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1 Morphodynamics of the Qiantang Estuary, China: Controls of
2 river flood events and tidal bore

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10 Highlights:

- 11 • Qiantang Estuary shows strong seasonal and inter-annual morphological changes.
- 12 • The tidal bore transports sediment landward and plays an important role for the long-term
13 morphological evolution.
- 14 • A power function has been found between the high river discharge and channel volume of
15 the upper estuary.
- 16 • Dynamic equilibrium is maintained by high river discharge and the flood-dominant tide.

17

18 Abstract

19 The importance of seasonal variations in river discharge on the morphological development of
20 estuaries has been recognized in recent years, yet *in situ* observations about such variations are
21 rare. Here we report a long-term dataset of bathymetry in the Qiantang Estuary, characterized by
22 the presence of a large-scale sediment deposit system and tidal bore. Moreover, a hydrographic
23 survey of the bore dynamics was carried out covering a spring-neap tidal cycle in 2015.
24 Meanwhile, detailed seasonal bathymetric data together with daily river discharge of 2015 were
25 collected. The morphology shows strong seasonal and inter-annual variations. During high flow
26 season, the river flow erodes the bed and transports a large amount of sediments seaward. A good
27 power function exists between the high river discharge and the channel volume at the upper
28 estuary. Flood tides dominate under usual flow discharge condition. In particular, the tidal bore
29 during spring and intermediate tides which is characterized by large current velocity and
30 suspended sediment concentration, transports a large amount of sediment landward. Over a year,
31 a dynamic morphological equilibrium can be maintained. The estuary has also been significantly
32 influenced by the large-scale embankment in last decades, which constrained the lateral
33 migration of thalweg, bank erosion and point bar deposition, which usually occurs in natural
34 sinuous estuaries.

35 **Key words:** Morphodynamic equilibrium; river discharge; tidal asymmetry; tidal bore;
36 Qiantang Estuary; Hangzhou Bay.

37

38

39 1. Introduction

40 Estuaries are defined as semi-enclosed coastal bodies of water which have free
41 connection with the open sea (Fairbridge, 1980). They are among the most important interfaces
42 on earth. They provide navigation channels, ports, land resources, conditions for recreational
43 activities, and so on. They also play an important role in global carbon / biogeochemical cycling,
44 and provide habitats for flora and fauna. Estuaries are fairly ephemeral features at the geological
45 time scale and frequently influenced by natural changes and human interventions (e.g. Dyer,
46 1995; Savenije, 2005). From the management point of view, it is of major significance to
47 understand and predict the sediment transport and morphological evolution in estuaries.

48 Morphological evolution in an estuary is controlled by the nonlinear interactions among
49 hydrodynamics, sediment transport and bed level changes (e.g. Dyer, 1995; Hibma et al., 2004;
50 Dalrymple and Choi, 2007). A morphological equilibrium can be reached when erosion and
51 deposition balance over a long enough time span (e.g. Lanzoni and Seminara, 2002; Hoitink et
52 al., 2017). In recent years, many numerical models have found that an equilibrium state of tidal
53 channel morphology can be reached asymptotically, normally assuming that the river discharge
54 can be ignored or be a constant (e.g. Lanzoni and Seminara, 2002; van der Wegen and Roelvink,
55 2008; Yu et al., 2012; Bolla Pittaluga et al., 2015). On the other hand, it has been recognized that
56 seasonal variations of river discharge play an important role on the morphological development
57 of estuaries (e.g. Cooper, 2002; Savenije, 2005; Shaw and Mohrig, 2014; Zhang et al., 2016).
58 Recently, Hoitink et al (2017) proposed a conceptual model that in the case of a near-equilibrium,
59 sediment import during low flows can balance sediment export during high flow over a seasonal

60 cycle. It would be valuable to offer a better illustration of such concept, using a time series of
61 morphological data from a real estuary.

