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SEDIMENT TRANSPORT IN YALU RIVER ESTUARY

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ABSTRACT: Tidal cycle measurements of tidal currents, salinity and water temperature, and suspended sediment concentrations were measured at four stations, together with surveys along two profiles short core collection within the Yalu River estuary. Grain size analysis of the three core sediment showed that: 1) the sediment from B_1 to B_3 became finer, worse sorting and positively skewed; 2) the diversification of matter origin became more and more evident from east to west; 3) the sediments over the region were of the same origin, as indicated by their similar colors and grain sizes. The data indicated that stratification occurred in the flood season, from upstream to downstream, and a salt wedge was formed. The water column was well mixed, but the longitudinal gradient of the salinity was larger on spring tide. The results also showed that the dominating mechanism of suspended sediment transport in the Yalu River estuary was T_1, T_2, T_3 and T_5. The non-tidal steady advection transport was restricted by the net transport of suspended sediment induced by mass Stoked drift directed to landwards, then the net sediment transport rate were decreased and the turbidity maxima was also favored to forming and extending.

KEY WORDS: grain size; suspended sediment transport; turbidity maximum; the Yalu River estuary

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1 INTRODUCTION

Suspended sediment transport is a problem of marine sedimentary dynamics. Many important achievements about estuarine mass transport have been made since the 1970s (SU and WANG, 1986; WANG and SU, 1987), in particular, a flux decomposition formula was proposed to evaluate the different mechanisms of the horizontal flux of sediment. The Yalu River estuary is characterized by high suspended sediment concentration (SSC) and strong tidal currents. Therefore, a study on the relationship between suspended sediment transport and the forming of turbidity maximum is important for an understanding of the depositional environment in the Yalu River estuary, which is the purpose of the present study.

The Yalu River, originating from the Changbai Mountains, 790km in length, lies at the border of China and D. P. R. Korea. (Fig. 1). The annual runoff is $302 \times 10^6 m^3/a$, 36% of which occurred in July – September. The estuary is bell-shaped. Turbidity maxima are formed in the 24-km section between Niu Island and Wenzigou (JIN and LI, 2001). The area south of Niu Island is dominated by tide, where a series of sand ridges and tidal channels are developed (LIU and XIA, 1983; XIA and LIU, 1984). Majority of the area is now eroded in response to the construction of reservoirs since the 1970s. Therefore, the growth of the river delta was slowed (CHENG, 1988). Three major channels lie in the estuary, with the middle channel being the main watercourse into the sea (CHEN, 2000; Editorial Committee for Chinese Harbours and Embayments, 1998).

2 METHOD

2.1 In Situ Measurements

The observations of tidal currents, salinity and water temperature, and suspended sediment concentrations

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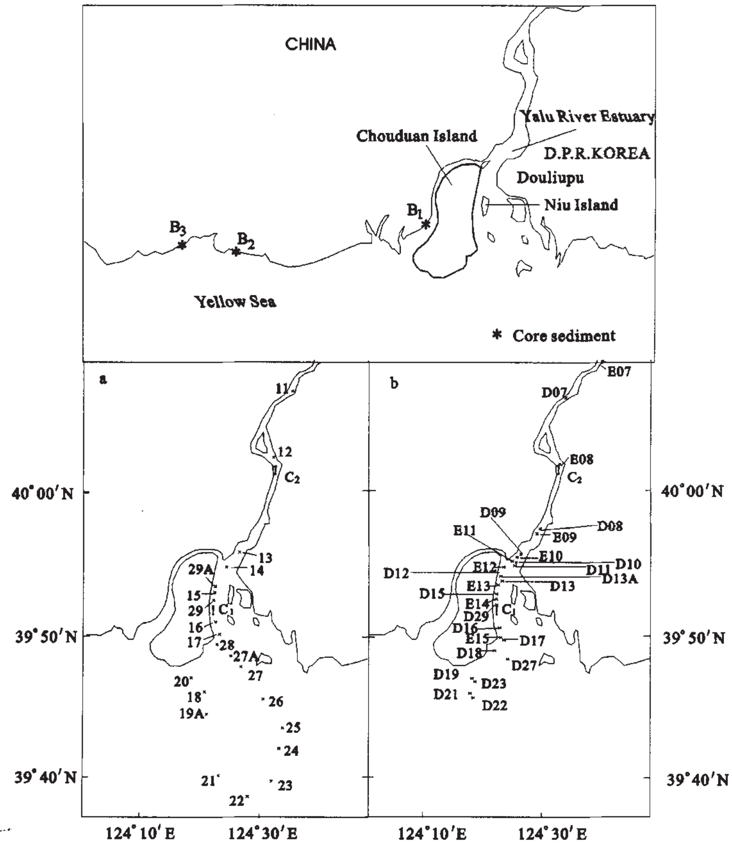

