Sediment dispersion pattern off the present Huanghe (Yellow River) subdelta and its dynamic mechanism during normal river discharge period

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ABSTRACT

Hydrological observations were conducted synchronically along three transects in the southeast, middle and northeast off the present Huanghe (Yellow River) subdelta during normal-discharge (approximately 200 m³ s⁻¹) period on August 8–13, 2003. Suspended sediment fluxes and dispersion patterns off the present Huanghe subdelta were studied based on the hydrographic data collected in these surveys. Along each survey transect, tidal shear fronts were identified that in combination with the tidal currents were the dominant factors controlling the pattern of sediment dispersal. Most of the river-laden suspended sediment from the river mouth was transported via hypopycnal flow and was limited within the 5 m isobath off the mouth due to the barrier effect of the tidal shear front and the weak river flow. In northern and southern areas off the subdelta, the sediment fluxes at stations farther from the coast were much higher than those at the nearshore ones, indicating that the river-laden sediments were transported to north and south offshore via deeper water areas at both sides of the river mouth. The tidal shear fronts revealed in the northern and southern nearshore areas of the subdelta, jointly with tidal currents barred the sediment transport from offshore to nearshore. This resulted in offshore sediment deposition on the northern and southern parts of the subaqueous subdelta, rather than in the nearshore area, thus forming nearshore erosion and offshore accumulation areas, respectively.

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1. Introduction

Worldwide, approximately 10–20 billion metric tons of fluvial sediment are transported into the ocean through rivers every year (Milliman and Syvitski, 1992). Most of these river-delivered sediment deposits in river–delta systems, which are vital for delta-coast construction and for environmental preservation (Chen et al., 2007a,b). With a drainage basin area of 794 712 km² and a total length of 5464 km in northern China (Fig. 1a), the Huanghe (Yellow River) has historically had a low runoff (<60 x 10⁹ m³ yr⁻¹), but one of the largest sediment loads (10.8 x 10⁹ t yr⁻¹) of any river in the world (Milliman and Meade, 1983). The Huanghe has been discharging into the Bohai Sea since 1855, forming the modern Huanghe delta with an accretion of more than 20 km² yr⁻¹ (Pang and Si, 1980). In total, eleven major shifts of the lower river course occurred between 1855 and 1976 due to rapid channel siltation, resulting in the formation of 8 subdeltas (Pang and Si, 1979; Fan et al., 2006). The latest major shift occurred in 1976 and formed the present Huanghe subdelta (Fig. 1b).

Suspended sediment dispersion in subaqueous delta in the form of hypopycnal and hyperpycnal flows has been studied in detail since the 1980s (Wiseman et al., 1986; Wright et al., 1986, 1988, 1990; Li et al., 1998; Wang et al., 2007b). Approximately one third of the suspended sediment delivered from the Huanghe is deposited around the subaerial delta, while the other two-thirds is transported to coastal areas and the Bohai Sea (Pang and Si, 1980; Wu et al., 1994). Approximately 70% of sediment transported to coastal areas is deposited in the subaqueous delta region no more than 15 km away from the mouth of the river (Qin and Li, 1983). However, only 1% of the Huanghe sediment discharge is transported to the Yellow Sea through the southern part of the Bohai Strait (Martin et al., 1993). The suspended sediment delivered from the mouth of the Huanghe is transported westward along the coast of Laizhou Bay (Jiang et al., 2000, 2004).

