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Temporal and spatial changes of suspended sediment concentration and resuspension in the Yangtze River estuary

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Abstract: A detailed analysis of suspended sediment concentration (SSC) variations over a year period is presented using the data from 8 stations in the Yangtze River estuary and its adjacent waters, together with a discussion of the hydrodynamic regimes of the estuary. Spatially, the SSC from Xuliujing downwards to Hangzhou Bay increases almost constantly, and the suspended sediment in the inner estuary shows higher concentration in summer than in winter, while in the outer estuary it shows higher concentration in winter than in summer, and the magnitude is greater in the outer estuary than in the inner estuary, greater in the Hangzhou Bay than in the Yangtze River estuary. The sediments discharged by the Yangtze River into the sea are resuspended by marine dynamics included tidal currents and wind waves. Temporally, the SSC shows a pronounced neap-spring tidal cycle and seasonal variations. Furthermore, through the analysis of dynamic mechanism, it is concluded that wave and tidal current are two predominant factors of sediment resuspension and control the distribution and changes of SSC, in which tidal currents control neap-spring tidal cycles, and wind waves control seasonal variations. The ratio between river discharge and marine dynamics controls spatial distribution of SSC.
Key words: suspended sediment concentration; temporal and spatial changes; sediment resuspension; Yangtze River estuary
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1 Introduction

Suspended sediment concentration (SSC) in estuaries and adjacent coastal waters are closely associated with hydrodynamics. If tides or wind waves are strong, correspondingly the SSC is high. Hydrodynamics is a dominant factor affecting estuarine geomorphology and evolution (Gao, 1998), in which sediment transport is the tache between hydrodynamics and geomorphic evolution. SSC changes are direct results of various sediment movement processes such as sediment transport, deposition, resuspension, etc. Suspended sediment movement plays an important role in the estuarine environment evolution. Suspended sediments deposit in ports and shipping channels, which must be dredged to maintain navigation (Chen and Gu, 2000; Zhang *et al*, 2003). On the other hand, fine-grained sediments are also an important carrier of various nutrients and pollutants (Webster and Lemckert, 2002). Therefore, estuarine environmental research is also required with regard to estuarine suspended sediment regime. The temporal and spatial changes of SSC due to marine dynamic actions as riverine sediments discharged to sea are the first priority to be considered for harbor construction, depositional landform evolution and environmental research.

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The Yangtze River (Changjiang) estuary is the sea outfall of the Yangtze River, which is the largest river in China and the third in the world (after the Nile and Amazon), where both the actions of river runoff and marine dynamics are very strong. The Yangtze River is rich in water and sediments, its average annual water and sediment discharges are up to 9.04×10^{11} m^3 and 4.35×10^{8} tons (at Datong, from 1951 to 2000) respectively. The discharges show pronounced dry-season/wet-season variations. The grain size of fluvial sediment is fine with the medium grain size of 27 μm (Yang, 1999). A large amount of the fine sediments become the material base of morphological evolution of the estuary and its adjacent regions. The Yangtze River diluted water, the tidal wave from the East China Sea and wind waves out the estuary are main dynamics of sediment transport in the offshore sea. For the dispersion of sediments discharged by the Yangtze River into the sea, many researches have been conducted on the basis of satellite images, hydrodynamics and estuarine fronts etc. (Yun *et al.*, 1981; Su and Wang, 1986; He and Yun, 1998; Zhou *et al.*, 1999). For the local region, Li *et al.* (2000) studied sediment resuspension in the mouth bar area of the estuary. For the sediment dispersion, research in the past tended to start with the flow, and often ignored the resuspension in the process of sediment dispersion, which led to the conclusion that sediments always transport from areas of high concentration to that of low concentration. However, in fact, it is not the case. A large number of researches have proved that the sediments in Hangzhou Bay are originated from the supply of sediments by the Yangtze River discharge (Cao *et al.*, 1989; Chen *et al.*, 2001). But the sediment concentration in the Hangzhou Bay is much higher than that in the Yangtze River estuary. It is obvious that the sediment dispersion has no correlation with sediment concentrations. The sediment dispersion is of profound meaning and dynamic mechanism. The researches of SSC changes in the past were mostly based on short-term data (Zhang *et al.*, 1999; Gu, 1986). It is lack of deep understanding on the long-term changes and large spatial distribution of SSC. Because of the complexity and randomness of sediment processes in estuarine systems, it is necessary to understand the macroscopical regime of suspended sediment distribution and changes before carrying out detailed studies of sediment transport processes and mechanism. The purpose of this paper is to describe temporal and spatial changes of SSC and to probe into underlying dynamic mechanism.

