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Distributions of surficial sediments and its response to dynamic actions in the Xiamen Bay sea area, China

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Abstract

Sediment distribution is important for morphodynamic evolution and shoreline changes in coastal zones and estuaries. In the study, the data of 230 surface sediment samples collected from the Xiamen Bay sea area in September 2008 are used to investigate the spatial distribution and sediment transport pathway. The grain size distribution of surficial sediments in the Xiamen Bay area is shown distinctly in this study. In addition, the Grain Size Transport Analysis model is used for conveying trend analysis of the sediment in this area, particularly for determining the sediment movement trend. The results indicate that eight sediment types are present for samples, with clayey silt comprising the highest percentage in the study area at 65.22%. Moreover, in the different subareas, the characteristics of grain size parameters are obviously different owing to different sediment sources and hydrodynamic conditions. Furthermore, runoff, tides, and waves are the main forces dominating sediment dynamics on the seabed and tidal flats, and the sediment movement trend is closely related to hydrodynamic conditions.

Key words: Xiamen Port, Jiulongjiang Estuary, Xiamen Bay, surface sediments, grain size, dynamic response

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1 Introduction

Estuaries serve as an important interface and buffer zone between the sea and the land. Because of their low and gentle topography, high productivity and biodiversity, and navigational value, they have become important habitats for more than 5×10^9 of the human population in the world (Dai et al., 2014). Moreover, estuaries are also environmentally sensitive and vulnerable and are subject to changes by nature and anthropogenic activities (Yan et al., 2011). The combined effects of human activities such as damming in the drainage basin and natural processes such as typhoons have threatened estuary health. Although the sediment load from the Jiulongjiang River has been intensely changed by increasing human interference such as reservoir construction at the upstream site, the material fluxes delivered from the river to the sea preserve the record of both natural and anthropogenic environmental changes (Bianchi and Allison, 2009). The spatial distribution of surface sediments contains valuable information on sedimentary environments such as the sources and sinks of sediment, migration trends, and influence of ocean dynamics (Yang, 1999; Le Roux et al., 2002; Yang et al., 2008; Ma et al., 2010). To understand the response of the estuary to human interference, it is important to understand the sediment processes in the estuary. The spatial and temporal distribution of estuarine surficial sediment is affected by the complex interaction of river runoff, tides, and waves (Yan et al., 2011; Dai et al., 2011; Zhang et al., 2014). Therefore, understanding the sediment distribution process is very important for understanding the sediment transport process.

During the past decades, many studies focused on hydrodynamics, suspended sediment concentration, morphological effects, and harbor sedimentation in the sea area of Jiulongjiang Estuary and Xiamen Bay (Liu et al., 1984; Zeng, 1987; Cai et al., 1991, 1999; Chen et al., 2012; Luo et al., 2012). The research of the variation in sediment grain size in the entire littoral zone is rather little. Although some work has been conducted on surface sediment properties and distributions, the scope of these studies is limited with focus on only part of the area (Liao et al., 1987; Wang and Chen, 2006).

To study the sediment distribution of the entire Xiamen sea area, the present work provides an understanding of the overall characteristics of the surface sediment distributions and sediment transport trend to detect and their possible implications for dynamic actions, sediment transport, and estuary development.

2 Study areas

The Xiamen Bay, including the Jiulongjiang Estuary, is loc-

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ated in the southern coastal district of Fujian Province and belongs to a subtropical climate with warm and wet conditions throughout the year (Fig. 1). The coastal landform of Xiamen Bay is complicated. Land near the bay belongs to the Fujian and Guangdong coastal granite hilly district and is strongly weathered. In the bay, the shoreline is irregular and includes capes, small bays, and many islands. The Xiamen Bay is a tidal inlet type bay controlled by the local geological structure (Liu et al., 1984).