Shear fronts, interfaces between two bodies of water with opposing flow directions or significantly different velocities, have been observed in many estuaries (Nunes and Simpson, 1985; Huzzey and Brubaker, 1988; Zhu, 1995; Li et al., 2001; Wang et al., 2006b). The tidal shear front off the mouth of the Huanghe was first...
The annual water and sediment discharges from the Huanghe into the sea were recorded at the Lijin Gauge (some 100 km upstream from the river mouth, Fig. 1a) and have been drastically reduced from 25.1 km$^3$ to 634 Mt observed between 1976 and 1996–7.49 km$^3$ (29.8% of the previous value) and 150 Mt (23.7%) during the period from 1997 to 2003 due to extensive human activities (Wang et al., 2006b, 2007b); and 3) The Huanghe water and sediment discharges into the sea have been controlled since 2000 by the operation of the Xiaolangdi Reservoir, the largest reservoir in the mainstream, through the Project of “Artificial Regulation of the Huanghe Water and Sediment” (Wang et al., 2005; Yang et al., 2008). This project determined that high water and sediment discharges into the sea are regulated, and only occur once or twice a year for periods of approximately 15–30 days to scour the riverbed and transport a relatively large amount of sediment into the sea. Water flow into the sea is kept at low levels (<500 m$^3$ s$^{-1}$) for most of the year (e.g., 360 days in 2001). As a result, low water flow with low sediment discharge into the sea is now the dominant and normal hydrographic regime for sediment transport off the present subdelta and the low water discharge in previous publications corresponds to the normal water discharge in this paper. These recent changes have altered the boundary conditions and the seasonal allocation of water and sediment in a year, which have significant impacts on the dispersion of sediment off the present subdelta.

Most previous studies have focused on the flood season of the Huanghe when sediment discharge is high and a unique sediment hypopycnal flow from the river mouth to the sea is observed (Wright et al., 1986, 1988, 1990; Li et al., 1998; Wang et al., 2007b). Less attention has been paid to the sediment dispersion pattern during normal water flow or to the dispersion pattern off northern and southern parts of the present subdelta. No studies have yet demonstrated the sediment dispersion process or have quantitatively assessed the general pattern of sediment dispersion in the whole area off the present Huanghe subdelta.

This paper demonstrates suspended sediment transport processes, fluxes, and the mechanism and dispersion pattern of sediment off the present Huanghe subdelta during normal discharge period through the new river course. Observations are based on hydrographic data collected during synchronic multistation hydrographic time-series surveys along three transects in the southeast, middle and northeast off the present Huanghe subdelta in August, 2003. The geomorphological response of the subaqueous delta to the suspended sediment dispersion is discussed based on multi-year observations of bathymetry over the whole delta region.

2. Study area

The Bohai Sea, a receiving basin of the Huanghe sediment, is a semi-enclosed shallow shelf sea with an average depth of approximately 18 m (Wang, 1996). The Huanghe delta composed of 8 subdeltas is located to the west of the Bohai Sea. The tidal regime is dominated by an irregular semi-diurnal tide with an average tidal range of 0.6–0.8 m at the river mouth area that increases both southwards and northwards, reaching 1.5–2.0 m in the south at Laizhou Bay and Bohai Bay. The tidal currents have an average speed of 0.5–1.0 m s$^{-1}$, and are in parcelling to the coast and flow southward during the flood tide, move northwards during the ebb tide. The tidal currents have a clockwise current rotation during the transitional period of the tidal phase. The flood tidal duration is 60–90 min longer than that of the ebb tide during one tidal cycle (Cheng and Cheng, 2000). The waves off the Huanghe delta vary strongly by season and are generated by local winds in the Bohai.
Sea. The prevailing southerly waves in the winter are stronger than the dominant northerly waves in the summer. The surface residual currents, driven by the winds, move southward in the summer and northward in the winter (Zhang et al., 1990).

The surface sediment of the seabed in the study area is generally fine. The main compositions of the sediment are silt and clayey silt with a grain size of less than 0.01 mm (Qin et al., 1985). Conversely, sediments in the river mouth on the platform and delta front areas are coarser and include some sand (Bornhold et al., 1986). The suspended sediment delivered from the Huanghe is mainly transported northwest by ebb currents (Wiseman et al., 1986).

The Huanghe water and sediment discharges into the sea have a significant seasonal variability due to the effects of the summer monsoon. More than 60% of water and sediments are discharged into the sea during the flood season (Wang et al., 2007b). The water is highly turbid in the river mouth with an average suspended sediment concentration of approximately 25 g l\(^{-1}\) (Wright and Nittouer, 1995) and a peak value of approximately 200 g l\(^{-1}\) (Ren and Shi, 1986), forming prominent hyperpycnal flows in the bottom layer of the water column during the flood season. However, since the 1970s, the water and sediment discharges decreased dramatically due to a reduction of precipitation and construction of dams within the drainage basin (Wang et al., 2006a, 2007a), resulting in infrequent hyperpycnal flows, even during the flood season.

