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Controls on suspended sediment concentration profiles in the shallow and turbid Yangtze Estuary

J.H. Liu, S.L. Yang*, Q. Zhu, J. Zhang

State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China

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A B S T R A C T

The vertical distribution of suspended sediment in continental shelf waters has significant implications for water quality, aquatic ecology, and sediment transport. Nevertheless, there have been relatively few systematic field studies aimed at determining whether a general vertical trend in suspended sediment concentration (SSC) exists, or how any such vertical trend can be expressed mathematically. In this study, based on 402 individual SSC profiles measured hourly during 16 dual-tide voyages at 8 stations in the outer Yangtze Estuary, we found that SSC followed an average depth profile that was smoothly concave-up. This average profile, and the relationship between SSC and height above the seabed, was exponential ($R^2 > 0.99$). In comparison, the traditional Rouse equation based on hydrodynamics describes the measured average SSC profile poorly, in that the greater the distance from the near-bed height (where the reference SSC is taken), the greater the deviation of the simulated SSC from the measured SSC. However, in this study, a new approach was developed to overcome this flaw in the Rouse equation, which divides the equation into two parts. One part uses a reference SSC from a near-bed level, and an upwards decreasing coefficient, in the same way as the conventional Rouse equation. Conversely, the other part uses a reference SSC from at the water surface, and a downwards decreasing coefficient. Our modified hydrodynamics-based equation expresses the measured SSC well, with an R^2 between the simulated and measured SSCs exceeding 0.99. According to the average SSC profiles, the near-bed SSC was 2.8 times greater than the SSC at the water surface (close to the value of 3 suggested for modeling studies in the absence of empirical data), and the depth-averaged SSC was 1.8 times greater than the SSC at the water surface. We also found that the average SSC profile showed a uniform (from water surface to seabed) decline in SSC (25%) in response to the dramatic decline in the suspended sediment load supplied by the Yangtze River over the past three decades. However, the shape and vertical ratio of the average SSC profile have changed little, which suggests that the general form of the SSC profile is determined mainly by local hydrodynamics and sediment properties, and not by fluvial sediment supply.

1. Introduction

Suspended sediment concentration (SSC) has significant implications for ecology, biogeochemistry, and geomorphology (Schoellhamer et al., 2007; Li et al., 2012). The flux of suspended sediments is determined by the flow velocity and SSC. In comparison with SSCs in rivers, the SSC of estuarine and coastal waters is highly variable in time and space due to the effect of tides and waves (Davies and Xing, 2002; Murphy and Voulgaris, 2006). Numerous studies have examined temporal variations in estuarine and coastal SSCs, covering intra-tidal to annual time-scales (e.g., Ridderinkhof et al. (2000), Schoellhamer (2002), Yang et al. (2004), Uncles and Stephens (2010)). In recent years, along with the development of remote sensing techniques, spatial variations in the SSC of estuarine and coastal waters have received greater attention (e.g., Shen and Pan (2001), Doxaran et al. (2002), Miller and McKee (2004), Shen et al. (2010), Fettweis et al. (2012)). In some cases, multi-year and multi-station time series of estuarine and coastal SSCs were established, based on daily sampling of surface water, for the purpose of examining long-term trends and spatial patterns of SSC (Butt and Russell, 1999; Tattersall et al., 2003; Chen et al., 2006; Li et al., 2012; Dai et al., 2013). However, the studies based on data from remote sensing and surface water sampling can only investigate variations in near-surface suspended sediments. Under the influence of gravity and turbulence, vertical changes in SSC can be significant and complex (Whitehouse et al., 2000). Hence, relying solely on knowledge of suspended sediments behavior in surface waters is inadequate if we would like to fully understand suspended sediment processes throughout the water column.

* Corresponding author. Tel.: +86 21 62233115; fax: +86 21 62546441.
E-mail addresses: slyang@sklec.ecnu.edu.cn, 13651656907@163.com, ljhlion1982@163.com (S.L. Yang).

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Another issue associated with the vertical variability of SSC in estuarine and adjacent coastal waters is the effect of a decline in riverine sediment discharge and SSC, and the shift from accretion to erosion in the subaqueous delta. Due to human activities such as dam construction, water diversion, and soil conservation within watersheds, more and more estuaries are experiencing sediment starvation (e.g., Stanley and Warne (1993), Sánchez-Arcilla et al. (1998), Li et al. (2000), Yang et al. (2005), Syvitski et al. (2009), Wang et al. (2011)). It is necessary to compare the vertical variability of SSC between the past and present in such influenced deltaic waters.

The processes that determine the vertical variability of SSC are well understood for non-cohesive sands (Soulsby, 1997), with the balance between upward diffusion and downward settling of sand grains resulting in an equilibrium profile. In comparison, the processes that control the vertical changes of SSC for cohesive muds are complex and remain poorly understood. As a result of these complexities, vertical SSC profiles of mud are multiform (Shi et al., 1996; Whitehouse et al., 2000; Zhang et al., 2007). Although many studies have examined the vertical variability of SSC in estuarine and coastal waters (e.g., Hay and Sheng (1992), Shi et al. (1996), Holdaway et al. (1999), Whitehouse et al. (2000), Zhang et al. (2007)), some questions remain: e.g., Does the in situ measured mean SSC profile show an ideal trend? Is this vertical trend linear (Holdaway et al., 1999) or acceleratory (generating a concave-up profile) (Whitehouse et al., 2000; Yang et al., 2007a)? Can the vertical trend be well expressed using some hydrodynamic models? How far do individual profiles deviate from the mean profile? What is the magnitude of the ratio of near-bed SSC (or depth-averaged SSC) to surface SSC? In addition, the height of the near-bed layer differed greatly among the previous studies, ranging from <5 to 50 cm (e.g., Holdaway et al. (1999), Orton and Kineke (2001), Dyer et al. (2004), Zhang et al. (2007), Wang et al. (2012)), it is necessary to examine the influence of this height on the vertical SSC profiles.

