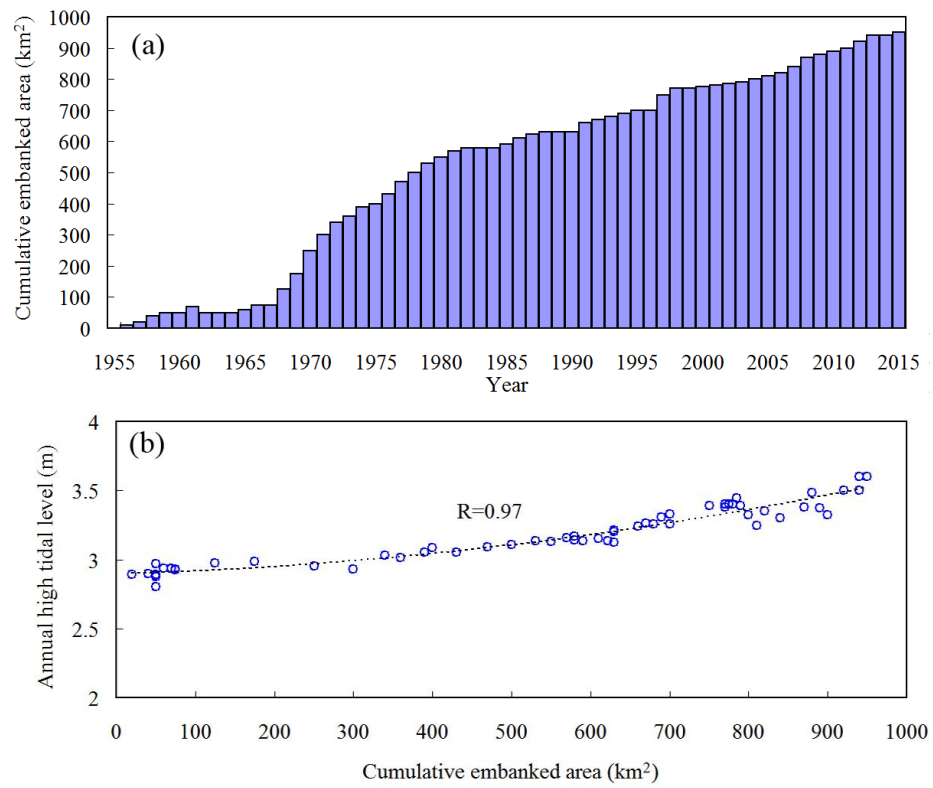
449 Figure 12 illustrates the relationships between the water and sediment fluxes across the
450 Jinshan transect and the tidal range at the Luchaogang gauging station at the time of the
451 cruises in 1983 and 2015. As can be seen, both water and sediment fluxes correlate well
452 with the tidal range. At a mean tidal range of 3.2 m, the water fluxes in 1983 and 2015
453 were $108 \times 10^8 \text{ m}^3$ and $80 \times 10^8 \text{ m}^3$, respectively, indicating that the gross water flux
454 decreased by about 25% over the last 30 years (Fig. 12a). The decrease in the tidal
455 prism is related to the decreasing tidal flat (e.g. Van der Wal et al., 2002; Winterwerp
456 and Wang, 2013). However, the sediment fluxes remained similar over the same period.
457 At the mean tidal range of 3.2 m, the sediment flux in the two reference years was
458 $1.45 \times 10^6 \text{ t}$.



459

460 Fig. 10. Annually-averaged high- and low-tide levels (a), tidal range (b) and flood/ebb
 461 durations at the Ganpu gauging station. (data from Zhejiang Hydrographic Office).

462



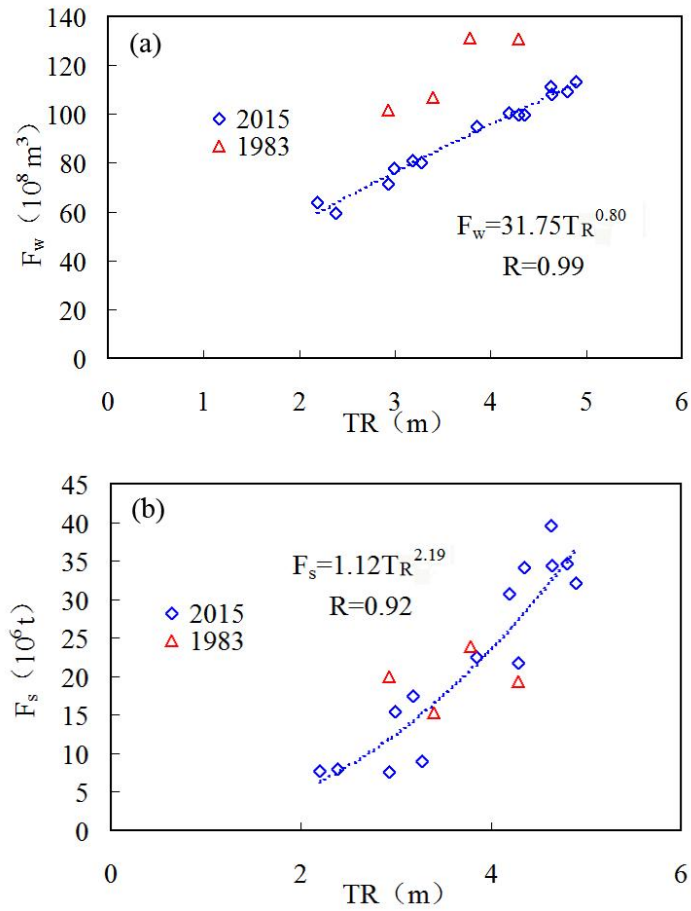
463

464 Fig. 11. Time series of the cumulative embanked area in the Qiantang – Hangzhou Bay

465 area (a) and the relationship between the cumulative embanked area and the annual high