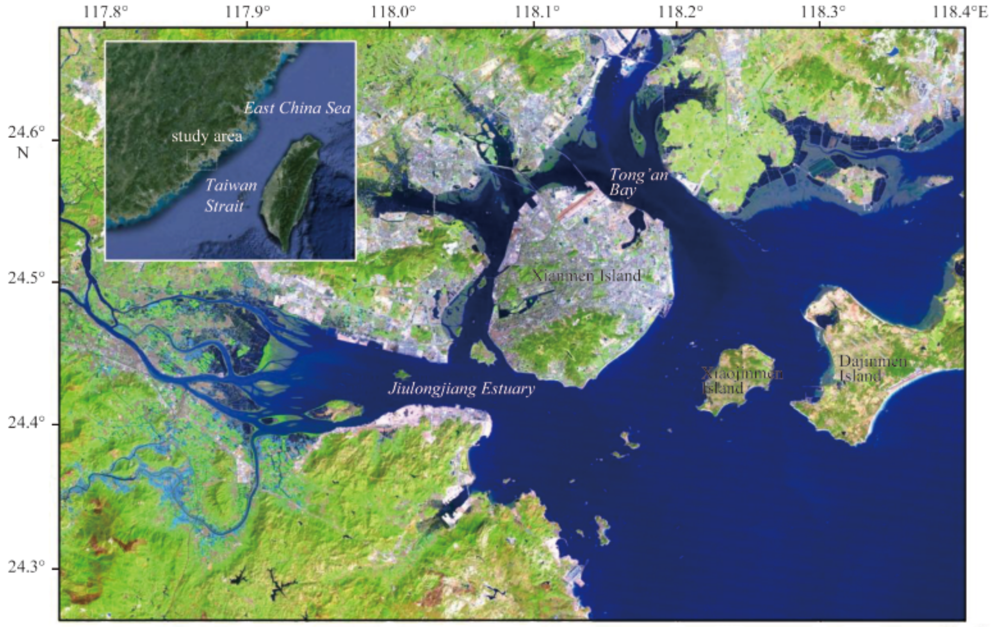

Fig. 1. Satellite image of the Xiamen Bay sea area.

Wind data of the Xiamen weather station from 1952 to 1999 in this region indicate a prevailing wind direction of NE with a frequency of 15%. The directions of the strongest and sub-strongest winds are NE and ESE with maximum wind speeds of 28 m/s and 19 m/s, respectively. Waves are primarily wind waves with the prevailing wave direction of E to SE. Tides of the Xiamen sea area are irregular semi-diurnal with a mean tide range 4.08 m and an extreme tide range of 6.42 m at Gulangyu Station (Zuo et al., 2014).

The area of Jiulongjiang Estuary and Xiamen Bay is a region of interaction between river runoff and ocean tide interaction area. The Beixi River and Xixi River, two main streams of the Jiulongjiang River, provide an influx of water and sediment, and tidal movement originates from the tidal current of the Taiwan Strait. This area is influenced by its unique coast, underwater topography, and littoral islands such as Xiamen Island, Dajinmen Island, and Xiaojinmen Island. Therefore, the sediment and hydrological conditions are more complicated, particularly in the different runoff and tide combined actions.

The Jiulongjiang River is the largest river discharging into the Xiamen Bay. Located at 24°13′–25°51′N, 116°47′–118°02′E, it is the second-largest river in Fujian Province, with a total length of 285 km and a drainage basin area of 14 740 km^2. Hydrological records show that the average annual water discharge was 1.21×10^{10} m^3, the average annual sediment discharge was 2.86×10^6 t from 1991 to 2009, and the largest annual sediment discharge was 6.29×10^6 t in 2006.

3 Materials and methods

A clamshell sampler was used to obtain a total of 230 surface sediment samples from the following six areas of the Jiulongjiang Estuary and Xiamen Bay in September 2008: I. the branch area of the Jiulongjiang River, II. the estuary area of Jiulongjiang River, III. the west sea area of Xiamen Island, IV. the east sea area of Xiamen Island, V. the Xiamen Bay mouth area, and VI. Tong'an Bay. The exact locations of the samples were determined by Global Positioning System (GPS, Fig. 2).

At each site, the readings of latitude and longitude were recorded and were used to determine its location on a topographic map. All the samples were collected from top 5–10 cm of the seabed, which should be associated with a time scale on the order of 1–10 years. Grain size distributions were determined in the laboratory, using an NSY-2 wide domain particle size analyzer by Hohai University, after sodium hexametaphosphate solution and ultrasonic dispersion. Statistical values such as median size, sorting coefficient, and skewness were defined on the basis of the analysis. Furthermore, the samples were classified on the basis of the different percentages of sand, silt, and clay by dry weight.