2 Data source and method

The Yangtze River estuary starts to bifurcate from the node of Xuliujing. Below this point it takes on a configuration of three-grade bifurcations and four mouths into the sea. The data used in this analysis are mainly collected from the surface suspended sediment concentrations of eight fixed stations from Xuliujing seawards to Hangzhou Bay, in which very few data are interpolated linearly. The study area and location of observation stations are given in Figure 1. These stations are representative in spatial distribution, although they are not synchronous completely (Table 1). According to the synchronous observations at

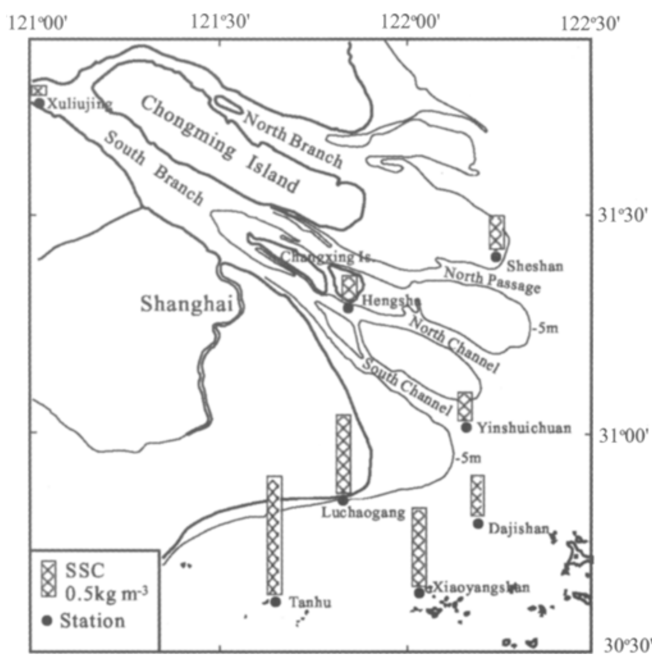

Figure 1 Study area and location of observation stations

Table 1 Observation stations and suspended sediment concentration data

Station No.	Station	Geographical location	Observational date	Sampling time
1	Xuliujing	The bifurcation node of North and South Branch	August 1998 to July 1999	0800 and 1400 each day
2	Hengsha	The bifurcation point of North Channel and South Channel	August, 1998 to July 1999	0800 and 1400 each day
3	Sheshan	-5m shoal in outer North Passage	August, 1998 to July 1999	0800 and 1400 each day
4	Yinshuichuan	Mouth of South Channel	August 1982 to July 1983	High water level and 1400 each day
5	Dajishan	The transition between the Yangtze River estuary and Hangzhou Bay	August 1982 to July 1983	High water level and 1400 each day
6	Luchaogang	North bank of Hangzhou Bay mouth	May 2002 to April 2003	High water level each day
7	Xiaoyangshan	Outer Hangzhou Bay mouth	August 1997 to July 1998	High and low water level each day
8	Tanhu	Inner Hangzhou Bay mouth	September 1992 to August 1993	0800 and 1400 each day

Xuliujing, Hengsha and Sheshan over three years, inter-annual surface concentrations are not changed significantly. Therefore, the unsynchronous data used here should not significantly affect the temporal and spatial comparison in a significant way.