466 tidal level at Ganpu station (b). Data in panel (a) is from Tang and Cao (2016).

467



468

469 Fig. 12. The relationships between flood/ebb-averaged water fluxes (F_w) (a) and
 470 sediment fluxes (F_s) (b) across the Jinshan transect versus the tidal range at the
 471 Luchaogang station (T_R) during the winter cruises of 1983 and 2015.

472

473 Because sediment flux is a function of water flux and suspended sediment
 474 concentration, it is obvious that the SSC increased in recent years. This is related to the
 475 stronger tidal currents caused by the narrowed cross-section. However, in comparison to
 476 the water fluxes, the net sediment flux is very small, being the difference between the
 477 very large flood and ebb fluxes, and is therefore extremely difficult to measure or
 478 compute with any degree of confidence (Townend, 2005). Given that the sediment flux
 479 has not changed, but that the flood dominance has been enhanced over the last 30 years,

480 it is reasonable to assume that, at present, more sediment is transported landward in one
481 tidal cycle. This explains the increasing accumulation rate in the inner Hangzhou Bay.

482

483 **5. Discussion**

484 **5.1 Influence of the decreasing sediment load from the Changjiang River**

485 The sediments in the Hangzhou Bay and the Qiantang Estuary are mainly derived from
486 the Changjiang River (e.g. Su and Wang, 1989; Chen et al., 1990). After the river-borne
487 sediments enter the Changjiang Estuary, about one-half is deposited within the estuary,
488 most of the other half being dispersed to the south, the remainder northward to the
489 Jiangsu coastal sea (Chen et al., 1985; Milliman et al., 1985). The reduction of the
490 Changjiang sediment load caused wide concern of what influence this would have on
491 sediment delivery to the Hangzhou Bay and the associated morphological development.

492

493 The results of the present analysis show that, in recent years, the sedimentation rates in
494 the Hangzhou Bay and the QE as a whole has not decreased, but rather increased to
495 some extent, as shown in Fig.7 and Table 2. This can be attributed to the adjustment of
496 the area of the outer Changjiang Estuary. The reduction of the sediment load from the
497 Changjiang River is mainly related to the flood season from June to September (e.g. Dai
498 et al., 2016; Xie et al., 2017). Recent research showed that in the outer Changjiang
499 estuary, the SSC has not decreased in the flood seasons of the last few decades (Xie et
500 al., 2017). During the last 7000 years of the post-glacial transgression, the large
501 amounts of sediment from the Changjiang formed an elongated, up to 50 m thick mud
502 belt that stretches from the Changjiang Estuary almost up to Taiwan (Liu et al., 2007).
503 The tides in this region play an important role in sediment transport. Large tidal ranges

504 and strong tidal currents, in combination with shallow water depths, small seabed slopes
505 and little wave action, have resulted in active resuspension of fine-grained sediment
506 from the local seabed (Gao et al., 2015).

507

508 As pointed out by Kennedy (1984), estuaries trap significant quantities of material and
509 thus act as filters between land and the oceans. The principal sediment supply of the
510 Hangzhou Bay is neither from the Qiantang River nor directly from the Changjiang
511 River. Instead, there are two filters, i.e. the Changjiang Estuary and the mud area in the
512 outer Changjiang Estuary. The drastic reduction in the sediment load of the Changjiang
513 River would thus initially be recorded in two buffer areas. This can be supported by the
514 recent study of Yang et al (2011) and Luo et al (2017) who found that the Changjiang
515 subaqueous delta is experiencing overall net erosion since the construction of the Three
516 Gorges Dam in 2003 and suggested that the delta recession will continue to occur in the
517 near future because the Changjiang sediment discharge will further decrease in the near
518 future due to the construction of new dams. On the other hand, recent hydrological
519 surveys revealed that the annually-averaged net sediment flux into the Hangzhou Bay
520 has decreased slightly by about 10% after 2003 (Xie et al., 2017), whereas the net
521 sediment fluxes in the coastal area south of Zhoushan islands have not detected to be
522 decreased apparently in last decades (Deng et al., 2017). The slight decrease sediment
523 supply at the mouth of the bay caused the erosion in the outer bay in recent years (Fig.
524 7b and c). Its influence on the inner bay and the QE has been overcome by the coastal
525 embankment, because the sediment in the inner bay and the QE comes from the outer
526 bay (Chen et al., 1990). This phenomenon agrees with the long-term morphodynamic
527 model by Yu et al (2012) that with the sediment supply decrease at the seaside of the

528 estuary, erosion will firstly observed at the mouth area. The morphological effects on
529 the inner bay and the QE are expected to lag behind by a relatively longer time.