3. Data and methods

Synchronous time-series hydrographic surveys of multiple stations along three transects in the southeast, middle and north-east off the present Huanghe subdelta (Fig. 1b) were conducted from August 8–13, 2003 during the low-discharge period when the water and sediment discharges at Lijin Station were approximately 20 m\(^3\) s\(^{-1}\) and 200 kg s\(^{-1}\), respectively. Observations were conducted under calm weather conditions with a maximum wind speed of approximately 3 m s\(^{-1}\). Five stations were surveyed in the southeast transect (B) and the middle transect (C), and four stations were surveyed in the northeast transect (A). Hydrographic data including current velocity, temperature and water depth were recorded, and water samples were collected for 25 h at each station in 1-h time intervals. Water samples of 500 ml were collected at three water layers, the surface and depths of 0.6 and 0.9, and the salinity and suspended sediment concentrations (SSCs) were measured in the laboratory. The current velocities and temperatures were measured at the corresponding sampling layers using an LS25-1A propeller current meter and a high-resolution Aanderaa thermometer, respectively. A single frequency (208 ± 2 kHz) echo sounder bathometer was employed to record the water depth.

The salinity of the water samples was measured in the laboratory by a SYA2-2 salinometer using the Practical Salinity Scale. The water samples were filtered through pre-weighed paired micro-pore filters of 47 mm diameter with a pore diameter of 0.45 μm by pumping. The filters with sediments were washed three times with distilled water to remove the remaining salt, and dried at 60 °C before being weighed again using a high-resolution electronic balance. The suspended sediment concentrations (in g l\(^{-1}\)) were calculated from the final sediment weights and volumes of filtered water.

Bathymetric records of 36 offshore transects covering the area from the coast to the outer edge of the Huanghe subaqueous delta (at approximately the 16 m isobath) were collected in 1976 and 2003 to illustrate the deposition pattern of the present Huanghe subdelta. These bathymetric data were collected every two years by the Yellow River Conservancy Committee.

4. Results

4.1. Hydrodynamics and tidal shear front

4.1.1. Tidal currents off the present Huanghe subdelta

Based on the in-situ measurements, the mean surface tidal current velocities in the ebb and flood tidal phases were calculated using the method of Reiche (1938). The tidal currents off the present Huanghe subdelta are reciprocating flows. In the northeast and middle transects off the present Huanghe subdelta, the currents flowed southward during the flood tide and northward during the ebb tide (Fig. 2). The lowest tidal current velocities were observed at the two stations closest to the shore, A1 and B1 (Table 1). The mean current velocities in the ebb and flood tides at these stations were 21.9 and 24.5 cm s\(^{-1}\), respectively. The tidal currents at most stations in transect B, except for station B5, were flowing from west to east and differed from the north–south direction of the tidal currents at all stations along the northeast

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Fig. 2. Mean vectors of the tidal current velocities at the surface layer in each station during flood tides (a) and ebb tides (b). The arrows marked in grey indicate the predicted current directions based on the mean vectors of the tidal current.
transsects (A) and middle transect (C). During the flood tide, the currents flowed southward and turned southwest when passing the protrusion of the abandoned river mouth, Qingshuigou (station B5), where the mean current speed was 41.4 cm s⁻¹ and the azimuth was 192°. The currents changed direction further west at station B4 (28.9 cm s⁻¹/261.4°) and began flowing northwest at stations B3 (41.7 cm s⁻¹/282.4°) and B2 (33.3 cm s⁻¹/302.2°). However, the dominant direction of flow during the flood tide was southwest at station B1, where the mean velocity was 21.9 cm s⁻¹ and the azimuth was 223.8°. Thus, a swirling water mass was formed off the southern part of the delta due to the protrusion of the abandoned river mouth at Qingshuigou. During the ebb tide, the currents flowed southeastward off the southern part of the delta and turned northeastward at station B5 after passing Qingshuigou. The current then flowed northwest after passing the current river mouth, continuing northwest all the way to the northern part of the delta (Fig. 2).