For the daily SSC more than one time observation, its calculated average value is approximately taken as daily mean SSC, and moreover monthly mean SSC are calculated. The SSC shows irregular fluctuating changes temporally. Such irregular fluctuating change can be seen as the superposition of many periodic fluctuations. The method of frequency spectrum analysis (refer to Huang, 1983) can be applied to the study of daily mean SSC and the amplitude of periodic fluctuations. Through the data analysis of SSC combined with hydrodynamic conditions, this paper probes the mechanism of SSC temporal and spatial changes.

3 Temporal and spatial changes of SSC

SSC is highly variable in both time and space since it is subjected to effects such as topography, water discharge, tidal current, wind wave, etc. But long-term observations show that there also exist clear characteristics of temporal and spatial changes. The time scales of SSC fluctuations include turbulence (seconds), tidal period (hours), the spring-neap tidal cycle (days), and seasonal wind waves (months). The daily observed SSC is able to reflect a neap-spring tidal cycle and seasonal changes.

3.1 Spatial changes of yearly mean SSC

Yearly mean SSC represents average regime over one year, which has a relatively stable value. It can be distinctly seen from the distribution of yearly mean SSC shown in Figure 1 that the SSC from Xuliujing via the estuarine mouth to Hangzhou Bay shows an increasing tendency. The yearly mean SSC at Xuliujing is only 0.1289 kg/m^3. While it is up to 0.3580 kg/m^3 at Sheshan, nearly 3 times of the concentration at Xuliujing. The value reaches to 1.5558 kg/m^3 at Tanhu station in Hangzhou Bay, nearly 12 times of that at Xuliujing in the upper part of the Yangtze River estuary. It is obvious that the SSC increases continuously from the upstream of the Yangtze River estuary to its outer estuary, i.e., the SSC in the outer estuary is higher than that in the inner estuary and it is the highest in the Hangzhou Bay.

It is worth mentioning that the estuarine turbidity maximum zone (ETM) near the Yangtze River estuarine mouth is not the area with the SSC being the highest in the estuary and its adjacent waters. For example, at three stations of Hengsha, Sheshan and Yinshuichuan located in the ETM, the sediment concentrations are considerably lower than that at Dajishan, which is located in the south side of the ETM. In fact, the ETM forms under special conditions in estuarine mouths, including topography, hydrodynamics, the mixture of freshwater with saltwater, etc. (Shen and Pan, 2001), in which the high SSC is relative to its upper reach and down sea in the longitudinal direction. However in the transverse direction from the Yangtze River estuary to Hangzhou Bay, the SSCs increase continuously. A large amount of observations and surveys suggest that the maximum SSC occurs in the Hangzhou Bay, and its magnitude is much larger than that in the ETM area.

As a whole, the SSC is higher in the Hangzhou Bay than in the Yangtze River estuary, in the outer estuary than in the inner estuary, and in the estuarine mouth than in the inner estuary.

