A New Method for Estimating Fine-Sediment Resuspension Ratios in Estuaries—Takes the Changjiang Estuary as an Example

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Abstract Based on the principle of conservative matter removal in estuary, a new method is proposed for estimating the ratio of sediment resuspension in estuaries with fine-suspended sediments. Nearly half of the particulate matter in the turbidity maximum zone (TMZ) of the Changjiang (Yangtze) estuary originates from sediment resuspension, indicating that sediment resuspension is one of the major mechanisms involved in formation of the TMZ. Compared with traditional method for calculating these ratios in the estuary, this new method evaluates the dynamic variation of SPM content carried by river runoff from the river mouth to the ocean. The new method produced more reliable results than the traditional one and could produce a better estimation of resuspension flux for particulate matter in estuaries.

Keywords Sediment · Suspended particulate matter · Resuspension ratio Estimate method · Turbidity maximum zone · Changjiang (Yangtze) estuary

The turbidity maximum zone (TMZ) is a prevalent phenomenon in rivers within estuaries, and it plays many important roles in sediment processes in estuarine environments (Pan et al. 1999). The study of suspended matter in estuaries has become a hot topic in marine sciences (Allen et al. 1980; Herman and Heip 1999; Turner and Millward 2002; Webster and Lemckert 2002; Suzumura et al. 2004). The study on measuring sediment resuspension is an important subject. Current methods to measure sediment resuspension involve using optical and acoustical instruments, instantaneous multiple point water samplers, sediment traps, sediment cores and grabs, radiotracers (e.g., Pb-210, Cs-137 and Be-7), mass balance calculations, various modeling approaches, statistical methods (correlation analysis), and laboratory experiments (Bloesch 1994).

Globally, the Changjiang (Yangtze) River is the third largest river in length (6300 km) and the fourth largest in sediment discharge (5×10^8 t a^{-1}). Thus, the study of SPM in the TMZ of the Changjiang estuary has received much attention

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from oceanographers. These studies include, for example, the distribution, transport, and diffusion of SPM (Milliman et al. 1985; Su and Wang 1986; He and Yun 1998) and sediment resuspension (Li and Zhang 1998; Li et al. 2000). However, there are few reports on measuring sediment resuspension in the Changjiang estuary. Chen et al. (2004) estimated the ratio of sediment resuspension in the Changjiang estuary using a traditional method based on a constant suspended sediment load along the estuary. Shen et al. (2008) suggested a new method to calculate the ratio of sediment resuspension in the TMZ in the Changjiang estuary. This section takes the TMZ of the Changjiang estuary as an example, the two estimation methods (Shen's and traditional methods) are compared, and the principles of Shen's method are introduced herein. These principles underpin a better approach for estimating the ratio.

1 Study Area and Sampling

The average runoff of the Changjiang River to the East China Sea is about 29,000 m^3 s^{-1} or 9282×10^8 m^3 a^{-1}, most of which occurs in the flood season from May to October, accounting for over 70% of the annual total of runoff. Investigations were carried out on February, May, September, and November, 2005. Water samples were collected for SPM and salinity (S) from the surface layer at 40 stations, from station 35 in downstream Xuliujing to 123° 20′E and 30° 45′–32° 00′N (Fig. 1). Near Xuliujing at the river mouth, Changjiang River divides into South and North Branches, with runoff and SPM being transported to the ocean mainly through the South Branch (Milliman et al. 1985). A special high SPM content zone was found in the river mouth-bar area, where the TMZ exists all year round. Tides in the Changjiang estuary are of moderate intensity and are of regular semi-diurnal type, with an average tidal difference of 2.67 m at the river mouth. The turbidity maximum in Changjiang estuary is induced by runoff-tidal current interaction and salt and freshwater mixing. The space-time distribution of the turbidity maximum changes with changes in runoff, tidal currents, and salt and freshwater mixing (Pan et al. 1999). Maximum water depths are about 50 m over the whole observation area and 12 m in the TMZ itself. The TMZ is often stratified in the flood season at water depths of more than 10 m. Seasonal variations in wind-driven waves in the estuary are apparent: in winter northern wind waves are vigorous, while in summer southeast and southern ones are dominant but less vigorous. Average wave height is 10 cm higher in winter than in summer, with wind waves greater than Scale 5 in winter, which is 3 times more than those in summer (Luo and Shen 1994). Influenced by wind, tides, and currents, SPM in the TMZ of the estuary is frequently disturbed by cycles of suspension, sedimentation, resuspension, and resedimentation (Shen and Pan 2001). Much previous research has reported that sediment resuspension occurs 3–4 times in a tidal cycle in the river mouth-bar area (Pan et al. 1999; Li et al. 2000). Hence, sediment resuspension is important with respect to changing SPM content in the estuarine waters.