4.1.2. Tidal shear front off the present Huanghe subdelta

A tidal shear front was recorded off the abandoned Qingshuigou river mouth in 1994 and 1995 (Li et al., 1994; Wang et al., 2007b). A front was also observed along the three offshore transects in 2003. The tidal shear front was detected in our surveys from the surface to the bottom of the water column, and was most obvious in the surface layer. Accordingly, we used the records of the tidal currents in the surface layer to show the evolution of the tidal shear fronts along the three transects (Fig. 3). The shear front along transect C off the present Huanghe river mouth occurred in the first hours of both the flood and ebb tidal phases. Two types of tidal shear front were clearly identified, inner-ebb-outer-flood type (IEOF) and inner-flood-outer-ebb type (IFOE). The IEOF type of shear front occurred at 19:00–21:00 on August 9 between stations C3 and C4 when the tidal currents at station C3 were ebbing (flowing northwest) while those at station C4 were flooding (flowing southeast; Fig. 3a). The front then moved seaward and was found between stations C4 and C5 at 21:00–22:00 on August 9. The IFOE shear front was recorded at 1:00–3:00 on August 10 between stations C3 and C4 when the tidal currents at station C3 were flooding while those at station C4 were ebbing. The front then moved seaward and disappeared at about 4:00 on August 10. Two types of tidal shear fronts occurred alternately within one tidal cycle. The movement of the tidal shear front indicated by our records agreed with the conclusion presented by Wang et al. (2007b). In addition, the total duration of the two types of tidal shear fronts off the Huanghe mouth was approximately 4–5 h, which was in agreement with previous studies (Wang et al., 2007b). The tidal shear front along transect A was also observed based on the current velocity records (Fig. 3b). It lasted 3–5 h during one tidal cycle and alternated between the two types of tidal shear fronts, moving from a shallow to a deep area, the same as along transect C. The front disappeared around station A3 at a water depth of approximately 13 m. Qiao et al. (2008) suggested that the tidal shear front off the river mouth was caused by a tidal phase gradient along the delta slope, and the topography, a steep slope, was the dominant factor causing the formation of the tidal shear front off the Huanghe mouth. Additionally, they concluded that the tidal shear fronts could be generated in both the region of the present river mouth and in the region of the abandoned Diaokou river mouth area due to the strong slopes in both of these areas (locations are shown in Fig. 1b). The tidal wave propagates southward from the area by the northern Huanghe delta (Shi and Zhao, 1985) and forms a tidal shear front by the abandoned river mouth area due to the tidal phase gradient along the delta slope. The tidal phase gradient still exists when the tidal wave propagates to the north of the Huanghe delta, and when the tidal shear front could occur along the east coast of the Huanghe delta but would not be limited to the area near the river mouth. Thus, the records of the tidal shear front in the northern part of the study area (along transect A) confirmed the numerical simulation results reported by Qiao et al. (2008). The tidal shear front along transect B occurred between stations B1 and B2, but was quite different from the fronts observed along transects C and A in two ways. First, the front in transect B only occurred during the flood tide and lasted through the whole flood tide (approximately 6 h in one tidal cycle), but did not occur during the first 2–3 h of either the ebb and flood tides as it occurred in transects A and C. Second, it did not occur at neighboring station B3 or at other stations further seaward, which means that it did not move from the nearshore area to the offshore area (Fig. 3c). We suggest that these differences arose as follows: the currents turned during the flood tide, changing from southwest to northwestward towards the southern coast after passing the protruding abandoned Qingshougou river mouth, and flowed through stations B4, B3 and B2 into the southern sea area next to the subdelta. This resulted in increased water levels in the area between the southern coastline and transect B. When the flood tidal currents oriented towards the coast and those flowing northwest reached the northwestern coast of Laizhou Bay, they were forced to turn southeast, flowing seaward from the nearshore area at station B1, following the local topography and the rising water level (Fig. 2). Thus, the current directions at station B1 were the opposite of those at station B2, resulting in the formation of a shear front between stations B1 and B2.