62 Sediment deposit, one of the most important morphological features within an estuary,
63 can form when the estuary received sufficient sediment supply (Dyer, 1995; Dalrymple and Choi,
64 2007; Gao and Collins, 2014). One typical example is the large subaqueous deposit in the upper
65 and middle reaches of the Qiantang Estuary, China. It starts at about 80 km from the mouth,
66 extends by about 130 km longitudinally, and has a height of 10 m above the baseline at the top of
67 the deposit (Fig. 1). Based on sedimentological surveys, it has been revealed that the sediment of
68 this large sedimentary system is from the adjacent Changjiang River (Chien et al., 1964; Chen et
69 al., 1990; Zhang et al., 2015). Recent modeling by Xie et al (2017a) found that the deposits
70 would grow unlimitedly under normal discharge condition due to the continuous sediment import
71 by flood dominance, and the growth can be constrained by high discharge. Xie et al (2017b) also
72 analyzed the morphological response of the Qiantang Estuary-Hangzhou Bay system to the
73 reduction of sediment load from the adjacent Changjiang Estuary and the large-scale
74 embankment within the estuary. However, few field data have been reported on the
75 morphological equilibrium, leaving a gap between the sediment transport and morphological
76 evolution because of the lack of observed hydrological data.

77 The Qiantang Estuary is strongly influenced by the river flood events and tidal bore. In
78 addition, the estuary is mainly composed of fine sediment that can be easily resuspended and
79 transported. As a result, the estuary is characterized by active morphological changes on seasonal
80 and inter-annual time scales. In this study, we analyze the seasonal and long-term

81 morphodynamic evolutions of the bar in the Qiantang Estuary, quantify the roles of the flood
82 events and the tidal bore and explore the underlying physical mechanisms for the dynamic
83 equilibrium.

84 2. Study area

85 The Qiantang Estuary is located on the coast of the East China Sea (Fig.1a). It is 282-km
86 long convergent estuary, with the width decreasing from 98.5 km at the mouth to less than 1 km
87 at the landward end. The upper 75 km reach from Fuchun power station (FPS) to Zakou is
88 dominated by river flow, the middle reach of 122 km (from Zakou to Ganpu) is controlled by
89 both the river flow and tides, while the lower reach of 85 km (downstream of Ganpu), also well
90 known as Hangzhou Bay, is dominated by tidal currents (Han et al., 2003). The middle and upper
91 reaches of the estuary is overwhelmed by a large longitudinal sediment deposit that elongated
92 from Zapu in the middle of Hangzhou Bay to about 130 km upstream. The bed level rises
93 gradually from 10 m below mean sea level (MSL) to 1 m above MSL and then lowers to more
94 than 10 m below MSL (Fig. 1b).

95 The tidal wave deforms rapidly landward due to estuarine convergence and shallowing
96 water depth. The mean tidal range increases upstream from about 3.2 m at the mouth, with the
97 maximum of 6 m at Ganpu, and then gradually decreases landward. The tidal wave evolves into
98 a tidal bore at Yanguan section. It is the largest in the world, with the averaged bore height being
99 1-2 m and the maximum exceeding 3 m (Bartsch-Winkler and Lynch, 1988; Pan et al., 2007;
100 Chanson, 2012).

101 The annual mean discharge of the Qiantang River is 952 m³/s. Due to the monsoon climate,
102 the river discharge shows a clear seasonal variation: the low discharge occurs from August to
103 next March and the high discharge occurs from April to July. It also varies on the inter-annual
104 time scale, with sometimes continuous high or low flow years (Han et al., 2003).

105 Sediment in the Qiantang Estuary is mainly composed of fine and well-sorted silt and clay,
106 with the median grain size between 20 to 40 μm, mainly dispersed from the adjacent Changjiang
107 Estuary (Milliman et al., 1985; Chen et al., 1990).

108 Since the 1960s, a large-scale coastal embankment in the QE has been carried out for the
109 purpose of flood defense, land requirements, etc.. Up to date, more than 1000 km² land has been
110 reclaimed and the width of the estuary has been largely narrowed, especially at the middle reach,
111 i.e., between Zakou and Ganpu (Fig. 1a).

112 3. Data and analysis

113 The bathymetry in this reach has been investigated in every April, July and November
114 since the 1980s, representing the periods before and after flood season and low river discharge of
115 the year. During each bathymetric investigation, the bed elevation along 60 cross-sections
116 covering the middle Qiantang Estuary was observed using an Odom Hydrotrac echo-sounder.
117 The error of the measured bed level is 0.1 m, and a global positioning system (GPS) by Trimble
118 was used that gave the positioning error within 1 m. After each investigation, the volumes below
119 multi-year averaged high water level (MHL) between the cross-sections were calculated. In this
120 contribution, we collect the volume data of the sections Zakou-Yanguan (ZY) and

121 Yanguan-Ganpu (YG), as well as the monthly river discharge from FPS since 1981, in order to
122 provide a comprehensive picture of the inter-annual and seasonal changes of the inside bar.