530

531 **5.2 Morphological development of the southern flat**

532 Tidal flats are important geomorphological units in estuarine and coastal environments,
533 which provide habitat for wild lifes, resources for land reclamation and protection
534 against extreme storm events, and play an important role in global carbon cycling and
535 climate change (e.g. Allen and Pye, 1992; Yang et al., 2005; De Vriend et al., 2011;
536 Friedrichs, 2011). The accreting southern tidal flat in the Hangzhou Bay plays as a sink
537 for sediment from Changjiang Estuary under the role of the secondary plume of
538 Changjiang Estuary, also for the sediment output from the QE during high river flow
539 season or years (Li and Xie, 1993). In the last centuries, the flat advanced fast with the
540 average rate of about 25 m/y and vertical sedimentation rate of about 5 cm/y, under
541 natural condition (Chen et al., 1990).

542

543 The strong sedimentation of the southern flat is related to the large-scale flow patterns
544 in the Hangzhou Bay. The northern bay is dominated by flood currents while the
545 southern bay is dominated by ebb currents (e.g. Cao et al., 1985; Su and Wang, 1989;
546 Xie et al., 2009). Ebb currents diverge at the front of the southern flat due to the
547 increasing cross-sectional width. Subsequently, the sediment transport capacity of ebb
548 currents decreased, and strong sedimentations occur (Cao et al., 1985; Han et al., 2003).
549 Because the embankments in the last decades have been mainly carried out above MSL,
550 the changes of large-scale flow patterns has been limited (Shao, 2016). In addition,
551 SSCs in the front of tidal flat area is high, with the vertically averaged SSC usually

552 above 3 kg/m³ (Fig. 5). The sedimentation rate of the southern flat has been increased
553 apparently in the last decades, compared to the above-mentioned rate of about 5 cm/y in
554 natural conditions (Fig. 8). This is probably related to the increasing SSC in the front
555 area. Recent study of Van Maren et al (2016) revealed that land reclamations in
556 estuaries will lead to an increase in SSC because of the decrease in accommodation
557 space for fine-grained sediments. This can also be evaluated from the fact that despite
558 the water fluxes into the inner bay have decreased apparently since 1980s, the sediment
559 fluxes can be more or less maintained (Fig. 12).

560

561 The cross-sectional profiles of the accretion-dominated tidal flat are normally convex
562 (Fig. 8), similar to other accretional intertidal flats in the world (Kirby, 2000; Yang et
563 al., 2005; Friedrichs, 2011; Wang et al., 2014). Apparent reductions in width of the
564 southern flat, due to coastal embankments by building sea dykes, have resulted in
565 steeper fronts. This is similar to the observations in the Changjiang Estuary and Jiangsu
566 coast (Yang et al., 2005; Van Maren et al., 2013; Wang et al., 2014). Wind waves can
567 cause erosion on the wide intertidal flat (Kirby, 2000; Yang et al., 2005; Wang et al.,
568 2014). The reduction in the intertidal flat width can cause a concentration of wave
569 energy on the lower flat and in the sub-tidal area, with relative deep water, resulting in
570 bed erosion (Wang et al., 2014). A model applied to the accreting intertidal flat shows
571 that tidal flats with abundant sediment supply can persistently prograde with the similar
572 slope, remaining in the equilibrium shape under natural conditions (Liu et al., 2010).
573 However, southern flat in the Hangzhou Bay is not the case. The front area of the flat has
574 become progressively steeper because of the constraint by the main channel of the bay.

575

576 **5.3 Morphological response model of the Hangzhou Bay**

577 Over the last decades, the annual tidal levels in the outer Changjiang Estuary and in the
578 Hangzhou Bay have fluctuated around their multi-year averages. Hence the influence of
579 sea-level rise on sediment transport and morphological evolution of the Hangzhou Bay
580 have been minor. The main channel of the QE used to meander continuously, and the
581 coastal wall revetments used to collapse frequently, resulting in serious economic losses
582 and even losses of human lives, besides making the development of resources such as
583 navigation channel maintenance difficult. Since the 1960s, large-scale coastal
584 embankments in the QE have been carried out for the purpose of flood defense, urban
585 land requirements, etc. (Li and Dai, 1986; Han et al., 2003; Pan et al., 2010).
586 Embankments occurred gradually over time (Fig. 3a and 7), having to date resulted in
587 more than 1000 km² of reclaimed tidal flats. In the process, the estuarine width was
588 greatly reduced, for example from about 10 km to 2.5 km at Yanguan and from about
589 22 km to 18 km at Ganpu.