2 Calculation Method

2.1 Calculation Method and Principle

The new method introduced in detail in this paper is based on the principle of conservative matter removal from the estuary, using potential mixing/dilution lines (theoretical dilution lines) for fresh- and salt-water in Changjiang estuary, and comparing this to measured values, in order to calculate the ratios of sediment resuspension in the TMZ (see shaded area in Fig. 1). The method is expected to be applied only for fine-grained material in estuaries, as their behaviors in estuaries are close to that for conservative matter. Correlation statistics show that there are strong negative linear relationships between SPM and salinity with the correlation coefficients *r* of 0.491 (p = 0.003), 0.356 (p = 0.036), 0.604 (p = 0.00041), and 0.641 (p = 0.000059) in February, May, September, and November, respectively, suggesting that the behaviors of SPM in the Changjiang River estuary were conservative to a great extent. Due to the mixing of river water and seawater, SPM carried by river runoff is diluted and diffused, and its content decreases gradually in the transport from the river mouth

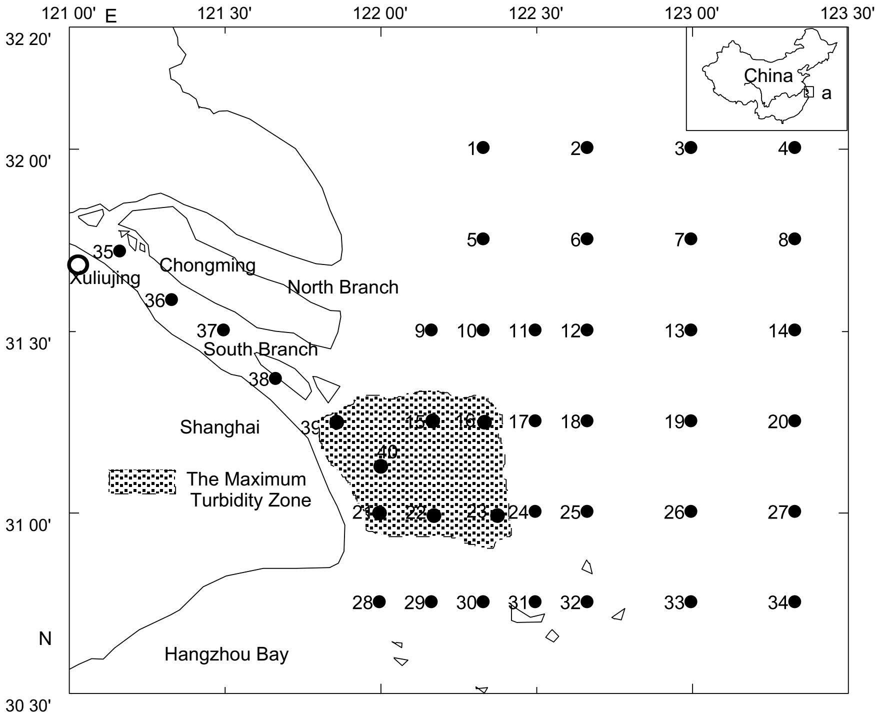

Fig. 1 Sampling stations in the Changjiang estuary: The shaded area is the TMZ (Shen and Pan 2001); a observation area

to ocean. It is a dynamic variation process. The freshwater end-member is at station 35 in downstream Xuliujing (salinity ≈ 0), whereas the seawater end-member varies seasonally with Changjiang runoff. Average salinities in seawater end-members were 33.26 in February (winter, stations 19 and 20), 33.63 in November (autumn, stations 8, 13, 14, 19, 20, 26, 27, 33, and 34), 31.13 in May (spring, station 20), and 32.89 in September (summer, stations 26 and 27). The line between fresh and seawater end-members represents the fresh–saltwater mixing/dilution line.