123 A detailed hydrographical survey was conducted during 9-17th October, 2015, at YG01
124 station located at the Yanguan section, where the tidal bore is strongest (Fig.1a). The flow
125 velocity was measured by an Acoustic Doppler Current Profiler (ADCP), and SSC was measured
126 using an Optical Back Scatter (OBS). The OBS instrument was calibrated against water samples
127 collected at the same site. Because both flow velocity and SSC increase drastically at the bore
128 arrival, the records was at one minute intervals in the hour around the bore arrival, and half an
129 hour in the rest of the tidal period. No extreme conditions like flood events or storms occurred
130 during the survey.

131 Furthermore, the daily river discharge from FPS and the detailed bathymetrical data in
132 April, July and November in 2015 at the Zakou-Ganpu reach, were collected in order to relate
133 the short-term hydrodynamics to long-term bathymetrical changes. The digital elevation models
134 (DEM) were reconstructed by interpolation of the data using the Surfer software package,
135 making use of the Kriging interpolation technique, which has been widely used in previous
136 studies (e.g. [van der Wal and Pye, 2002](#); [Blott et al., 2006](#); [Dai et al., 2014](#)). Spatial deposition
137 and erosion patterns and associated volume changes were calculated by subtraction of the DEMs.

138 4. Results

139 The volumes of ZY and YG sections are characterized by seasonal and inter-annual
140 variations (Figs. 2a and 2b). Over ZY section, the volume in July is apparently larger than that in

141 April, and the volume in November is clearly smaller than in July and a little larger than in April.
142 The mean values since 1981 in April, July and November are 294, 364 and $312 \times 10^6 \text{ m}^3$,
143 respectively. Moreover, the volumes in wet years (1987-1999 and 2010-2016) are larger than in
144 dry years (1981-1986 and 2003-2009), by about 1.5 times on average. The volume in July at the
145 ZY section correlates well with the mean river discharge during April-July (Fig. 2c):

$$146 \quad V = 7.57Q^{0.54} \quad (1)$$

147 in which V is volume in 10^6 m^3 , Q is river discharge in m^3/s . The correlation coefficient is 0.91,
148 indicating the river flow dominance on the morphology during the high discharge season.

149 The volume over the YG section has a decreasing trend which is related to the large-scale
150 embankment in the Qiantang Estuary in the last decades (Xie et al., 2017b). Overall, the seasonal
151 variation of the volume at YG section is opposite to that of ZY section, with the mean volumes
152 3304, 3173 and $3285 \times 10^6 \text{ m}^3$, in April, July and November respectively, indicating the active
153 sediment exchange between the two sections. The maximum volume change in the wet season of
154 1995 over ZY and YG sections can be 200 and $400 \times 10^6 \text{ m}^3$, respectively. It should be noted that
155 the volume changes of the ZY and YG sections are not always comparable because there exists
156 active sediment exchange between the YG section and the lower estuary, i.e., the Hangzhou Bay
157 (Chen et al., 1990; Han et al., 2003; Xie et al., 2017b).

158 The hydrodynamics at YG01 station during spring and intermediate tides in October 2015
159 were characterized by the tidal bore (Fig. 3). Upon the arrival of the bore, the water level
160 increased by about 3 m within one minute. The velocity reversed from ebb current of less than

161 1.5 m/s to flood currents of 2.7 m/s in one minute and the maximum of 4.2 m/s was reached
162 within half an hour. The SSC increased from less than 2 to about 15 kg/m³ and the sediment flux
163 reversed from less than 60 kg/s/m seawards to more than 300 kg/s/m landwards. The sediment
164 fluxes during ebb tides were comparable to that of the adjacent Changjiang Estuary, which is
165 normally less than 50 kg/s/m (Milliman et al., 1985; Su and Wang, 1986; Li et al., 2011); but the
166 sediment fluxes under the tidal bore were clearly much larger than that of Changjiang Estuary,
167 because of the large current velocity and associated SSC. During neap tides, undular bores were
168 present and the capacity of sediment transport decreased significantly. The flood and ebb
169 sediment fluxes were large, being about 900 t and 500 t per m during spring tides, respectively.
170 The sediment fluxes during flood or ebb tides correlated well with the tidal range at Ganpu
171 (Fig.3c). Overall, the net sediment transport was distinctly directed landward during spring and
172 intermediate tides, whereas it was seaward during neap tides. In the spring-neap tidal cycle, the
173 net landward sediment flux per m width was about 2000 t, indicating distinct accretion would
174 occur in the dry season.