590

591 The morphological response in the QE is related to progressive coastal embankment.
592 Before 2006, the QE and the inner Hangzhou Bay showed sediment accretion (Fig. 9).
593 The accumulation in the QE needed sediment supply from downstream (i.e. the inner
594 Hangzhou Bay). After 2006, when the morphological evolution in the QE has been
595 basically stable, accumulation shifted downstream. As a consequence, the accumulation
596 rate in the inner Hangzhou Bay increased (Fig. 7 and 9), the sediment source being the
597 outer Hangzhou Bay. This is consistent with Chen et al (1990), who showed, based on
598 sedimentological analysis, that the sediment in the QE comes mainly from the
599 Hangzhou Bay, whereas the sediment in the inner Hangzhou Bay derives mainly from

600 the outer bay. Overall, the sediment accretion in the Hangzhou Bay and the QE is
601 characterized by the gradually seaward shifting trend.

602

603 Worldwide, land reclamation and dredging have been, and still are, common practice in
604 many estuaries, many researchers reporting increased sedimentation as a consequence
605 (e.g. English and Kestner, 1958; Sherwood et al., 1990; Pye and French, 1993; Van der
606 Wal et al., 2002). This can mainly be attributed to enhancement of flood dominance due
607 to decrease tidal flat area (Van der Spek, 1997). In the viewpoint of the estuarine
608 convergence, stronger convergence results in the large longitudinal sandbar in the QE
609 shifts seaward (Yu et al., 2012). The increasing sedimentations in the Hangzhou Bay-
610 QE system in last decades observed in this study agree with their numerical model
611 results.

612

613 In response, the northern bay-mouth switched from a depositional mode to an erosional
614 mode in recent years. This is in agreement with previous observation by Dai et al
615 (2014). Besides the above-mentioned causes, there are probably several other factors.
616 First, there are probably direct sediment exchanges between the northern bay mouth and
617 southern CE mouth across the front of the Nanhui shoal (Su and Wang, 1989; Chen et
618 al., 1990). With the reduction of the Changjiang sediment load, the progradation rates of
619 tidal flats along the CE slowed down or even reversed to erosion (Yang et al., 2005;
620 Van Maren et al., 2013; Wang et al., 2015). Hence the SSC in the outer CE has
621 decreased by about 20-30% after the Three Gorges Dam construction in 2003 (Li et al.,
622 2012; Xie et al., 2017). The SSC decrease of the outer CE would decrease the direct
623 sediment supply to the northern Hangzhou Bay. On the other hand, more than 150 km²

624 along the Nanhui shore of the northern mouth has been reclaimed since the 1980s (Fig.
625 3b). The reclamation intercepted large amounts of sediment, which could be originally
626 transported into the northern Hangzhou Bay. On the other hand, the eastward
627 propagation of the Nanhui flat by about 10 km in recent years has increased the distance
628 and changed the route by which Changjiang sediment can enter the Hangzhou Bay (Fig.
629 3b).

630

631 **5.4 Future morphological evolution trends**

632 Progressive land reclamation in coastal environments continually change the
633 circumjacent hydrodynamics and sediment transport (e.g. Van der Spek, 1997; Van der
634 Wal., et al., 2002; Wang et al., 2015). During the last decades, both the annually-
635 averaged high and low tidal levels in the inner bay have been increased due to shoreline
636 constriction and sediment accumulation. The annually-averaged durations of rising and
637 falling tides have been shorten and lengthened, respectively, indicating that the flood
638 dominance in the inner bay has been enhanced (Fig. 10). As a result, the net landward
639 sediment flux over one tidal cycle at the interface between the inner and outer bay has
640 been increased to some extent (Fig. 12). In return, this nonlinear feedback mechanism
641 has promoted the sediment accumulation in the inner bay.

642

643 At present, the large-scale coastal embankments in the QE have continuously increased
644 the constriction of the estuary over several decades. In the near future, only some local
645 areas will be reclaimed (Pan et al., 2010). However, the sediment accumulation will not
646 cease synchronously due to the enhanced flood-dominance and landward sediment
647 transport. The temporal scales of estuarine morphodynamics are related to the spatial

scales involved (De Vriend, 1996). The larger the spatial scale is, the longer the time that would be needed for the morphological adjustment. In view of the large spatial scale of the Hangzhou Bay and the complex sediment transport behavior, the timescale for morphological readjustment in the Hangzhou Bay is expected to be in the order of several decades. The accumulation trend of the inner bay will continue for some time, while erosion of the outer bay will also continue in order to supply sediment to the inner part.

6. Conclusions

Although the sediment load from the Changjiang River has reduced, especially since 2003 when the Three Gorges Dam was constructed and operated, the sedimentation rate in the adjacent Hangzhou Bay has not decreased as expected. The outer Changjiang Estuary acts as a buffer area and sediment sources for the Hangzhou Bay. Besides other reasons, such as land reclamation in the Qiantang and Changjiang estuaries, the documented erosion in the northern Hangzhou Bay can be partly attributed to the drastic reduction of the Changjiang sediment load because that part directly exchanges sediment with the Changjiang Estuary.