4.2. Suspended sediment dispersion along three transects off the present Huanghe subdelta

4.2.1. Suspended sediment dispersion off the river mouth along transect C

The salinity increased seaward along transect C. The lowest salinity values were recorded at stations C1 and C2, located in the river channel (shown in Fig. 1b), with a maximum value of approximately 1.0 during the whole tidal cycle, indicating that the river water dominated this part of the channel and that almost no salt water intrusion was occurring from the sea (Fig. 4a, b). The water was much more turbid in the river channel than in the Huanghe river mouth. The highest SSC value of approximately 1.3 g l⁻¹ was recorded at station C2 during slack water after the ebb.

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<tr>
<th>Station</th>
<th>Mean velocity</th>
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<td>Flood tidal phase</td>
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<td>Magnitude (cm s⁻¹)</td>
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<td>A1</td>
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<td>A3</td>
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<td>B5</td>
<td>41.4</td>
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a Consistency ratio varying from 0.0 to 1.0 indicates the dispersion of the tidal current direction. If consistency ratio is zero, the current directions follow a random distribution. If consistency ratio is 1.0, all the current vectors are in the same direction.
Fig. 3. A comparison of current vectors of tidal currents in the surface layer along transects C (a), A (b) and B (c). The slanting lines represent the vectors, with the length of the lines indicating the current magnitude and the angle (in degrees) indicating the direction of the current (N = 0°). The marked shadow areas indicate the periods for the formation of tidal shear fronts, and the widths of the shadow areas correspond to the durations of tidal shear fronts.
The SSCs ranged from 0.1 to 0.7 g l\(^{-1}\) at station C1, much lower than those at station C2. The structures of the water masses at two stations in the river channel were fairly uniform throughout the survey. The salinity increased rapidly at station C3 and varied periodically from 13.0 to 30.0 with the tidal phase. Observations with lower salinity values and evident stratification were recorded at the end of the ebb tides and at the beginning of the flood tides after slack water, e.g., at 1:00–4:00 and 12:00–15:00 on August 9 (Fig. 4c). The SSCs at station C3 decreased rapidly to 0.01–0.4 g l\(^{-1}\), with lower salinity values, indicating that the river effluent could reach station C3 at the end of ebb tides and during the early flood tides. The temporal variation of the salinity at station C4 was almost the same as that at station C3, although higher salinities (25.0–32.0) were observed at this station in comparison to station C3 (Fig. 4d). A highly stratified water column with a low salinity value was also detected in the first hours of the flood tides. The SSCs at station C4 decreased further, reaching values of 0.01–0.1 g l\(^{-1}\) varied as those at station C3. The salinity at station C5 (30.0–32.0) was the highest among all stations during the whole tidal cycle, with the smallest fluctuations observed at the surface and bottom layers. The water column at this station was not as stratified as at station C4 (Fig. 4e).

The SSCs at station C5 ranged from 0.01 to 0.06 g l\(^{-1}\), values that were much lower than those at other stations, implying that the Huanghe effluent has little impact on the variation of SSCs at station C5.

4.2.2. Suspended sediment dispersion in the northeast of the present Huanghe subdelta along transect A

The salinity along transect A increased seaward from station A1 to A4. The salinity was lower at station A1 than at the other stations along transect A throughout the entire tidal cycle (Fig. 5). Salinity values varied between 31.0 and 32.0 without any evident periodic variation with the tidal phase, while the SSCs in flood tides were slightly higher than those in the ebb tides. For example, the SSCs during the flood tide between 12:00–18:00 on August 8 were slightly higher (0.03–0.34 g l\(^{-1}\)) than those in the ebb tide between 18:00–1:00 on August 9 (0.01–0.14 g l\(^{-1}\)), indicating that the river effluent carried by the ebb currents had little impact on the water at station A1 (Fig. 5a). The salinity at station A2 seemed to vary slightly with the tidal phase, decreasing during ebb phases with a minimum value of approximately 31.5 and increasing during flood tides with a maximum value of approximately 32.8. The SSCs at station A2 ranged from 0.002 to 0.02 g l\(^{-1}\), and were much lower than those at station A1 (Fig. 5b). Variations in the salinity at station A3 were similar to those at station A2 (Fig. 5c). However, the pattern of SSC variation at station A3 seemed to be quite different from that at station A1, as indicated by the high turbidity in both the surface and bottom layers at station A3 during ebb tides (e.g., 19:00–23:00 on August 8 and 05:00–10:00 on August 9) compared to those observed during flood tides (Fig. 5a and c). The bottom SSC even exceeded 0.45 g l\(^{-1}\) at 6:00 on August 9 (ebb tide) at station A3. At station A4, the salinity fluctuated slightly and was higher than the salinity values observed at the other stations throughout the tidal cycle, whereas the SSCs were much lower than those at stations A1 and A3 (Fig. 5d).

