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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 $m^3\ s^{-1}$) 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.

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 km^2 and a total length of 5464 km in northern China (Fig. 1a), the Huanghe (Yellow River) has historically had a low runoff ($<60 \times 10^9\ m^3\ yr^{-1}$), but one of the largest sediment loads ($10.8 \times 10^9\ t\ yr^{-1}$) 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 $km^2\ yr^{-1}$ (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

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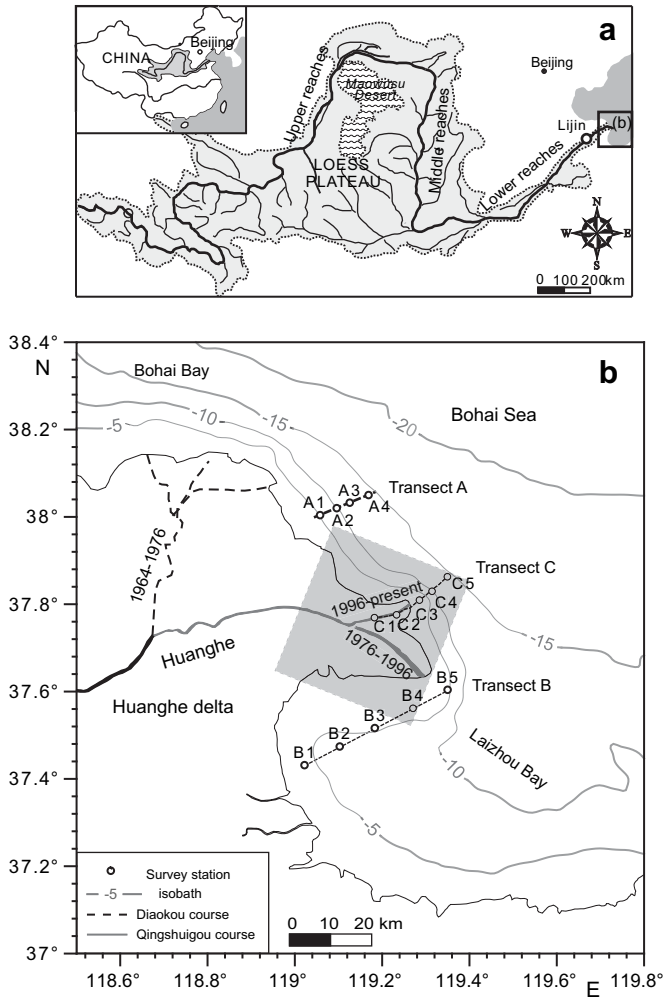

Fig. 1. The Huanghe drainage basin, the location of the present Huanghe subdelta (land area in shadow rectangle) (a) and the three survey transects, as well as the survey stations (b).

reported by Li et al. (1994) based on *in-situ* measurements in 1991 during a period of high water discharge (approximately 2600 $m^3\ s^{-1}$ at Lijin Station). These measurements indicated that suspended sediment delivered from the mouth of the Huanghe was aggregated and deposited rapidly along the shear front zone due to the low velocity in this region. Wang et al. (2007b) presented the features and results of the barrier effect on the suspended sediment dispersion of tidal shear fronts off the mouth of the Huanghe using 25 h *in-situ* observations at five time-series stations across the subaqueous slope in 1995. Their results suggested that the hyperpycnal flows generated near the mouth of the river were terminated within shallow waters due to the barrier effect of the shear front. Nevertheless, their study area was local and limited to the area near the Qingshuigou river mouth. An overall picture of river sediment dispersion over the whole present subdelta or the new river mouth area (since 1996) has not yet been achieved, and it is critical for understanding the pathway of sediment transport and flux off the Huanghe delta.

To date, most publications that have discussed the Huanghe sediment dispersion in the coastal region near the delta and the Bohai Sea are largely based on datasets prior to 1996. Since that time, several significant changes have occurred that directly affect the sediment dispersal pattern off the delta: 1) The deltaic course shifted significantly in 1996, and the river mouth moved approximately 20 km northeast of the old river mouth (Fig. 1b); 2) 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 hyperpycnal 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 multi-station 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 paralleling 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