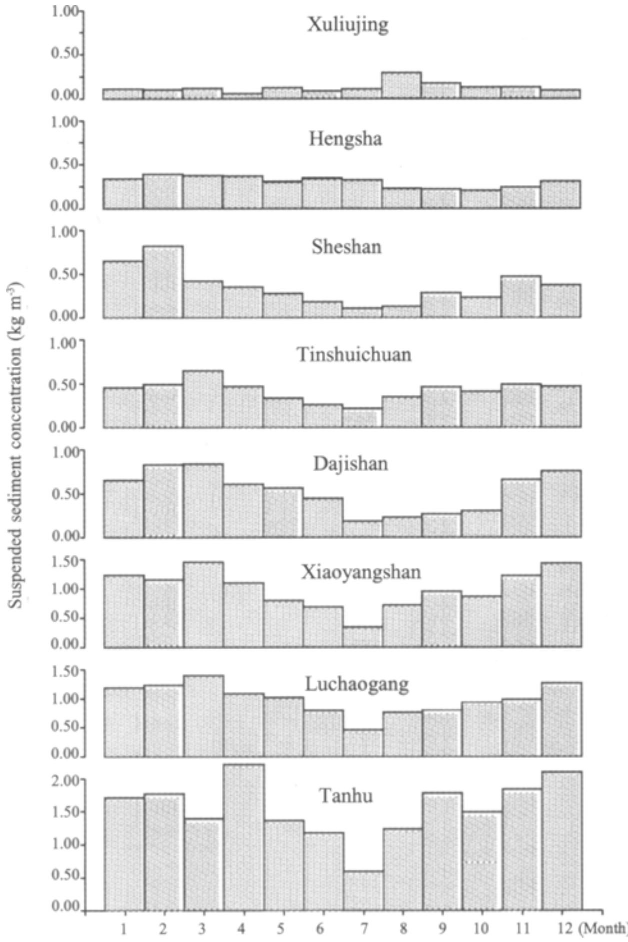

Figure 2 Monthly mean suspended sediment concentration in the Yangtze River estuary

3.2 Seasonal changes

The suspended sediment concentrations in the Yangtze River estuary and Hangzhou Bay have strong periodic variations (Chen, 2001), in which seasonal cycle is one of the most obvious features. Monthly mean SSCs for eight stations show that each station presents a seasonal variation (Figure 2 and Table 2), but because these stations are located in different waters, the SSC seasonal changes present some differences, even entire dissimilarity.

The Xuliujing station in the inner estuary, located at the node of bifurcation of North Branch and South Branch of the estuary, 140 km upstream from the estuarine mouth, presents much more distinctively fluvial features. The monthly mean SSCs show high values in summer and low values in winter, with a maximum of 0.223 kg/m^3 occurring in August and a minimum of 0.061 kg/m^3 in April. The SSC is higher in summer half year (from May to October) than in winter half year (from November to April of the next year). The Hengsha station is near to the estuarine mouth, its monthly mean sediment concentrations are higher in winter than in summer, but its amplitude is less varied. The SSC difference between the maximum and the

Table 2 Statistic results for surface sediment concentration in the Yangtze estuary (kg/m^3)

Station	Xuliujing	Hengsha	Sheshan	Yinshuichuan	Dajishan	Xiaoyangshan	Luchaogang	Tanhu
Maximum	0.2926	0.3912	0.6473	0.8170	0.8360	1.4500	1.3965	2.2080
monthly mean	Aug	Feb	Mar	Feb	Mar	Mar	Mar	Apr
Minimum	0.0610	0.2052	0.2134	0.1100	0.1890	0.3480	0.4575	0.5951
monthly mean	Apr	Oct	July	July	July	July	July	July
Summer half year	0.1550	0.2700	0.3384	0.2028	0.3325	0.7297	0.7902	1.2741
Winter half year	0.1028	0.3362	0.5048	0.5132	0.7240	1.2652	1.1896	1.8375
Yearly mean	0.1289	0.3031	0.4216	0.3580	0.5283	0.9974	0.9899	1.5558

minimum is only 0.1860 kg/m^3, and the SSC is larger during winter half year than during summer half year. The Sheshan station is located at the -5m shoal near the mouth of North Passage, the maximum monthly mean occurred in March and the minimum occurred in July. The SSC difference between winter and summer greatly increases. The Yinshuichuan station is located at the mouth of South Channel, its maximum monthly mean occurs in February, and the minimum occurred in July. The SSC is higher during winter half year than during summer half year. The Dajishan station is located at the transition between the Yangtze River estuary and the Hangzhou Bay, its maximum monthly mean occurred in March, and the minimum occurred in July. The Xiaoyangshan, Luchaogang and Tanhu stations are located in Hangzhou Bay, their maximum monthly mean occurred in March or April, and the minimum all occurred in July where the SSC shows a high value and great difference between winter and summer.