175 Figs. 4a and 4b illustrate the erosion and deposition patterns during April-July and
176 July-November, 2015. Only one river flood event occurred in June, with the peak discharge
177 being 12.600 m³/s (Fig. 4c). Overall, the bed level changes were consistent with the numerical
178 model of Xie et al (2017a) that during high flow, the upper part was eroded whereas the lower
179 part was deposited. Clearly, the measured bathymetries provide more information on the spatial
180 distribution of bed level changes. Despite the short duration of the river flood (about 10 days),
181 the bed upstream of Yanguan was seriously eroded. The erosion mainly occurred around the

182 thalweg, and the maximum erosion was more than 5 m. The volume over ZY section increased
183 from 301×10^6 to $424 \times 10^6 \text{ m}^3$, indicating an erosion of $123 \times 10^6 \text{ m}^3$. The eroded sediment was
184 transported seaward and deposited in the reach downwards of Yanguan, i.e., YG section and the
185 Hangzhou Bay. The volume over YG section decreased from 2762×10^6 to $2692 \times 10^6 \text{ m}^3$,
186 indicating a decrease of $70 \times 10^6 \text{ m}^3$. The bed level changes from July to November were
187 opposite: sedimentation of $46 \times 10^6 \text{ m}^3$ at ZY section and erosion of $25 \times 10^6 \text{ m}^3$ at YG section.

188 Assuming that the observed data during October 2015 can represent the period between
189 July and November, and considering that the width at Yanguan section is about 2.5 km, the
190 cumulative landward sediment transport from July to November was about $80 \times 10^6 \text{ t}$. Given that
191 the dry density of the sediment is 1650 kg/m^3 , the net sedimentation was about $48 \times 10^6 \text{ m}^3$,
192 consistent with the volume change based on the DEM comparison.

193 5. Discussion and conclusions

194 Results in this study support the conceptual model of [Hoitink et al \(2017\)](#) who proposed
195 that seasonal variations of river flow can play an important role on the estuarine morphodynamic
196 equilibrium. Under usual flow discharge conditions, sediment transport is directed landwards.
197 The role of the big tidal bore on the landward sediment transport is not intrinsically different from
198 the flood dominance in other estuaries ([Dronkers, 1986](#); [Wang et al., 2002](#); [Bolle et al., 2010](#)).
199 On the other hand, the capacity of sediment transport of the bore is much larger than normal tidal
200 currents. The flood current velocities during spring and intermediate tides can be more than 4
201 m/s, about twice of the maximum velocity of ebb tides, which results in extreme flood

202 dominance. Furthermore, the sediment in the estuary is composed of silt and clay that can be
203 easily resuspended and transported, with a critical velocity for erosion of 0.3-0.4 m/s (Chien et
204 al., 1964; Han et al., 2003). When the bore arrives, SSC also increases drastically and hence the
205 sediment flux per unit width during flood tides is very large, up to 300 kg/s/m. Whereas the
206 current velocity and SSC during ebb tides are much less, and the sediment flux during ebb is less
207 despite the much longer ebb duration. As a result, the net sediment transport over a tidal cycle is
208 directed landward. The river flood events produce remarkable erosion. The larger the river
209 discharge, the more sediment can be transported seaward. In a seasonal timescale, the
210 morphology in the estuary is apparently deviated from its equilibrium; but within a whole year,
211 the two opposite processes can be balanced and subsequently a dynamic equilibrium can be
212 maintained.

213 One of the most striking features of Qiantang Estuary is bed erosion during river flood
214 events, especially in the upper reach of the estuary (Fig. 4b). The serious bed degradation can be
215 explained by the fact that the discharge during a river flood event is much larger than the normal
216 discharge which is around 1000 m³/s (Chen et al., 2006; Xie et al., 2017a). In previous studies,
217 the cross-sectional area and the cross-sectionally averaged depth, have been found as a power
218 function of the river discharge (Leopold and Maddock, 1953; Smith, 1974; Han et al., 2009).
219 Considering that the volume is a function of cross-sectional area and the length, it is reasonable
220 that the volume adjusts in a power relation with the changes of river discharge, as fitted by Eq.(1).
221 Such formula provides a simple tool to predict the bathymetry of the estuary, given the river
222 discharge is available.