The large-scale human interventions played an important role in the morphological evolution of the Hangzhou Bay-Qiantang Estuary system. The coastal embankment increased the estuarine constriction and, to a certain extent, enhanced the flood dominance in the inner part. Subsequently, the sedimentation rate in the estuary increased. The morphological changes have been related mainly to the implementation process of the coastal embankment. With progressive seaward coastal embankment, sediment accumulation has resulted in gradual seaward aggradation. The annually-

673 averaged high and low tidal levels in the inner bay have been increased and the flood
674 dominance in the inner bay has been enhanced apparently. The tidal prism at the
675 interface between the inner and outer bay has decreased by about 25% since 1980s,
676 while the net landward sediment flux has been intensified to a certain extent. The
677 enhancing flood dominance and landward sediment transport are responsible for the
678 increasing sedimentation in the estuary. Furthermore, stronger sedimentations have
679 occurred at the southern shoreline, and the upper and sub-tidal flat has been steeper due
680 to coastal embankments and the constraint of the main channel of the bay. Although the
681 coastal embankment will cease in the near future, the morphological response is
682 expected to continue on for a longer time.

683

684 **Acknowledgements**

685 This research was supported by the National Natural Science Foundation of China
686 (grant number 41676085, 51379190); Zhejiang Provincial Natural Science Foundation
687 of China (grant number LY16D060004). We wish to thank two anonymous reviewers
688 for their constructive comments to improve this work greatly. We also thank Mr.
689 Chengfei Hu for his help in the preparation of the figures.

690

691 **References**

692 Allen, J.R.L., Pye, K., 1992. Coastal saltmarshes: their nature and importance. In: Allen,
693 J.R.L., Pye, K. (Eds.), *Saltmarshes, Morphodynamics, Conservation and Engineering*
694 *Significance*. Cambridge Uni. Press, Cambridge, U.K, pp. 1-18.
695 Aubrey, D.G., 1986. Hydrodynamic controls on sediment transport in well-mixed bays
696 and estuaries. In: Van de Kreeke, J. (Ed.), *Physics of Shallow Estuaries and Bays*.
697 *Lecture Notes on Coastal and Estuarine Studies Vol. 16*. Springer-Verlag, Berlin, pp.
698 245–276.

699 Blott, S.J., Pye, K., Van der Wal, D., Neal, A., 2006. Long-term morphological change
700 and its causes in the Mersey Estuary, NW England. *Geomorphology* 81(1-2), 185–206.

701 Burrough, P.A. McDonnell, R.A., 1998. *Principles of Geographical Information*
702 *Systems*. Oxford University Press, Oxford, UK, 352 pp.

703 Cao, P.K., Gu, G.C., Dong, Y.F., Hu, F.X., 1985. Basic characteristics of sediment
704 transport in Hangzhou Bay. *J. East China Normal Uni.*, (3), 75-84 (in Chinese with
705 English abstract).

706 Chen, J.Y., Wang, B.C., Yu, Z.Y., 1989. *Developments and Evolution of China's Coast*.
707 *Shanghai Sci. Tech. Pub.*, Shanghai, 556 pp (in Chinese).

708 Chen, J.Y., Zhu, H.F., Dong, Y.F., Sun J.M., 1985. Development of the Changjiang
709 Estuary and its submerged delta, *Cont. Shelf Res.* 4, 47-56.

710 Chien, N., Sie, H. S., Chow, C. T., Lee, Q.P., 1964. The fluvial processes of the big
711 sand bar inside the Chien Tang Chiang Estuary. *Acta Geograph. Sin.*, 30(2), 124-142 (in
712 Chinese with English abstract).

713 Dai, Z.J., Fagherazzi, S., Mei, X.F., Gao, J.J., 2016. Decline in suspended sediment
714 concentration delivered by the Changjiang (Yangtze) River into the East China Sea
715 between 1956 and 2013. *Geomorphology* 268, 123–132.

716 Dai, Z.J., Liu, J.T., Xie, H.L. Shi W.Y., 2014. Sedimentation in the Outer Hangzhou
717 Bay, China: the influence of Changjiang sediment load. *J. Coast. Res.* 30, 1218–1225.

718 Deng, B., Wu, H., Yang, S.L., Zhang, J., 2017. Longshore suspended sediment transport
719 and its implications for submarine erosion off the Yangtze River Estuary. *Estuarine*
720 *Coastal Shelf Sci.* 190, 1-10.

721 De Vriend, H.J., 1996. Mathematical modelling of meso-tidal barrier island coasts. Part
722 I: Emperical and semi-emperical models, In: Liu, P.L.F. (Ed.), *Advances in Coastal*
723 *Ocean Engineering*. World Scientific, Singapore, pp. 115-149.

724 De Vriend, H.J., Wang, Z.B., Ysebaert, T., Herman, P.M.J., Ding, P.X., 2011. Eco-
725 Morphological Problems in the Yangtze Estuary and the Western Scheldt. *Wetlands*,
726 31(6), 1033-1042.

727 Dronkers, J., 1986. Tidal asymmetry and estuarine morphology. *Nether. J. Sea. Res.* 20
728 (2/3), 117–131.

729 Dyer, K.R., 1997. *Estuaries - physical introduction*, 2nd ed. John Wiley and Sons,
730 Chichester. 195 pp.

731 Editorial Committee for Chinese Harbors and Embayment (ECCHE), 1992. Chinese
732 Harbors and Embayment (Part V).. China Ocean Press, Beijing. 357pp (in Chinese).