As a whole, the SSCs in the Yangtze River estuary and its adjacent waters differ greatly. For the area upstream the Hengsha Island in the inner estuary, the SSC shows high in summer and low in winter; but in the outer estuarine mouth, the SSC shows high in winter and low in summer, especially from the outer estuary of the Yangtze River to Hangzhou Bay, the seasonal changes increase remarkably. The SSC in the Xuliujing (inner estuary) shows high value in summer and low value in winter, but in the Hengsha (near the estuarine month) it is slightly high in winter and low in summer. Accordingly it can be deduced that there is a transitional zone where the SSC has no seasonal changes between Xuliujing and Hengsha and near Hengsha Island. The zone is approximately located near the upper side of Changxing Island.

3.3 Neap–spring cycle

Time series of daily suspended-sediment concentrations of the Yangtze River estuary show undulating changes. Figure 3 presents the daily mean SSC changes at the three stations of Hengsha, Sheshan and Luchaogang. It can be seen that superimposed on the seasonal cycle is a neap-spring cycle. Results of frequency spectrum analysis further demonstrates that the daily mean suspended sediment concentration at every station presents a neap-spring cycle (Table 3), which is consistent with a tidal semi-monthly cycle of approximately 14.765 days. Typically SSC varied with the neap-spring cycle, with greater SSC during spring tides and smaller SSC during neap tides. The amplitudes increase from the inner estuary to the outer estuary. The minimum amplitude occurs at the Xuliujing station that is considerably affected by the river discharge and where the tidal effect can be ignored. The neap-spring cycle in the tidally-dominated Hangzhou Bay is of great significance. From Hengsha to the outer estuary, the SSC shows an increasingly pronounced neap-spring variation.

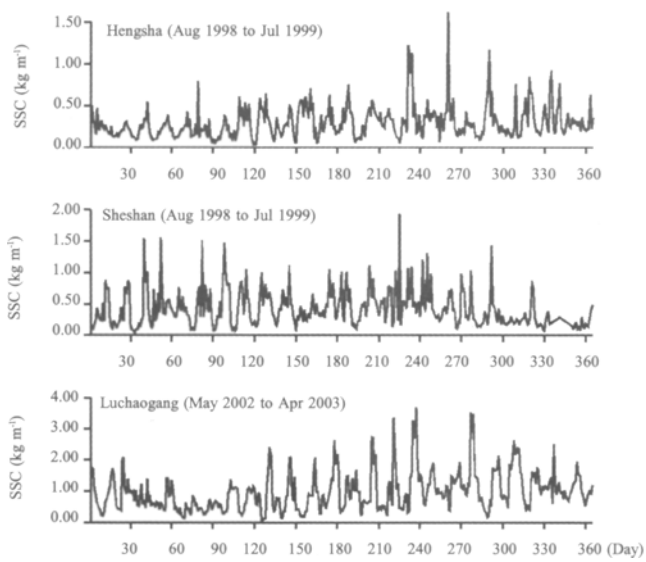

Figure 3 Fluctuations of daily mean suspended sediment concentration

Table 3 Neap-spring tidal amplitudes of SSC in the Yangtze River estuary

Station	Xuliujing	Hengsha	Sheshan	Yinshuichuan	Dajishan	Luchaogang	Xiaoyangshan	Tanhu
Amplitude (kg/m^3)	0.0366	0.0906	0.1053	0.172	0.185	0.2420	0.3584	0.4132

4 Sediment resuspension and mechanism

Large tidal velocities, spring tides and wind waves in shallow water are all capable of resuspending bottom sediments (Li *et al.*, 2000). The suspended sediments in estuaries and their nearshore shallow waters originate only from horizontal input (advection) and resuspension of bottom sediments. But the suspended sediments carried by advection are also due to resuspension and transportation by tidal currents, i.e., ex-situ resuspension. Therefore, the following sediment resuspension mentioned above includes in-situ resuspension and ex-situ resuspension of sediments carried by tidal currents.