In the present study, we aim to investigate the vertical variability of cohesive SSC in the outer Yangtze Estuary. Our major objectives are to: (1) calculate the average and standard deviation of the individual SSC profiles; (2) determine the depth-related trend in the average SSC profile; (3) compare the observed profile with profiles predicted using some well-known hydrodynamic models; (4) improve the existent approach to better simulate the SSC profile observed in the study area.

2. Study area

This study is based on field observations at eight sites at the mouth of the Yangtze River and adjacent shallow continental shelf (Fig. 1). The Yangtze River is one of the world's largest rivers. In recent decades, numerous dams, in particular the Three Gorges Dam (TGD), the world's largest, have been constructed within the Yangtze watershed, resulting in a drastic (more than 70%) decline in suspended sediment discharge to the sea (Xu et al., 2006; Yang et al., 2007b; Gao and Wang, 2008; Wang et al., 2011). As a result, SSCs have shown a significant decrease in the Yangtze Estuary and adjacent continental shelf except at the mouth bar area (Li et al., 2012; Dai et al., 2013). Meanwhile, strong erosion has occurred at the subaqueous delta front (Yang et al., 2011).

More than 99% of the sediment discharged from the Yangtze is as suspended load (Yang et al., 2002). The annual median size (D_{50}) of the suspended sediments at Datong (Fig. 1a) ranges from 6 to 13 μm, and is 10 μm on average (Yangtze River Water Resources Committee (YRWRC), 2001–2012). Due to the post-TGD riverbed erosion (Luo et al., 2012), the D_{50} at Datong has shown an increasing trend. Governed by the Asian monsoon, the water and sediment discharge, and the SSC of the Yangtze River show a significant seasonality, with values in summer (wet season) being several times greater than those in winter (Yang et al., 2002; Xu and Milliman, 2009). Along with the recent decrease in annual sediment discharge and SSC, the seasonal differences in sediment discharge and SSC have also reduced (Yang et al., 2002; Xu and Milliman, 2009).

Since the 1950s, more than 98% of the Yangtze's water and sediment has discharged into the sea through the three outlets of the South Branch (Chen et al., 1985; Yang et al., 2003). Off the Yangtze River mouth, on the inner continental shelf, a strong southward long shore current develops, particularly under the influence of northerly winds in winter, which annually transports about 200 Mt/yr of the riverine suspended sediments southward to the Zhejiang coast (Milliman et al., 1985), resulting in the development of an enormous mud wedge there (Liu et al., 2007; Xu et al., 2012).

Tides in the Yangtze Estuary and adjacent waters are semi-diurnal, and there is a diurnal inequality. In the mouth area, the tidal range is around 2.7 m on average but rises to nearly 4 m on spring tides, and the average annual salinity is 5–15 (Li et al., 2012). Intra-tidal and spring–neap flows are highly variable, with peak velocities of more than 2 m/s (Yan, 2010). The multi-year average wind speed at the delta front is 4–5 m/s, although a maximum of 36 m/s was once recorded (GSII, 1996). Waves are wind-dominated, with a mean wave height of around 1.0 m at the river mouth (Group of Shanghai Coastal Comprehensive Investigation (GSCCI), 1988). Wave activity and sediment suspension are greater during the winter than in the other seasons (Group of Shanghai Coastal Comprehensive Investigation (GSCCI), 1988; Chen et al., 2006). At the mouth bar area, a turbidity maximum zone (TMZ) develops (Shi, 2004a). The SSC within the TMZ is highly variable in time and space, ranging from <0.1 to >2 g/l (Shi et al., 1996; Zhang et al., 2007; Yan, 2010; Li et al., 2012). Flocculation was widely found in the Yangtze Estuary in particular within the TMZ. The D_{50} values of the flocs range from 40 to 192 μm, and are 86 μm on average (Tang et al., 2008). The settling velocities of the flocs range from 0.2 to 4.0 mm/s (Shi, 2004b), and are 0.5 mm/s on average (Shi et al., 2003; Shi, 2004b; Hu et al., 2009; Guo and He, 2011). The inner continental shelf on which the Yangtze River delta is built has a gradient of less than 1‰ (Yang et al., 2003). Our study area (5–20 m in water depth) lies mainly within the TMZ (Fig. 1b). During our observations (in 2009–2012), the riverine SSC ranged from 0.08 to 0.22 g/l, which was less than 1/3 of the riverine SSC before the 1980s (Yang et al., 2011); and the wind speed ranged from 3.5 to 4.6 m/s, which approximate the multi-year average (Group of Shanghai Coastal Comprehensive Investigation (GSCCI), 1988).

3. Methods and materials

Sixteen dual-tide monitoring voyages were conducted at eight sites (A–H) at, and just off, the mouth of the Yangtze River where a turbidity maximum zone had developed (Fig. 1b). Site A was located at the mouth of a main channel, the North Channel, where the average water depth was 7.2 m. Sites B–D were located within and along a sheltered creek, with average water depths of 6 m, 9 m, and 5 m, respectively. Sites E–H were located in the shallow open sea, and had mean water depths of 10, 6, 8, and 20 m, respectively. Each voyage covered two complete and consecutive semi-diurnal tidal cycles. An OBS-3A (a pressure–temperature–conductivity probe, Campbell Scientific, Logan, UT, USA) was used to measure turbidity profiles between the water surface and the near-bed layer (0.5 m above the seabed), with a measurement interval of 1 s, and each profile contained at least 20 data points