Fig. 1 Location map of the Yalu River estuary and measuring stations in 1994 (a) and in 1996 (b)

were carried out using the Liaodan 112 surveying ship at C_1 and C_2 station in May 1994 and August 1996. Further, measurements along Section 1 (Stations 11 – 19A) were undertaken during ebb tide on 14th August, 1994, and along Section 2 (Stations 20 – 29A) during flood tide on 18th August, 1994 (Fig. 1a). These measurements were carried out along Stations E07 – E15 during ebb tide on 7th May, 1996, and along another 17 stations during flood tide on 6th May, 1996 (Fig. 1b). Three short cores (B_1, B_2 and B_3) were collected from inter-tidal flats in September 2001 (Fig. 1). Subsamples were taken in 2-cm intervals, and were analyzed using a Malvern 2000 Laser Analyzer to obtain grain size data. Grain size parameters i. e. mean grain size, sorting coefficient, and skewness are calculated by a moment method (MCMANUS, 1988).

2.2 Suspended Sediment Transport Rate Calculations

Instantaneous velocity $u(z, t)$ can be decomposed to different components according to tidal and vertical average (SU and WANG, 1986; WANG and SU, 1987; SHEN *et al.*, 1995).

$$u(z,t) = \bar{u}_0 + \bar{u}_t + u_0' + u_t' \quad (1)$$

where $\bar{u}_0$, $\bar{u}_t$, u_0' and u_t' is respectively denoted as a tidal mean part of vertical average, a tidal oscillation part of vertical average, a tidal mean part of the deviation from vertical average and a tidal oscillation part of the deviation from vertical average.

Similar expression can be derived for SSC:

$$c(z,t) = \bar{c}_0 + \bar{c}_t + c_0' + c_t' \quad (2)$$

where $\bar{c}_0$, $\bar{c}_t$, c_0' and c_t' is respectively denoted as a tidal mean part of vertical average, a tidal oscillation part of vertical average, a tidal mean part of the deviation from vertical average and a tidal oscillation part of the deviation from vertical average.

Mean suspended sediment transport rates at the two stations were calculated using the formula described by SHEN *et al.* (1995):

$$\frac{1}{T}\int_0^T\int_0^h u\cdot c\cdot dz\cdot dt = \underbrace{h_0\cdot\bar{u}_0\cdot\bar{c}_0}_{T_1} + \underbrace{\langle h_t\cdot\bar{u}_t\rangle\cdot c_0}_{T_2} + \underbrace{\langle h_t\cdot c_t\rangle\cdot\bar{u}_0}_{T_3} + \underbrace{\langle h_t\cdot\bar{u}_t\cdot\bar{c}_t\rangle}_{T_4} + \underbrace{h_0\overline{u_0'\cdot c_0'}}_{T_5} + \underbrace{\langle h_t\cdot u_0'\cdot c_0'\rangle}_{T_6} + \underbrace{\langle h_t\cdot u_t'\cdot c_0'\rangle}_{T_7} + \underbrace{\langle h_t\cdot u_t'\cdot c_0'\rangle}_{T_8} \quad (3)$$