4.1 Sediment resuspension rate

The magnitude of sediment resuspension can be considered by resuspension rate. The sediment resuspension rate (R) is defined as:

$$R = \frac{S_t - S_r}{S_t} \tag{1}$$

where S_t is suspended sediment concentration at stations, S_r is the suspended sediment concentration carried by river runoff. Multi-year average suspended sediment concentration at Datong hydrological station, 640 km upstream from the Yangtze estuarine mouth, is 0.19 kg/m^3 from 1951 to 1999, while the superficial SSC at Xuliujing, the node of the Yangtze River estuary, is 0.13 kg/m^3 per year. The two values are fairly close. Moreover the relationship between the suspended sediment concentration at Xuliujing and the sediment discharge at Datong (Figure 4) shows that the suspended-sediment concentration at Xuliujing increases in response to sediment discharge at Datong. Therefore, it can be considered that the suspended-sediment concentration is the sediment concentration carried by river water, such as that at Datong, which is not remarkably affected by marine dynamics. The suspended-sediment concentration at Xuliujing can be regarded as the background value of SSC carried by the Yangtze River runoff. Thus the sediment resuspension rate can be calculated according to the above definition. Results show that the resuspension rates of monthly and yearly suspended sediments present an increasing tendency from Xuliujing downward to the outer estuary (Table 4). For example, the resuspension rate of yearly SSC is 69.4% at Sheshan, 87.1% at Xiaoyangshan and up to 91.7% at Tanhu in Hangzhou Bay, which indicates that sediments in water column for the outer estuary and Hangzhou Bay are almost entirely composed of resuspended sediments. Moreover, the resuspension rate is higher during winter than during summer. For example, during summer (flood) season, in August for stations of Hengsha and Dajishan and in July and August for Station Yinshuichuan at the mouth of South Channel, the resuspension rates even occur in negative values, which indicates that a part of sediments deposit to bed. It is known that siltation-in-flood-season and scoring-in-dry-season is a common law in the Yangtze River estuary (Chen *et al.*, 1985). Sediment siltation leads to suspended

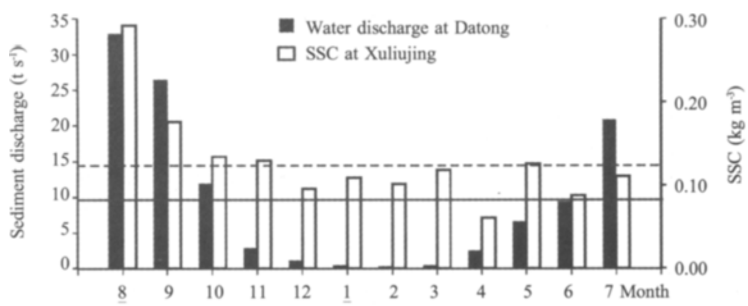

Figure 4 Monthly SSC at Xuliujing and sediment discharge at Datong from August 1998 to July 1999

Table 4 Seasonal variations of sediment resuspension rates in the Yangtze River estuary