2.2 Method for Estimating the Resuspension Ratio of Fine-Grained Sediments

The SPM in the TMZ of Changjiang estuary includes sediments from both river runoff and resuspension. After SPM from river runoff arrives at the river mouth area, a portion is intercepted in the TMZ, influenced by runoff, tides, salt–freshwater, and circumfluence (Shen and Pan 2001). Sediment in the TMZ is mainly composed of fine-grained clayey silt and silty clay, existing as mud with high-water content when depositing from seawater to seabed (Yang et al. 1992). This sediment resuspends easily, and is reworked by wind, tides, and currents. Xuliujing is located at the fork between the South and North Branches, about 140 km from the river mouth. The SPM content in Xuliujing was similar to that in Datong (about 640 km from the river mouth) and increased with SPM increases in Datong (Chen et al. 2004). Therefore, SPM content in Xuliujing is thought to be controlled by river runoff in the same manner as at Datong, rather than by oceanic dynamical factors (Chen et al. 2004). The relationships of SPM to salinity in the entire observation area are indicated in Fig. 2. Taking SPM content at station 35 in downstream Xuliujing as the background value of river runoff, four theoretical dilution lines (Fig. 2) between the freshwater end-member (station 35) and the seawater end-member can be drawn as follows:

February: SPM (mg L^{-1}) = $-$ 1.9159 S + 66.322
May: SPM (mg L^{-1}) = $-$ 0.9906 S + 40.916
September: SPM (mg L^{-1}) = $-$ 3.9699 S + 132.57
November: SPM (mg L^{-1}) = $-$ 1.0867 S + 42.747.

Without sedimentation or resuspension, SPM content carried by Changjiang River should plot on the theoretical dilution lines. In contrast, in the case of resuspension or resedimentation, SPM values should fall either above or below these lines. Because there is little combustible particulate matter (only 7% of the total suspended particles in the estuary in 2004), biological influence is not considered herein. Thus, difference in SPM content between measurement at each station and its corresponding point on the theoretical dilution line should be equal to the resuspension or deposition amount. The resuspension ratio *R* can be computed as follows (Shen et al. 2008):

$$R = (\mathrm{SPM}_1 - \mathrm{SPM}_2) / \mathrm{SPM}_1 \times 100\%$$

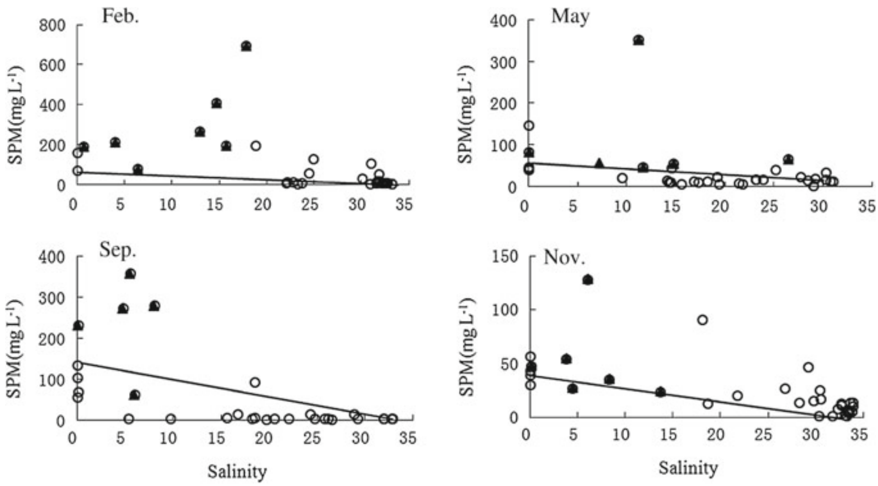

Fig. 2 The relationships of SPM to salinity in the Changjiang estuary: circle All data; filled triangle Data for the turbidity maximum zone; large dash lines Theoretical dilution lines between freshwater end-member (station 35) and seawater end-member ($r^2 = 1$, $n = 2$)

where, SPM_1 is the SPM content measured at a station in the TMZ, and SPM_2 is the corresponding SPM value at the theoretical dilution line. When *R* is positive, resuspension is indicated, and when *R* is negative, deposition is indicated.