223 In general, river flood induces active channel morphodynamics such as bank erosion and
224 point bar deposition due to increased discharge and enhanced sediment concentrations (e.g. [Mutti](#)
225 [et al., 1985](#); [Dalrymple and Choi, 2007](#)). However, such channel morphodynamics is apparently
226 not the case in the present Qiantang Estuary. Instead, the bed level rises and falls in response to
227 sediment import and export. This is because the estuary has been significantly influenced by
228 human intervention such as coastal embankments and the construction of unerodible artificial
229 levee (Fig. 1a). Actually, before the large-scale embankment in the estuary, pronounced lateral
230 migration of the thalweg occurred frequently, especially at the bends like Qibao and Jianshan
231 ([Chien et al., 1964](#)). This is mainly caused by the inconsistency of flood and ebb current routes,
232 which would adjust according to the seasonal changes of the relative strength of river flow to
233 tidal current.

234 6. Conclusions

235 The big dataset obtained from long-term bathymetry and hydrological survey in the
236 Qiantang Estuary provided a quantitative illustration of how a dynamic equilibrium is maintained
237 over a seasonal and inter-annual scale. The active morphological behaviors are controlled by
238 river flood events and the extreme flood dominance (the tidal bore). The tidal bore transports a
239 large amount of sediment landward, causing accumulation during normal river discharge periods.
240 Conversely, river flood events erode the bed severely. Furthermore, a power function was built
241 between the averaged river discharge in high flow season and the channel volume of the upper

242 part. The estuary has also been significantly influenced by the large-scale embankment in last
243 decades, which constrained the lateral migration of thalweg and point bar deposition.

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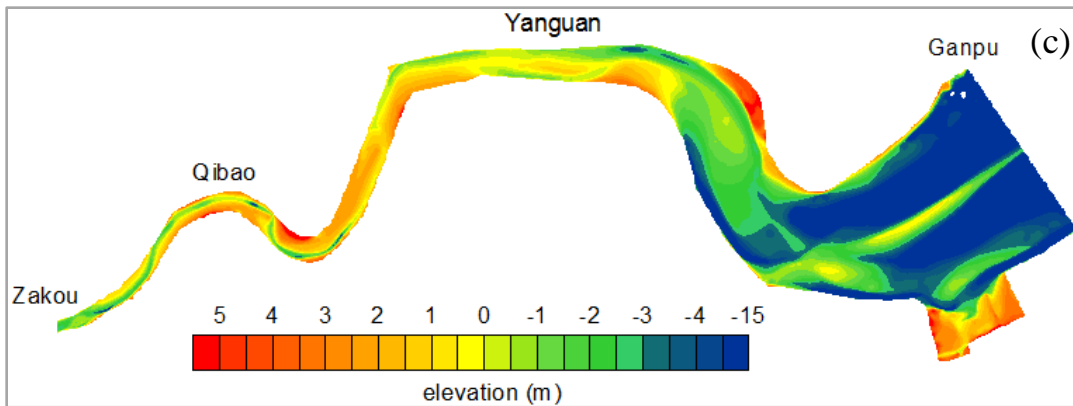
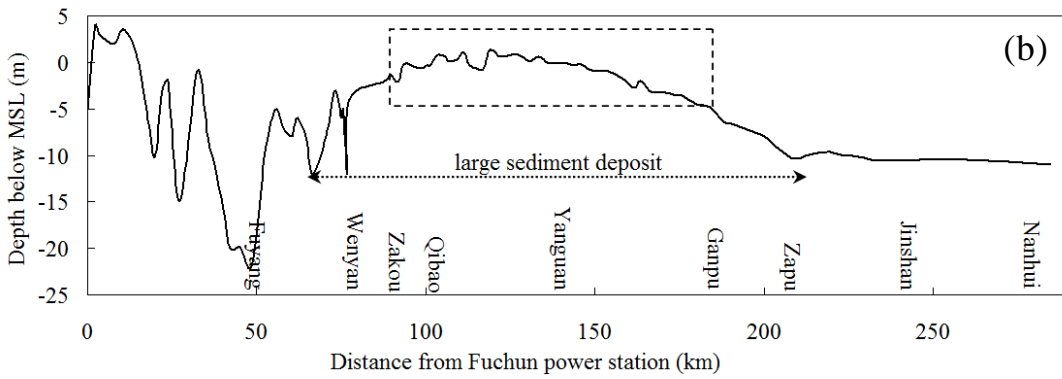
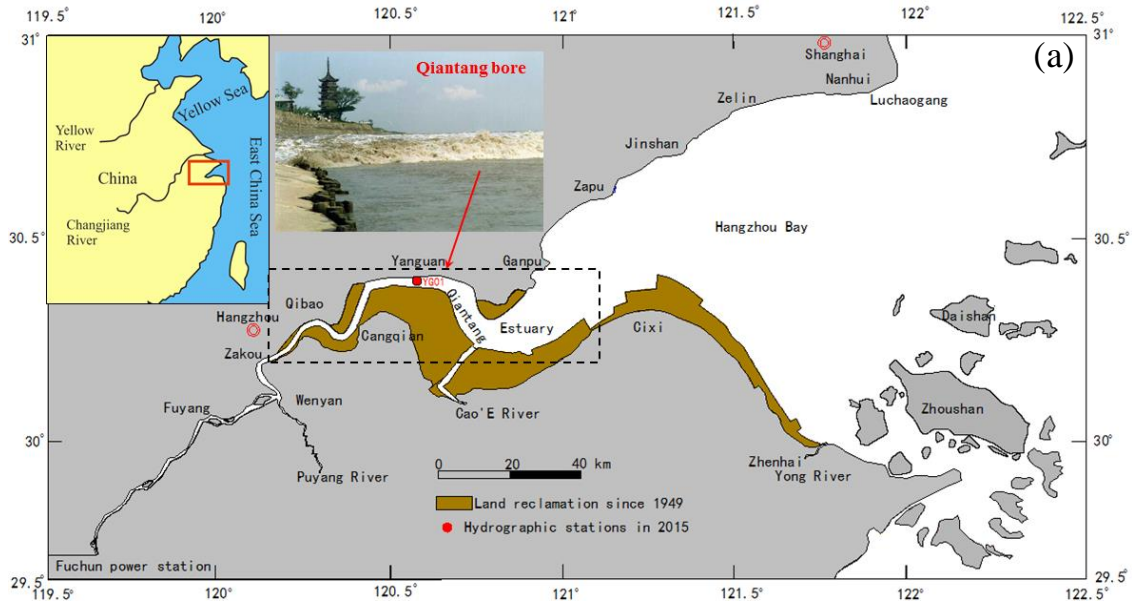
330 **FIGURE CAPTIONS**