where T_1 is the result of river flow, T_2 is Storkes drift, which is induced by progressive tidal waves, T_3 is due to correlation of tidal period variation of tidal height and SSC, T_4 is the third order correlation of tidal period variation in SSC, velocity and water depth, T_5 is the correlation of tidal period variations of SSC and current speed, T_6 is mean shear effect, T_7 is shear effect induced by tidal period variation, T_8 is shear effect due to tidal oscillation, h is the water depth, h_0 is a tidal mean part of vertical average water depth, z is relative water depth, t is time, and T is tidal period.

3 CHARACTERISTICS OF SEDIMENT AND ITS SOURCES

Changes of dynamic conditions and depositional environmental characteristics along the coastline were displayed by variations of the grain size parameters of the three cores. In Core B_1, with grey and black materials, the mean grain size, sorting coefficient and sediment component are relatively uniform except 0 – 10cm, 80 – 82cm and 86 – 88cm sections (Fig. 2). In Core B_2, mud with yellowish strips occurs in the 0 – 25cm sections, and the material is grey and black in 25 – 100 cm (Fig. 3). From depth of 12cm to 24cm, the sediment is coarser, more poorly sorted and positively skewed. The percentage of sand is up to 92 %. Here, the dynamic condition may have changed due to paroxysmal events, e. g. storm surges. In Core B_3, horizontal bedding is clearly defined, with grey-black materials except for the part of 25 – 50cm with French grey sediments (Fig. 4). The main fraction is silt. The vertical distribution of the three parameters indicates that the sediments with finer sizes are more poorly sorted and negatively skewed.

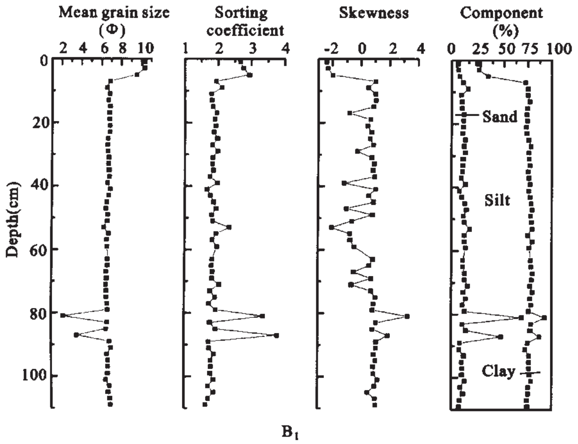

Fig. 2 Vertical distributions of sediment component and grain size parameters in B_1

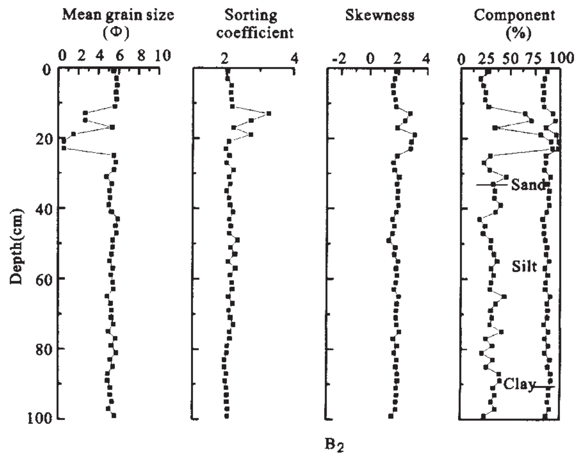

Fig. 3 Vertical distributions of sediment component and grain size parameters in B_2