4.2.3. Suspended sediment dispersion in the southeast of the present Huanghe subdelta along transect B

For the salinity of five stations along transect B, the salinity at station B1 was lower than that at the other stations, and was found to decrease during ebb tides and increase during flood tides.
However, the salinity at the other four stations had an opposite behavior, decreasing during flood tides and increasing during ebb phases (Fig. 6b–e). Station B2 had the highest salinity along transect B in the surface, middle and bottom layers during the whole tidal cycle, with a small fluctuation of 32.5–33.1. The SSCs at stations B1 and B2 were much lower than those at the other stations along transect B, ranging between 0.005 and 0.05 g l$^{-1}$ (Fig. 6a, b). The salinity decreased from stations B2 to B5 with the enhanced fluctuation, while the SSCs increased significantly at station B3 (e.g., 19:00–23:00 on August 11 and 3:00–6:00 on August 12) and ranged from 0.02 to 0.2 g l$^{-1}$ (Fig. 6c). SSC values then decreased slightly at station B4, but were much higher than...
those at stations B1 and B2 (Fig. 6d). The water at station B5 had a salinity range of 30.0–32.5 and was more turbid, with a peak SSC value of approximately 0.4 g l\(^{-1}\) in the surface and bottom layers, higher than the peak SSC values at the other stations (Fig. 6e). The water column structure along transect B was quite uniform during the 25 h survey.

4.3. Sediment fluxes along three transects off the present Huanghe subdelta

The sediment flux at each station was calculated based on the SSC value and the corresponding current velocity. The sediment fluxes along transect C showed that the river-laden sediment was transported northeastward parallel to the river channel and into the sea at stations C1 and C2. Flux values were approximately 6.6 kg s\(^{-1}\) at station C1 and increased to approximately 14.0 kg s\(^{-1}\) m\(^{-1}\) at station C2 (Fig. 7). At station C3, flux values decreased dramatically to approximately 0.7 kg s\(^{-1}\) m\(^{-1}\), approximately 0.5% that at station C2, indicating that the alongshore transport of river-delivered sediments within the 5 m isobath was dominant. The suspended sediments at both stations C3 at 5 m and C4 at 11 m dispersed southeastward with sediment fluxes of 0.7–0.9 kg s\(^{-1}\) m\(^{-1}\), indicating that the suspended sediment was primarily carried from the northern area by flood currents. The sediment flux at station C5 decreased dramatically to approximately 0.1 kg m\(^{-1}\) s\(^{-1}\) in comparison to 0.9 kg m\(^{-1}\) s\(^{-1}\) at station C4. The landward transport of sediment flux at station 5 indicated that the transport of river-laden sediments was mostly confined within the nearshore region shallower than 15 m.

Sediment fluxes along transect A showed that sediment was transported to the southwest at the nearshore station (A1) with a net sediment flux of approximately 0.13 kg s\(^{-1}\) m\(^{-1}\), 1.34 kg s\(^{-1}\) m\(^{-1}\) and 0.19 kg s\(^{-1}\) m\(^{-1}\), respectively. The sediment flux at station A3 was much higher than that at all the other stations, comprising approximately 76.5% of the total sediment flux along transect A. This suggests that the transport of river-laden sediment from the river mouth was primarily northward through station A3.