Month	Hengsha	Sheshan	Yinshuichuan	Dajishan	Xiaoyangshan	Luchaogang	Tanhu
Jan	0.677	0.761	0.831	0.832	0.911	0.907	0.936
Feb	0.740	0.793	0.876	0.878	0.912	0.918	0.943
Mar	0.683	0.816	0.716	0.858	0.918	0.915	0.915
Apr	0.834	0.871	0.827	0.900	0.944	0.944	0.972
May	0.585	0.626	0.541	0.776	0.842	0.877	0.908
Jun	0.741	0.661	0.520	0.801	0.872	0.887	0.925
Jul	0.657	0.477	-0.014	0.410	0.680	0.756	0.813
Aug	-0.286	0.166	-1.251	-0.289	0.594	0.611	0.763
Sep	0.183	0.618	0.383	0.334	0.816	0.777	0.901
Oct	0.343	0.668	0.419	0.561	0.843	0.855	0.910
Nov	0.457	0.737	0.725	0.803	0.894	0.869	0.930
Dec	0.687	0.794	0.740	0.873	0.933	0.923	0.954
Summer half year	0.426	0.542	0.236	0.534	0.788	0.804	0.878
Winter half year	0.694	0.796	0.800	0.858	0.919	0.914	0.944
Yearly mean	0.575	0.694	0.640	0.756	0.871	0.870	0.917

sediment concentration decreasing. During summer half year (from May to October), the mean resuspension rates of the four stations at Hengsha, Sheshan, Yinshuichuan and Dajishan are 42.6%, 54.2%, 23.6% and 53.4% respectively, but during winter half year (from November to April next year) they are 69.4%, 79.6%, 80.0% and 85.5% respectively, which can be seen that the sediment resuspension rates are higher during winter half year than summer half year.

The sediment resuspension in the Yangtze River estuary is strong in winter and weak in summer. During summer, the water discharge increases, and correspondingly marine dynamics decrease, thus the sediment resuspension is weak. In contrast, during winter, the runoff decreases, but the marine dynamics (tidal current and waves) increases, and furthermore wind waves are stronger, accordingly the sediment resuspension is quite intense. Therefore, the ratio between the river runoff and marine dynamics is the primary mechanism of sediment resuspension and suspended sediment concentration variations. The sediment resuspension induced by tidal currents and waves is the dominant cause of increased SSC in the outer estuary.

4.2 Mechanism

The Yangtze River carries a large amount of sediments annually, to discharge into the estuary and its adjacent waters incessantly, and to produce various processes such as transportation, deposition and resuspension under actions of hydrodynamics. The sediments in the Yangtze River estuary and its adjacent waters (even in wider scope) are ultimately derived from the Yangtze River. For the development and evolution of the Yangtze River estuary, previous understanding is that Yangtze River runoff carries sediments, after flowing out of Xuliujing, entering its estuary and adjacent waters, the flow is slowed down due to extension, thus results in a part of sediments in the water column to be deposited on the river bed and side banks, accordingly the estuarine delta extends seaward continuously. However, the suspended sediment concentration in the estuary and its adjacent waters presents an increasing tendency, which does not coincide with the conventional view: flow extends and sediments settle. In fact, the water movement in tidal estuaries is complicated and bi-directional, in addition due to the actions of wind waves, the magnitude of suspended-sediment concentration is not associated with morphological evolution in simple form. Fine-grained sediment transporting with tide is the main pattern of sediment movement in the Yangtze River estuary and its adjacent waters. Although the concentration of sediments carried by Yangtze River water is low, the sediments discharge into sea in an unidirectional way, and become the material base of the actions of marine dynamics (tidal current and wave). The sediment concentration in the Yangtze River estuary is of marine feature but not of fluvial feature.

Tide has a pronounced fluctuation of fortnightly neap-spring cycle. The tidal current velocity is high during spring tides, and deposited sediments are resuspended by high tidal induced shear flow, thus superficial SSC increases. But the tidal current velocity is reduced during neap tides, a part of sediments in the water column are deposited onto bed, accordingly the SSC in water decreases. Consequently, the suspended sediment concentration presents a fluctuation of neap-spring cycle with a high concentration during spring tides and low during neap tides. Spatially, from the upstream of estuary to outer estuary, the river flow weakens and tidal current strengthens, especially in the Hangzhou Bay the tidal current is much stronger. Correspondingly the SSC increases with decreased river flow and increased tidal current, which indicates that the sediments are transported from the waters of low sediment concentration to the waters of high concentration. The suspended sediments carried by Yangtze River water into the estuary are covered up by the sediments strongly resuspended in the outer estuary and transported by tides. Although the suspended sediment concentration is higher in the outer estuary than in the inner estuary due to sediment resuspension, the Yangtze River input sediments are still the main contributor of the estuary and its adjacent waters. Another characteristic of tidal currents is to-and-fro movement with flood and ebb. Fluctuations of suspended sediment concentration are closely associated with the to-and-fro movements of tidal currents and their resuspension. The tidal resuspension includes the in-situ resuspension and ex-situ resuspension. Precisely the sediment resuspension induced by tidal currents is the principal physical cause of sediment concentration increase in the estuary and its adjacent waters and shows fortnightly neap-spring variations.