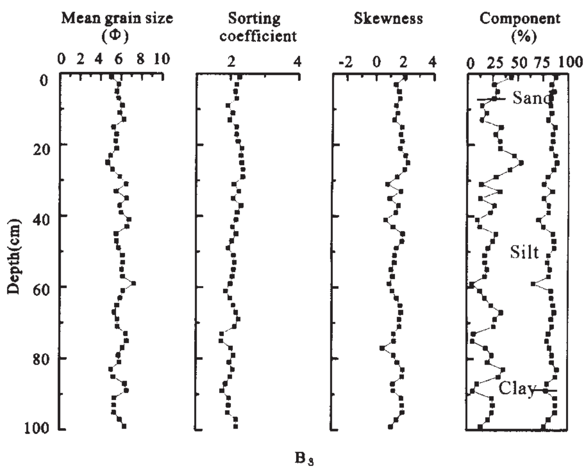

Fig. 4 Vertical distributions of sediment component and grain size parameters in B_3

These features show that the sediments over the region are of the same origin, as indicated by their similar colors and grain sizes. Previous studies show that the suspended sediment of the Yalu River estuary was derived from three sources: 1) river discharges (CHENG and ZHAO, 1985; QIU *et al.*, 1984); 2) erosion of the coast and seabed (LIU and XIA, 1983; XIA and LIU, 1984; CHENG and ZHANG, 1990); and 3) materials from open sea, according to the modeling results of DONG *et al.* (1989).

4 CHARACTERISTICS OF TURBIDITY MAXIMUM

4. 1 Current Speeds

Variations of current speeds at different stations are

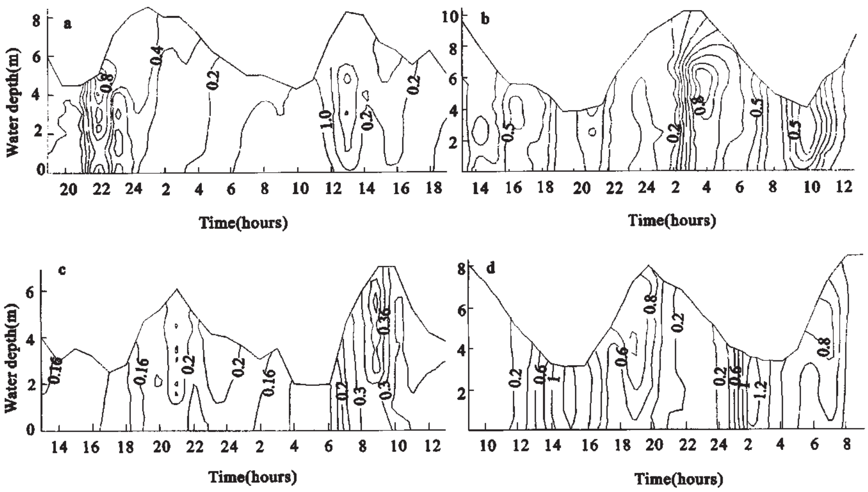

Fig. 5 Variations of current speed (m/s) at different stations
a: C_1-1994; b: C_2-1994; c: C_1-1996; d: C_2-1996

shown in Fig. 5. The strongest current speed at station C_1 took place during the flood phase, and the weakest current speed took place at slack water. At station C_2, both the largest and smallest velocities were observed during the ebb.

4.2 Suspended Sediment Concentrations

Influenced by turbidity maxima, the peak values of SSCs took place during flood phase at C_1, and at Station C_2 they occurred during flood phase or slack water (Fig. 6). The variation of SSCs at Station C_2 was larger than that at Station C_1.