The sediment fluxes along transect B showed that the suspended sediment was transported eastward or southeastward around the head of the river mouth that had been active between 1976 and 1996 (stations B3, B4 and B5 in Fig. 7). However, the suspended sediment at station B2 was transported northwestward in the opposite direction from sediment at stations B3, B4 and B5, with much lower flux values (0.10 kg s\(^{-1}\) m\(^{-1}\)) in comparison to those at stations B3 (0.4 kg s\(^{-1}\) m\(^{-1}\)), B4 (0.5 kg s\(^{-1}\) m\(^{-1}\)) and B5 (1.1 kg s\(^{-1}\) m\(^{-1}\)). The sediment at station B1 was transported southward along the coast, the opposite direction of the sediment at station B2 with a low flux of 0.05 kg s\(^{-1}\) m\(^{-1}\), indicating that a very small amount of suspended sediment was delivered to the nearshore area.

5. Discussion

5.1. The process and mechanism of suspended sediment dispersion

The tidal currents off the present Huanghe subdelta are recirculating flows with lower velocity in nearshore areas, and form a swirling of water body in the southern part off the present Huanghe subdelta due to the protrusion of the abandoned Qingshuigou mouth (Fig. 2). The tidal currents in combination with the tidal shear fronts which were identified along each transect off the present Huanghe subdelta (Fig. 3) control the suspended sediment dispersal in study area.

The barrier effect of the tidal shear front on the river-laden sediment dispersion seemed to be effective in trapping suspended sediment as the low water and sediment discharges weakened the extension of the river plume off the river mouth. The diluted water was restricted within the 5 m isobath due to the impact of the shear front, and was transported northward by tidal currents during ebb tides. However, during the transition period from the ebb tide to flood tide, the river water characterized by a low salinity and a high SSC was transported to the deeper sea due to the clockwise-rotating currents (Pang and Jiang, 2003) and the disappearance of a shear front. Therefore, the turbid water was transported southward by flood currents passing by stations C3 and C4, resulting in a decrease in salinity and an increase in SSSCs during flood tides (Fig. 4), along with the southward net sediment fluxes during the two tidal cycles at these two stations (Fig. 7). Additionally, the maximum SSC in the bottom water layer was approximately 0.2 g l\(^{-1}\), with a corresponding salinity value of approximately 25 in the river mouth area during the field survey (Fig. 4), and was much lower than 30 g l\(^{-1}\), the critical SSC for the formation of hyperpycnal flow (Pang and Yang, 2001). Therefore, the suspended sediment dispersion off the river mouth was predominantly in the form of hypopycnal flow during the low-discharge period, in contrast with the hyperpycnal flow observed by Wang et al. (2007b).

This relatively turbid water mass could not be carried close to the shore due to the barrier effect of the shear front formed in the shallower area and transported northward again by the ebb currents in the next tidal cycle through a deeper sea area, resulting in the SSC increasing during ebb tide (Fig. 5) and the northward net sediment flux of one tidal cycle at station A3 (Fig. 7). This water mass did not pass through the shallower area barred by the shear front between stations A1 and A2. This result generally agreed with the suspended sediment dispersion shown in a LANDSAT image acquired on May 5, 1998 (Fig. 8a). This image also indicated that
the turbid nearshore water along transect A seemed to be consistent with the resuspended sediment from the northern abandoned river mouth area. The seaward transport in this area was obstructed by the shear front between stations A1 and A2.

The turbid water in the southern area off the delta was derived from the river mouth, flowing southward during the flood tides and turning westward into Laizhou Bay after the protrusion of the abandoned Qingshuigou river mouth as observed on the LANDSAT satellite image acquired on May 2, 2000 (Fig. 8b), demonstrating that the water did not arise from the resuspension of the surface sediment as documented by previous publications (e.g., Jiang and Wang, 2005). Jiang and Wang (2005) suggested that resuspension might be the major source of the fine suspended sediment in Laizhou Bay. However, there was no evident relationship between the shear stress estimated on the near bottom velocity and the observed SSC, suggesting that the fine sediment off the Huanghe river mouth that was transported southward would be the primary sediment source for the suspended sediment in Laizhou Bay.