331 Fig.1. (a) Location of the Qiantang Estuary, in which YG01 denotes the hydrographic
332 observation station in October, 2015. (b) The lateral-averaged longitudinal bathymetry along the
333 estuary measured in 2014. (c) Bathymetry of the estuary measured in April, 2015. Fig. 1a and 1b
334 were modified from Xie et al., 2017a.

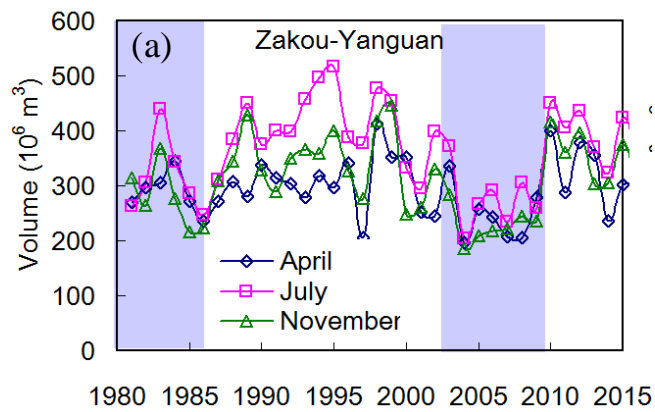
335 Fig. 2. (a, b) The volumes of ZY and YG sections in every April, July and November since 1981.
336 The shades denote the continuous dry years. (c) Relationship between the volume of ZY section
337 in July and the average river discharge from April to July. Data in April of Fig. 2A and 2B from
338 Xie et al. (2017b).

339 Fig. 3. (a, b) Time series of tidal level, depth-averaged current velocity, SSC and sediment flux at
340 YG01 station during 9-17th October, 2015. (c) Relationship between flood and ebb sediment
341 fluxes and tidal range at Ganpu station. (d) The cumulative and net sediment fluxes during the
342 measurement.

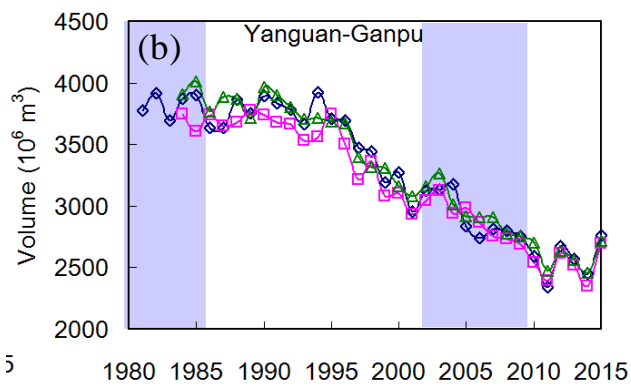
343 Fig. 4. (a, b) Bed erosion and accretion patterns from April to July and from July to November in
344 2015. (c) Time series of daily river discharge from FPS in 2015.