4.3 Longitudinal Distribution of SSC and Salinity

The data indicate that stratification occurred in the flood season; from upstream to downstream, the salinity increased from 0.1 at Station 13 to 6 at Station 16. A salt wedge was formed from Station 14 to 17 (Fig. 7a). The highest salinity was at Station 23 along Section 2 (Fig. 8a), and the extension of the salt wedge was from Station 23 to 27, with the salinity being reduced from 24 to 4. Sections 1 (Fig. 7b) and 2 (Fig. 8b) indicated that the highest SSC lie at the interface of saline and fresh waters; turbidity maxima with high stratification were formed from Station 12 to 16. The high SSC area

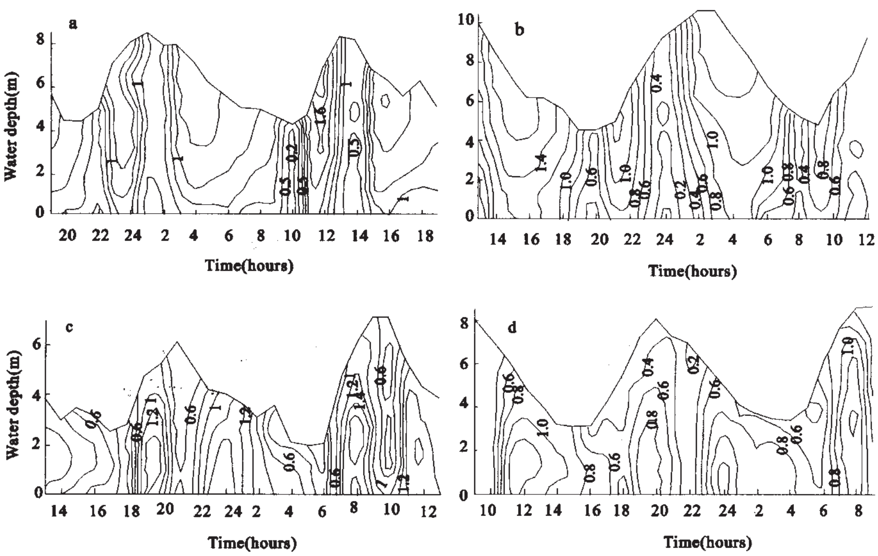

Fig. 6 Variations of suspended sediment concentration (g/L) at different stations
a: C_1-1994; b: C_2-1994; c: C_1-1996; d: C_2-1996

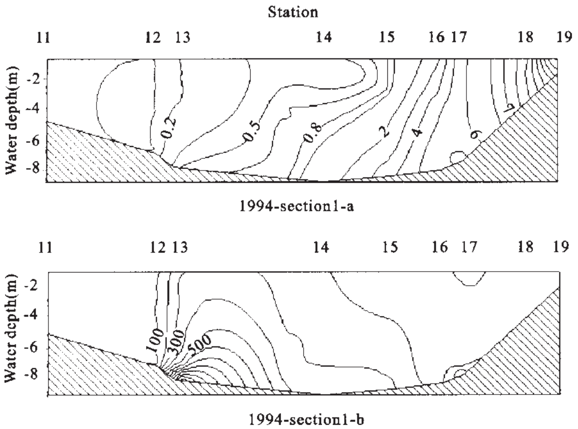

Fig. 7 Longitudinal salinity and SSC (mg/L) distribution during ebb tide in 1994 in the Yalu River estuary (1994-section1)

(a) Salinity; (b) SSC

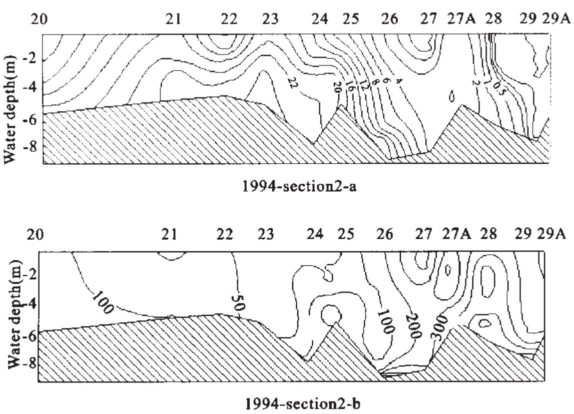

Fig. 8 Longitudinal salinity and SSC (mg/L) distribution during flood tide in 1994 in the Yalu River estuary (1994-section2)