3 Calculation Result

Based on observation data of SPM in the TMZ in February, May, September, and November, 2005, using the above method, the resuspension ratio of sediment in surface water of the TMZ was between 18.7 ± 27.9% and 73.9 ± 22.5%, with an annual average of 49.2% (Table 1). The maximum resuspension ratio of sediment occurred in winter, as expected. Changjiang estuary waters are predominantly controlled by strong Changjiang runoff, and marine dynamics (tides and waves) are relatively weak in summer. In winter, runoff decreases greatly and marine dynamics are relatively strong, with greater storm frequency (Chen et al. 2004). In winter, spring, and summer, nearly half of the SPM in surface waters of the TMZ came from sediment resuspension (Table 1), illustrating that sediment resuspension is one of the major mechanisms maintaining the TMZ (Li and Zhang 1998; Pan et al. 1999). Using the new method, the resuspension ratio of sediment in surface waters of the TMZ in 2005 was a little smaller than that in 2004 at 55.7% (Shen et al. 2008).

Table 1 Resuspension ratios of sediment in surface waters of the TMZ

Month	New method		Traditional method	
	Ratios (%)	S.D. (%)	Ratios (%)	S.D. (%)
February	73.9	22.5	65.7	25.4
May	57.4	22.1	39.2	27.5
September	46.7	27.9	41.8	24.4
November	18.7	27.9	16.0	26.0
Average	49.2		40.7	

S.D. Standard deviation

4 Comparison with Traditional Method

Chen et al. (2004) estimated the ratio of sediment resuspension in Changjiang estuary using a traditional method, which took SPM content in Xuliujing as the background value of the river runoff, and assumed that the difference in SPM content between the Xuliujing measurement and the measured value for a given station was equal to the resuspension amount calculated by:

$$R = (S_t - S_r)/S_t$$

[mistakenly reported as $R = (S_t - S_r)/S_r$ in the literature] where S_t is the SPM content measured at a station and S_r is the SPM content carried by river runoff (station 35). Results of the traditional method to calculate the resuspension ratio of sediment in surface waters of the TMZ in 2005 is also indicated in Table 1. Comparing calculation results of the two methods, we find that the resuspension ratios of sediment in seasonal and annual averages using the new method are ~20% higher than those obtained using the traditional method.

Comparing the two calculation methods, the traditional method regards the SPM content carried by river runoff as invariable, and the dynamic variation in SPM content during transport is not considered. In actual fact, the SPM content carried by river runoff (the background value) at Xuliujing would reduce during transport. Hence, calculation results with the new method should be higher than with the traditional method (Table 1). Furthermore, the results of the new method are more objective.

While we calculate the resuspension ratio of sediment in surface waters of the TMZ using the new method, it should be noted that not all resuspended material may reach surface waters. Commonly the resuspension ratio of sediment increases with water depth. For example, the ratio of resuspension of sediment in bottom waters of the TMZ was 66.1% of the total SPM greater than that in surface waters (55.7%), which is consistent with SPM content at the bottom being greater than that at the surface (Shen et al. 2008). In addition, sedimentation may occur in conjunction with resuspension.

Using the new method, the resuspension ratio of sediment can be estimated in waters of different areas and depths in different estuaries. In addition, based on sedimentation fluxes of various particulate materials (such as nutrients, and heavy metals) in estuaries, their resuspension and net sedimentation fluxes also can be calculated (Shen et al. 2008). The method may therefore provide a new approach for studying the biogeochemistry of various dissolved and particulate species in estuaries.

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