733 Eisma, D., 1998. Intertidal deposits: river mouth, tidal flats, and coastal lagoons. CRC
734 Press, Boca Raton. 495pp.

735 Fan, D.D., Tu, J.B., Shang, S., Cai, G.F., 2014. Characteristics of tidal-bore deposits
736 and facies associations in the Qiantang Estuary, China. *Mar. Geol.* 348, 1-14.

737 Fairbridge, R.W., 1980. The estuary: its definition and geodynamic cycle. In: Olausson,
738 E., Cato, I. (Eds.), *Chemistry and Biogeochemistry of Estuaries*. John Wiley & Sons,
739 New York, NY, pp. 1-36.

740 Friedrichs, C.T., 2011. Tidal flat morphodynamics: a synthesis. In: Hansom, J.D. and
741 Flemming, B.W. (eds), *Treatise on estuarine and coastal science*, vo.3: Estuarine and
742 coastal geology and geomorphology. Elsevier, pp. 34.

743 Friedrichs, C.T., Aubrey, D.G., 1988. Non-linear tidal distortion in shallow well-mixed
744 estuaries: a synthesis. *Estu. Coast Shelf Sci.* 27, 521-45.

745 Gao, S., Wang, Y.P., 2008. Material fluxes from the Changjiang River and their
746 implications on the adjoining continental shelf ecosystem. *Cont. Shelf Res.* 28, 1490-
747 1500.

748 Gao, S., Wang, D.D., Yang, Y., Zhou, L., Zhao, Y.Y., GAO, W.H., Han, Z. C., YU, Q.,
749 Han, Z.C., Dai, Z.H., Li, G.B., 2003. *Regulation and Exploitation of Qiantang Estuary*.
750 China Water Power Press, Beijing, 554pp (in Chinese).

751 Hibma, A., Stive, M.J.F., Wang, Z.B., 2004. Estuarine morphodynamics. *Coast. Eng.*
752 51, 765-778.

753 Inghish, C.C., Kestner, F.J.T., 1958. The long-term effects of training walls,
754 reclamation, and dredging on estuaries. *Proc. Institution Civil Eng.* 9, 193–216.

755 Kirby, R., 2000. Practical implications of tidal flat shape. *Cont. Shelf Res.* 20, 1061-
756 1077.

757 Kennedy, V. S., 1984. *The estuary as a filter*. Academic Press, New York. 511pp.

758 Lane, A., 2004. Bathymetric evolution of the Mersey Estuary, UK, 1906-1997: causes
759 and effects. *Estu. Coast. Shelf Sci.* 59, 249–263.

760 Li, G.B., Dai, Z.H., 1986. Fluvial processes and reclamation of the Qiantang Estuary.
761 *Inter. J. Sed. Res.* 1(1), 56–66.

762 Li, P., Yang, S.L., Milliman, J.D., Xu, K.H., Qin, W.H., Wu, C.S., Chen, Y.P., Shi,
 763 B.W., 2012. Spatial, temporal, and human-induced variations in suspended sediment
 764 concentration in the surface waters of the Yangtze Estuary and adjacent coastal areas.
 765 *Estu. Coast.* 35, 1316–1327.

766 Li, Y., Xie, Q.C., 1993. Dynamical development of the Andong tidal flat in Hangzhou
 767 Bay, China. *Donghai Mar. Sci.* 11(2), 25-33 (in Chinese with English abstract).

768 Liu, J.P., Xu, K.H., Li, A.C., Milliman, J.D., Velozzi, D.M., Xiao, S.B., Yang, Z.S.,
 769 2007. Flux and fate of Yangtze River sediment delivered to the East China Sea.
 770 *Geomorphology* 85(3-4), 208–224.

771 Liu, X.J., Gao, S., Wang, Y.P., 2011. Modeling profile shape evolution for accreting
 772 tidal flats composed of mud and sand: A case study of the central Jiangsu coast, China.
 773 *Cont. Shelf Res.* 31(16): 1750-1760

774 Liu, Y.F., Xia, X.M., Chen, S.L., Cai, T.L., 2016. Morphological evolution of Jinshan
 775 Trough in Hangzhou Bay (China) from 1960 to 2011, *Estuar. Coast. Shelf Sci.* In press.

776 Luo, X.X., Yang, S.L., Wang, R.S., Zhang, C.Y., Li, P., 2017. New evidence of
 777 Yangtze delta recession after closing of the Three Gorges Dam. *Sci. Rep.* 7, 41735.

778 Milliman, J.D., 1997. Blessed dams or damned dams, *Nature* 386, 325–326.

779 Milliman, J.D., Farnsworth, K.L., 2011. River discharge to the coastal ocean—A global
 780 synthesis. Cambridge Uni. Press, Cambridge, UK. 394pp.

781 Milliman, J.D., Shen, H.T., Yang, Z.S., Robert, H.M., 1985. Transport and deposited of
 782 river sediment in the Changjiang estuary and adjacent continental shelf. *Cont. Shelf*
 783 *Res.* 4, 37-45.