(a) Salinity; (b) SSC

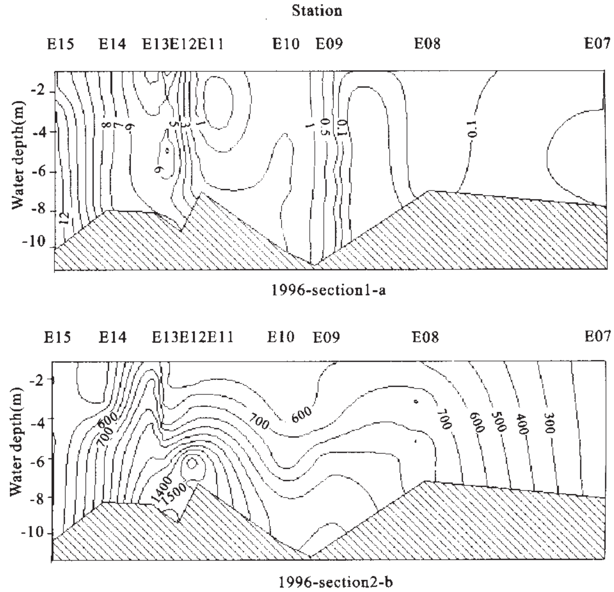

Fig. 9 Longitudinal salinity and SSC(mg/L) distribution in 1994 during ebb tide in the Yalu River estuary (1996-section1)

(a) Salinity; (b) SSC

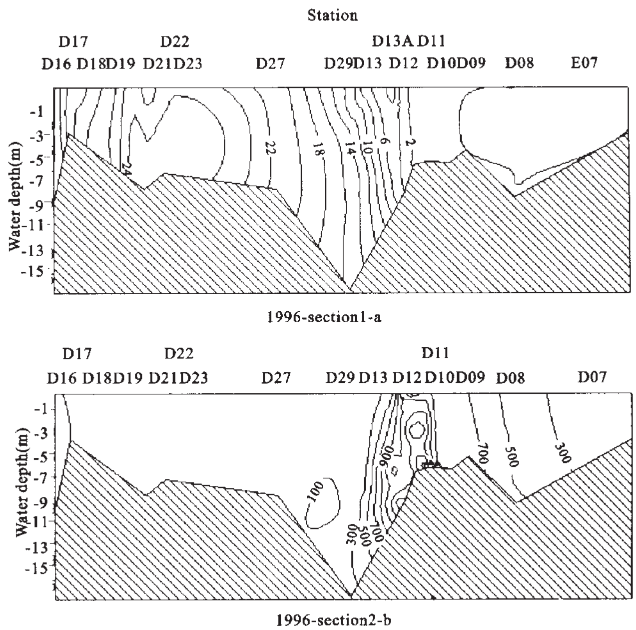

Fig. 10 Longitudinal salinity and SSC (mg/L) distribution during flood tide in 1994 in the Yalu River estuary (1996-section2)

(a) Salinity; (b) SSC

at Section 2 was located at Station 28, but maximum SSC occurred at Station 26 (up to 929g/m^3 in the bottom layer).

The water column was well mixed, but the longitudinal gradient of the salinity was larger on spring tide. Along Section 1, the salinity was rapidly decreased from Station E15 to Station E11 (Fig. 9a). Similar patterns can be seen at Section 2 (Fig. 10a). Maximum SSC of Section 1 occurred in the bottom layer of Station E12 (Fig. 9b), and the turbidity maximum existed from Stations E12 to E15. The turbidity maxima of Section 2 were located between Stations D15 and D07, and maximum SSCs occurred in the bottom layer at Station D13A (Fig. 10b).