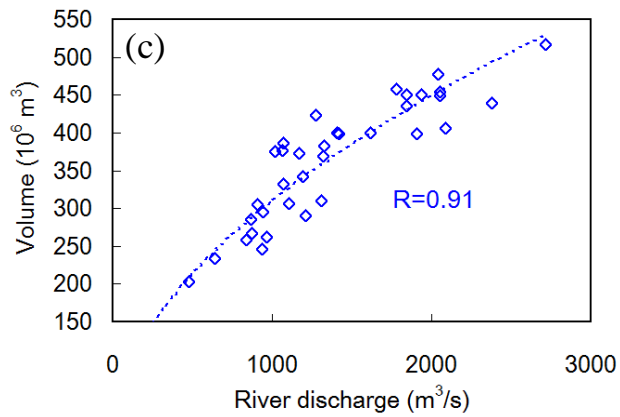
348 **Fig. 1.**



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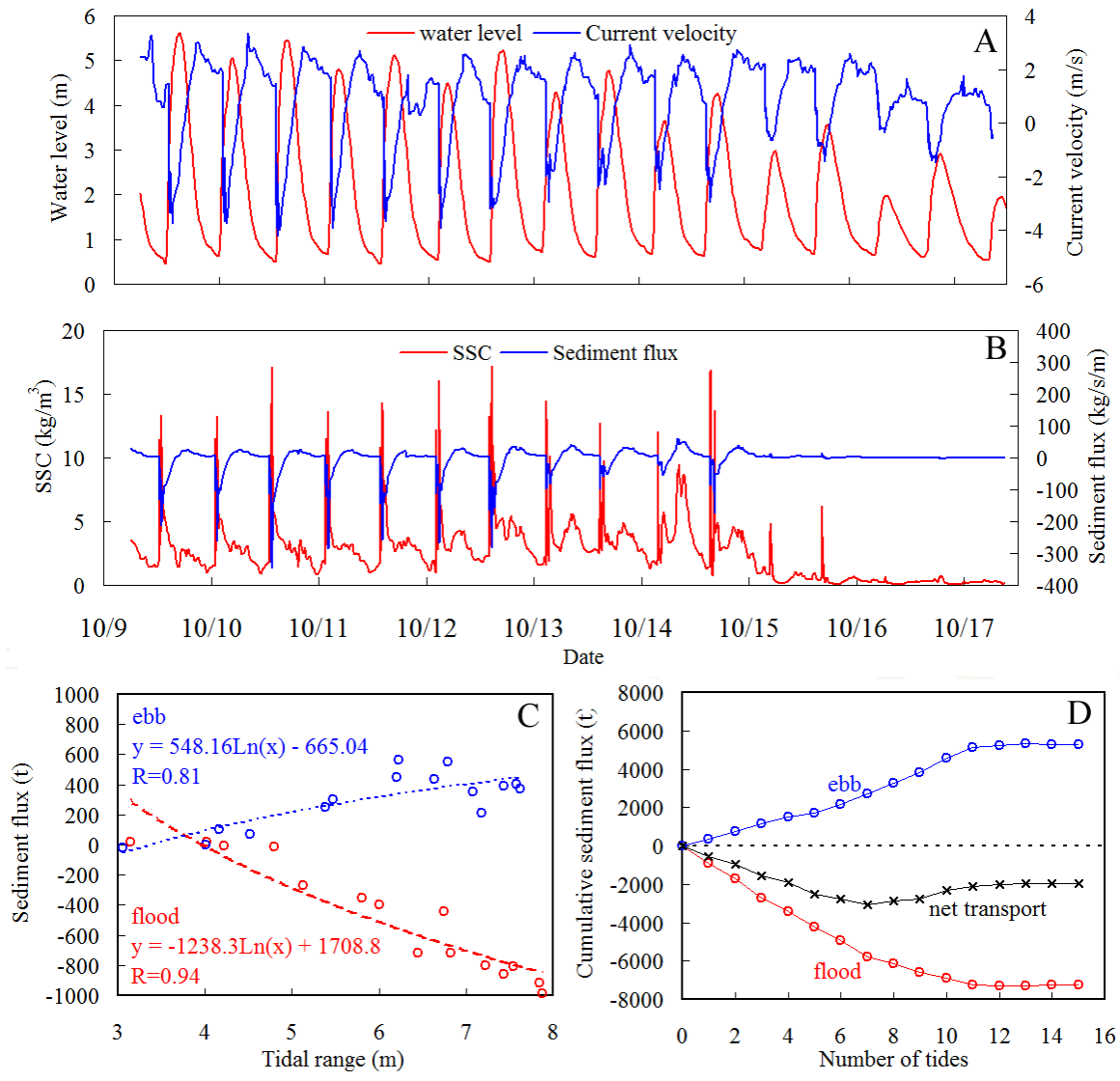