784 Pan, C.H., Shi, Y.B., Han, Z.C., 2010. Regulation of Qiantang River estuary and
 785 scientific and technological innovations. *China Water Resour.* 14, 13–16 (in Chinese
 786 with English abstract).

787 Pye, K., French, P.W., 1993. Erosion and accretion processes on British Saltmarshes,
 788 Vol. 5. Cambridge Environ. Res. Cons., Cambridge.

789 Shao, M.M., 2016. Impacts of reclamation of tidal dynamics in Hangzhou Bay. M.Sc.
 790 thesis, Zhejiang University.

791 Sherwood, C.R., Jay, D.A., Harvey, R.B., Hamilton, P., Simenstad, C.A., 1990.
 792 Historical changes in the Columbia river estuary. *Prog. Oceanogr.* 25, 299–352.

793 Su, J.L., Wang, K.S., 1989. Changjiang River plume and suspended sediment transport
794 in Hangzhou Bay. *Cont. Shelf Res.* 9(1), 93–111.

795 Syvitski, J.P.M., Vörösmarty, C.J., Kettner, A.J., Green, P., 2005. Impact of humans on
796 the flux of terrestrial sediment to the global coastal ocean. *Science* 308(15), 376–380.

797 Tang, Z.W., Cao, Y., 2016. Beach resources evolution and trend analysis of Qiantang
798 River estuary section under the condition of Narrowing river. *Zhejiang Hydrotec.*, (2):
799 20-23.

800 Townend, I., 2005. An examination of empirical stability relationships for UK estuaries.
801 *J. Coast. Res.* 21, 1042–1053.

802 Townend, I., Whitehead, P., 2003. A preliminary net sediment budget for the Humber
803 Estuary. *Sci. Total Environ.* 314–316, 755–767.

804 Trenhaile, A.S., 1997. *Coastal Dynamics and Landforms*. Clarendon, Oxford, UK.
805 382pp.

806 Van der Spek, A.J.F., 1997. Tidal asymmetry and long-term evolution of Holocene tidal
807 basins in The Netherlands: simulation of palaeo-tides in the Schelde estuary. *Mar. Geol.*
808 141, 71–90.

809 Van der Wal, D., Pye, K., Neal, A., 2002. Long-term morphological change in the
810 Ribble Estuary, northwest England. *Mar. Geol.* 189, 249–266.

811 Van der Wal, D., Pye, K., 2002. The use of historical bathymetric charts to assess
812 morphological and sediment budget change in estuaries. *Geogr. J.* 169(1), 21–31.

813 Van Maren, D.S., Yang, S.L., He, Q., 2013. The impact of silt trapping in large
814 reservoirs on downstream morphology: the Yangtze River. *Ocean Dyn.* 63, 691–707.

815 Van Maren, D.S., Oost, A.P., Wang, Z.B., Vos, P.C., 2016. The effect of land
816 reclamations and sediment extraction on the suspended sediment concentration in the
817 Ems Estuary. *Mar. Geol.* 376, 147-157.

818 Wang, Y.P., Gao, S., Jia J.J., Thompson, C.E.L., Gao, J.H., Yang, Y., 2012. Sediment
819 transport over an accretional intertidal flat with influences of reclamation, Jiangsu coast,
820 China. *Mar. Geol.* 291-294, 147-161.

821 Wang, Z.B., Jeuken, M.C.J.L., Gerritsen, H., De Vriend, H.J., Kornman, B.A., 2002.
822 Morphology and asymmetry of the vertical tide in the Wester-Schelde estuary. *Cont.*
823 *Shelf. Res.* 22, 2599–2609.

824 Wang, Z.B., Van Maren, D.S., Ding, P.X., Yang, S.L., Van Prooijen, B.C., De Vet,
 825 P.L.M., Winterwerp, J.C., De Vriend, H.J., Stive, M.J.F., He, Q., 2015. Human impacts
 826 on morphodynamic thresholds in estuarine systems. *Cont. Shelf Res.* 111, 174–183.
 827 Whitehouse, R.J.S., 2002. Predicting estuary morphology and process: an assessment of
 828 tools used to support estuary management. In: Editor (ED.), *Proc. Seventh Inter. Conf.*
 829 *on Estu. Coast. Model.*, St. Petersburg, Florida, USA, 2001, pp. 344–363.
 830 Winterwerp, J.C., Wang, Z.B., 2013. Man-induced regime shifts in small estuaries – I:
 831 theory. *Ocean Dyn.* 63(11), 1279–1292.
 832 Xie, D.F., Pan, C.H., Wu, X.G., Gao, S., Wang, Z.B., 2017. The variations of sediment
 833 transport patterns in the outer Changjiang Estuary and Hangzhou Bay over the last 30
 834 years. *J. Geophy. Res. Ocean*, 122, doi:10.1002/2016JC012264.
 835 Xie, D.F., Gao, S., Wang, Z.B., De Vriend, H.J., 2009. Numerical modeling of tidal
 836 currents, sediment transport and morphological evolution in Hangzhou Bay, China.
 837 *Cont. Shelf. Res.* 28, 316–328.
 838 Xue, H.C., 1995. Deposition character of Changjiang estuary in the past 100 years. In:
 839 Editor (Ed.), *Proc. 17th Symposium on Coastal Engineering*. Publisher, Beijing (in
 840 Chinese).
 841 Xie, Y.L., Huang, S.C., Wang, R.F., Zhao, X., 2005. Numerical simulation of effects of
 842 reclamation in Qiantang Estuary on storm surge at Hangzhou Bay. *Ocean Eng.* 25(3),
 843 61–67 (in Chinese with English abstract).
 844 Yang, S.L., Zhang, J., Zhu, J., Smith, J.P., Dai, S.B., Gao, A., Li, P., 2005. Impact of
 845 dams on Yangtze River sediment supply to the sea and delta intertidal wetland response.
 846 *J. Geophy. Res.* 110, F03006.
 847 Yang, S.L., Milliman, J.D., Li, P., Xu, K., 2011. 50, 000 dams later: erosion of the
 848 Yangtze River and its delta. *Glob. Planet. Change* 75(1-2), 14–20.
 849 Yu, J., Cao, Y., 2006. Sediment deposition after regulation and reclaiming of Qiantang
 850 Estuary. *J. Sed. Res.* (1), 17–24 (in Chinese with English abstract).
 851 Yu, Q., Wang, Y., Gao, S., Flemming, B., 2012. Modeling the formation of a sand bar
 852 within a large funnel-shaped, tide-dominated estuary: Qiantangjiang Estuary, China.
 853 *Mar. Geol.* 299–302, 63–76.
 854