In addition, in the Yangtze estuary and its adjacent waters, the water depth is shallow, but wind waves are strong and generally they are stronger in winter than in summer. According to the established views that waves stir up sediments and tidal currents transport then. In which the actions of wind waves mainly present incipient motion of bottom sediments, i.e., in-situ resuspension. The wind waves are stronger in winter than in summer, thus the SSC must be higher in winter and lower in summer. But the wind waves are difficult to go deep into the inner estuary, where the sediment concentration is dependent primarily on water and sediment discharges from the river. Figure 5 shows that in summer the water discharge is large and sediment discharge is also large, but in winter the water discharge is low and sediment discharge is much lower. Accordingly in the inner estuary, the SSC presents high-in-summer and low-in-winter.

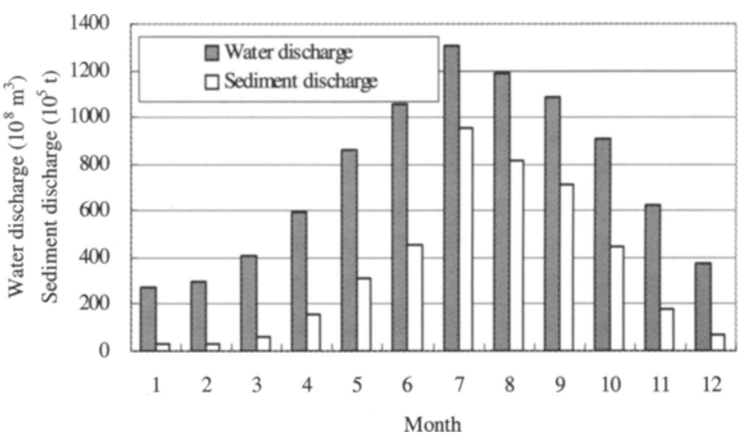

Figure 5 Monthly mean water discharge and sediment discharge at Datong station

5 Conclusion

From Xuliujing of the Yangtze River estuary to Hangzhou Bay, the river runoff decreases and tidal current increases, the SSC presents an upward tendency. The high concentration of suspended sediment in the estuarine turbidity maximum is comparatively speaking to its upstream or downstream, and its magnitude is clearly lower than that of its southern part of Hangzhou Bay.

The measured SSC shows marked seasonal variations. The suspended sediment in the inner estuary presents higher in summer and lower in winter, while in the estuarine mouth and outer estuary, it is higher in winter and lower in summer. The transitional zone, i.e. the zone that has no seasonal changes should be at the upper section of Changxin Island. The amplitudes of SSC show larger in the outer estuary than in the inner estuary and in the Hangzhou Bay than in the Yangtze River estuary.

The annual change and spatial distribution of suspended sediment concentration are strongly affected by resuspension of sediments discharged from Yangtze River. The resuspension by wind waves and tidal currents is believed to be a dominant factor controlling the SSC field. The advection affects SSC of flood or ebb, which the ultimate cause is also sediment resuspension. The sediments carried by Yangtze River water enter into the estuary endlessly. Although the sediment concentration is lower, a large amount of fine sediments discharge into the offshore sea in one way, which are the main source of resuspended sediments under marine dynamics.

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