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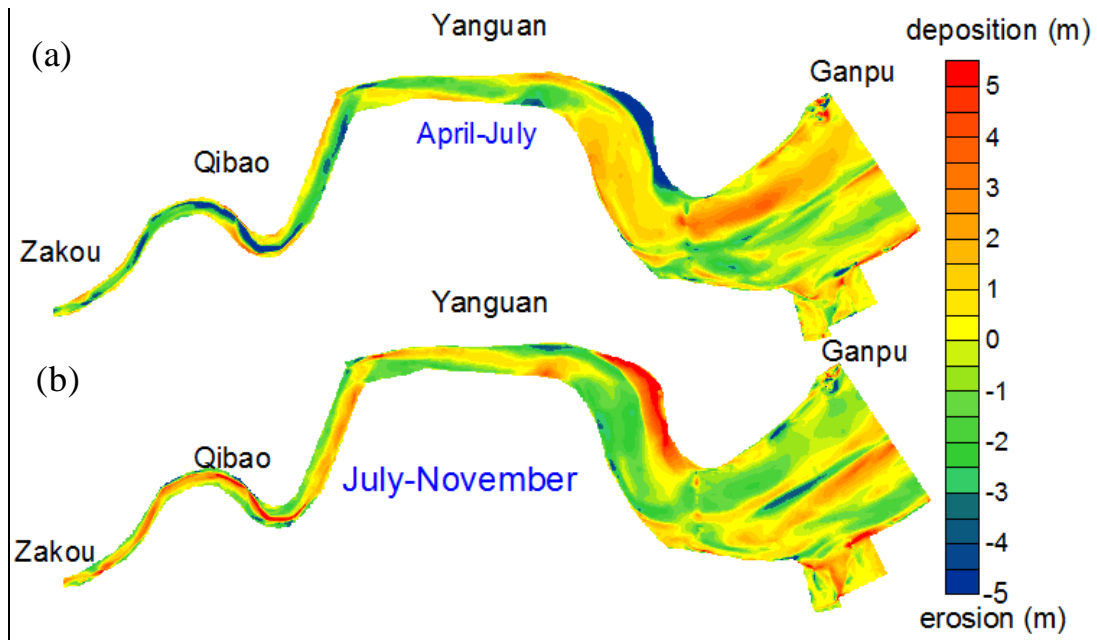
352 **Fig. 2.**



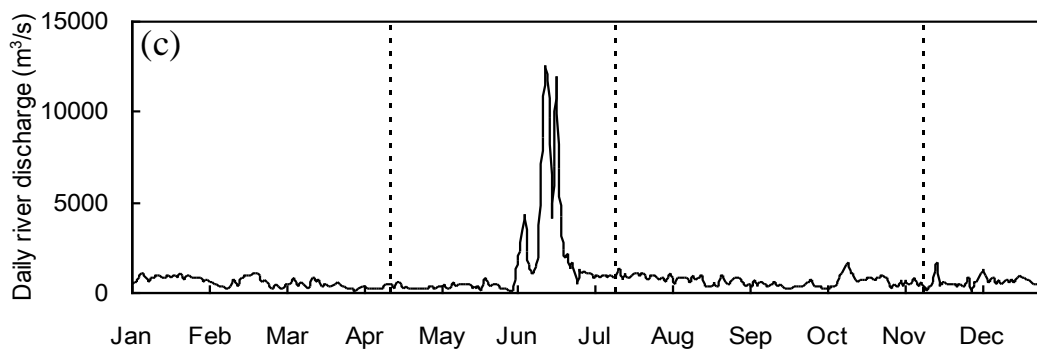
353

354 **Fig. 3.**

355



356



357 **Fig. 4.**