855 Table 1. Accumulation and erosion in Hangzhou Bay in different periods.

Time interval	Volume changes (10^6 m^3)				Accumulation rate (cm/y)			
	Zone A	Zone B	Zone C	Hangzhou Bay	Zone A	Zone B	Zone C	Hangzhou Bay
1887~1937				1800				0.8 a
1937-1987				3700				1.5 a
1959~2003	1715	724	2729	5168	2.4	1.0	3.9	2.4
2003~2010	952	-466	606	1092	9.0	-4.0	5.8	3.3
2010~2014	771	-126	-75	571	13.4	-1.9	-1.3	3.0

856 *Positive values denote sediment accumulation while negative values denote sediment
 857 erosion. The same below.

858 ^a Based on the data from Xue (1995).

859

860 Table 2. Net accumulation in the Hangzhou Bay-Qiantang Estuary system in different
 861 time intervals.

Time intervals	Hangzhou Bay		Qiantang Estuary		Hangzhou Bay-Qiantang Estuary system	
	VC	AR	VC	AR	VC	AR
1959~2003	5168	2.4	1916	6.4	7084	2.9
2003~2010	1092	3.3	477	9.8	1569	4.2
2010~2014	571	3.1	231	8.4	802	3.8

862 *VC: volume changes, in 10^6 m^3 ; AR: accumulation rate, in cm/y.

863

864 **Figure Captions**

865 Fig. 1. Temporal variations of annual water and sediment discharges measured at the
866 Datong gauging station located at the tidal limit 640 km upstream from the Changjiang
867 River mouth (data from the Changjiang River Hydraulic Engineering Committee).

868 Fig. 2. Locations in Hangzhou Bay referred to in the text. The dashed lines depict water
869 depths. The definitions of the three zones referred to in the statistics of Tables 1 are also
870 given.

871 Fig. 3. Coastal embankment in the Qiantang Estuary (a) and land reclamations in front
872 of the Nanhui flat bordering the Changjiang Estuary (b).

873 Fig. 4. Surface sediment grain size in Hangzhou Bay (from Xie et al., 2009).

874 Fig. 5. Suspended sediment concentration distribution during spring tide in the
875 Hangzhou Bay (modified from Han et al., 2003).

876 Fig. 6. The cross-sections illustrated in Fig. 8 and the hydrographic stations of 1983 (red
877 cycles) and 2015 (blue cycles).

878 Fig. 7. Rates of morphological change in Hangzhou Bay over successive periods: (a)
879 1959~2003; (b) 2003~2010; and (c) 2010~2014. The black areas denote land
880 reclamation and the shading areas denote the original shoreline and the latest
881 reclamation.

882 Fig. 8. Bed level changes along the cross-sections depicted in Fig. 6.

883 Fig. 9. Temporal changes in channel volumes below mean high-tide level in the
884 Qiantang Estuary and the inner Hangzhou Bay (zone A in Fig.2).

885 Fig. 10. Annually-averaged high- and low-tide levels (a), tidal range (b) and flood/ebb
886 durations at the Ganpu gauging station. (data from Zhejiang Hydrographic Office).

887 Fig. 11. Time series of the cumulative embanked area in the Qiantang – Hangzhou Bay
888 area (a) and the relationship between the cumulative embanked area and the annual high
889 tidal level at Ganpu station (b). Data in panel (a) is from Tang and Cao (2016).

890 Fig. 12. The relationships between flood/ebb-averaged water fluxes (F_w) (a) and
891 sediment fluxes (F_s) (b) across the Jinshan transect versus the tidal range at the
892 Luchaogang station (T_R) during the winter cruises of 1983 and 2015.

893