The tidal shear front, which occurred throughout the flood tide phase between stations B1 and B2, prevented the turbid water with high salinity from reaching the eastern coast of the southern delta. During the ebb tides, the tidal currents flowed southeastward at all stations except for station B5 (Fig. 2), carrying the turbid water away from the southeastern coast of the delta. Therefore, this turbid water mass could not reach the southeastern coast of the delta during the entire tidal period (Fig. 6). Thus, a narrow and relatively clear band of water with low salinity and low SSC was formed between the turbid water mass and the southeastern coast of the delta parallel to the shoreline, as shown by the satellite image acquired on August 28, 1999 (Fig. 8b).

5.2. Geomorphological response of the subaqueous delta to the suspended sediment dispersion

The erosion–accumulation pattern of the subaqueous delta was quantitatively estimated based on the bathymetric data recorded from 36 offshore transects off the Huanghe delta in 1976 and 2003. A drip-like accumulation area with an irregular edge was formed around the present sub-delta, including two accumulation centers around the present river mouth and the abandoned Qingshuigou river mouth. The two erosion areas were separated from each other by the accumulation area with two distinct accumulation–erosion transient zones north and south of the delta, respectively (Fig. 9). Erosion took place in the shallower nearshore areas and accumulation occurred in the deeper offshore areas in the two accumulation–erosion transient zones. This indicates that the alongshore deposition of the river-laden sediment took place in the offshore areas in the northern and southern areas of the subaqueous delta, coinciding with the net sediment fluxes along the transects.
The accumulation area extended northward via the deeper nearshore area, and the erosion area was located in the shallower area along transect A. The gradient of the accumulation thickness between stations C3 and C4 was very high, and decreased sharply around station C5 (Fig. 9), suggesting that most of the river-laden sediments deposited on the landward side of station C3, and station C5 (depth of approximately 15 m) with an accumulation thickness of approximately 2 m was close to the seaward boundary of river-laden sediment transport. A slight erosion zone where the coastline retreated landward, located on the southeastern coast of the delta, corresponded with the position of a clear water belt that was clearly observed on satellite images. Thus, fast seaward propagation of the central part of the subdelta with the retreat of its northern and southern coastline back towards the land was the direct consequence of the sediment dispersion.

Although high water and sediment discharges have made a significant contribution to the delta accretion, both in the past and during the water-sediment regulation periods over the past 7 years, the sediment dynamics and processes we discussed based on the low-discharge observation still played an important role in the river-laden sediment dispersal and thus controlled the geomorphology of the delta. Therefore, the sediment dynamics and delta response would provide a good reference for the safety of the coastal dike and development of the oil fields on the delta.

Note that strong wave action, especially in the winter seasons, could significantly reshape the deltaic geomorphology, as the high stress induced by waves in the shallow water could cause notable resuspension of sediments (e.g., Wang et al., 2006c). Observations near the Huanghe delta in 1987 indicated that storm-induced strong wave action directly induced a prominent slope failure of the subaqueous delta, and the down-slope transport of resuspended sediments reshaped the slope (Prior et al., 1989).

6. Conclusions

Tidal shear fronts with different formation mechanisms were found along three transects off the present Huanghe subdelta. The combined shear fronts and alongshore tidal currents were the major dynamic factors controlling the sediment dispersion near the present subdelta. Most of the sediment that was delivered to the sea in the form of hypopycnal flow was deposited within the 5 m isobath off the river mouth due to the barrier effect of the tidal shear front. The river-laden sediment was transported northward or southward through the deeper water at both sides of the river mouth under the joint effect of the shear fronts and tidal currents, but not through the shallower nearshore water along the coast. These observations were generally in agreement with the suspended sediment dispersal pattern indicated by satellite images. Two shear fronts and tidal currents in the northern and southern shallower nearshore areas of the delta prevented the sediment transport from the offshore areas towards nearshore areas, resulting in offshore sediment deposition in the northern and southern parts of the subaqueous delta, rather than in the nearshore areas. Thus, two inside erosion-outside accumulation transition zones were formed off the northern and southern parts of the delta, respectively.

Human activity has caused sharp decreases in water and sediment discharges from the river to the sea, and the area of accumulation and volume of the active river mouth is expected to decrease in the future due to insufficient sediment supply, while the erosion areas are expected to extend. These future challenges must be considered by the delta conservation community and in the future development plans of the Shengli Oil field in this region.

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