The mechanism forming turbidity maximum mainly consist of the settling and scouring lag effect, the flocculation, the estuarine circulation, the Stokes drift, the tidal current and resuspension of bottom sediment (SHI *et al.*, 1993). The Yalu River estuary is highly stratified with force and normal semidiurnal tide. Influenced by bed gradient ratio, river channel section, and water depth, the tidal asymmetry exist, i. e. the duration of flood is less than that of ebb. The tidal asymmetry is becomes stronger from downstream to upstream. The bed was composed of sand with the decrease of median size from 0.18 to 0.33mm towards the sea (CHENG and ZHANG, 1990). Because Station C_1 was located in the area controlled by the river, the variations of velocity in tidal cycle were uniform, and the mean current speed during the flood was larger than that during the ebb. Station C_2 was located in the region dominated by tidal currents, and the mean current speed of the flood was smaller than that during the ebb. Thus, suspended sediment was transported towards the upper reaches during the flood. In the ebb, the suspended matter conveyed towards upper reaches by flood currents was re-transported towards down stream. In addition, resuspension was strengthened. Therefore, maximum SSCs at Station C_1 is often present during flood phase, and at Station C_2 during ebb phase or at slack water. Thus, the turbidity maxima result from the effect of tidal asymmetry which causes sediment accumulation in the estuary.

5 SUSPENDED SEDIMENT TRANSPORT

As shown in Table 1, at C_2 suspended sediment was transported towards NNW during the flood phase, and was conveyed towards SSE in the ebb phase. The residual currents at C_2 were directed towards SE in 1996 and SSE in 1994.

The dominating terms of suspended sediment transport are T_1, T_2, T_3 and T_5 (Table 2). The non-tidal steady advection transport is restricted by the net transport of suspended sediment induced by mass Stoked drift directed to landwards, then the amount of net sediment transport were decreased and the turbidity maximum was also favored to forming and extending. Because of the strengthened runoff in the flood season, the contribution of T_2 in August was larger than that in May.

The sediment transport resulted from variation of water depth and SSC in a tidal cycle plays an important role in the suspended sediment transport. The transport pattern of T_3 shows that it was directed towards the sea at C_1, but towards the land at C_2. T_5 was caused by phase difference between velocity and SSC, effect of shoal and inlet, and could be increased by resuspension and sediment transport induced by tidal asymmetry (WANG and SU, 1987; SHEN *et al.*, 1995). The value of T_5 is small at both stations, but at C_1-1994 and C_2-1994 the relative large percentage may be caused by intensive change of bedform in the flood season. The suspended sediment transport induced by T_4, T_6, T_7 and T_8 was very small.

Table 1 Mean current speed and direction measured in the Yalu River estuary

Station	Ebb		Flood		Tide cycle	
	Mean velocity (m/s)	Direction(°)	Mean velocity(m/s)	Direction(°)	Residual current(m/s)	Direction(°)
C_1-1994	0.98	165.43	1.09	354.50	0.41	158.67
C_2-1994	0.90	155.71	0.49	338.18	0.13	153.51
C_1-1996	0.82	143.40	1.00	349.85	0.37	128.54
C_2-1996	0.66	150.00	0.58	338.68	0.21	139.84

Table 2 Distribution of suspended sediment transport influenced by different factors in the Yalu River estuary
(Transport rate: kg/m·s; Percentage: %; Seawards: +, Landwards: −; $\zeta = T_4 + T_6 + T_7 + T_8$)

Station	Type	T_1	T_2	T_3	T_5	ζ	Total
C_1-1994	Transport rate	0.5	−0.1	0.04	−0.01	0.004	0.48
	Percentage	110.8	−16.5	7.4	−2.5	0.7	100
C_2-1994	Transport rate	1	−0.2	−0.05	−0.02	−0.005	1
	Percentage	133.2	−25	−5	−2.5	−0.731	100
C_1-1996	Transport rate	0.3	−0.14	0.004	0.002	0.0025	0.17
	Percentage	183.6	−88.2	2.4	0.9	1.3	100
C_2-1996	Transport rate	0.9	−0.4	−0.1	0.008	−0.01	0.46
	Percentage	198.6	−79.2	−19.2	1.8	−1.886	100

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