The classification for the distinction of sand, silt, and clay were frequently used below as follows:

Sand (S) is between 0.063 mm and 2.0 mm. Sediment between 0.063 mm and 0.25 mm is fine sand (FS); that between 0.25 mm and 0.5 mm is medium sand (MS); that between 0.5 mm and 2.0 mm is coarse sand (CS); that between 0.004 mm and 0.063 mm is silt (T); and that <0.004 mm is clay (Y).

Sediment samples were grouped according to the following principles:

Clayey silt (YT) is sediment with >50% silt, 20%–50% clay, and <20% sand; silt (T) has >50% silt, <20% clay, and <20% sand; sandy silt (ST) has >50% silt, 20%–50% sand, and <20% clay; and sand (S) has >50% sand, <20% silt, and <20% clay. The parameters of the mean grain size (Mz), sorting coefficients (σ_1), skewness (S_{Ki}), and kurtosis (K_g) were calculated on the basis of the grain-size class of each sample by using the statistical moment

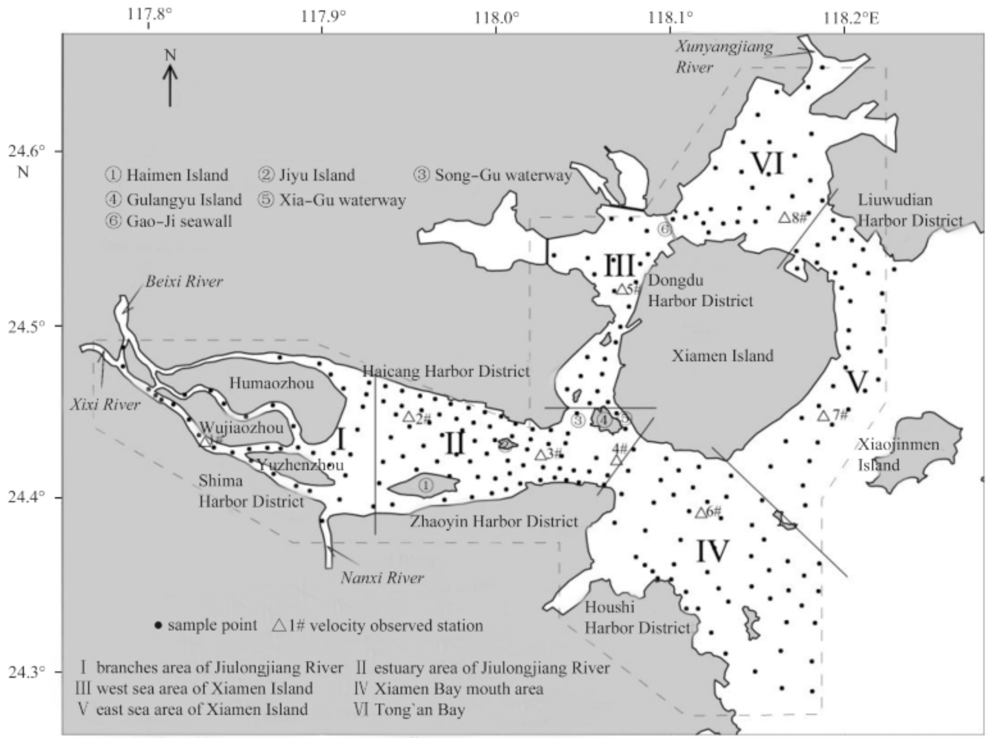

Fig. 2. Area distribution and sediment sampling points of the Xiamen Bay sea area.

method (McManus, 1988). In addition, the sediments were classified according to Folk's methodology (Folk et al., 1970), and the sediment components of all samples were calculated according to the grain-size classification scheme of "Specification for oceanographic survey—Marine geology and geophysics investigation" (CSOA, 1992).

The grain size trends analysis method was adopted for analyzing net transport pathways in the nearshore environment of the study area. The method was proposed by Gao and Collins (1991, 1992). The theoretical principles of this method are based on the two dominant trends of sediment transport, wherein sediment is finer, better sorted, and more negatively skewed in the downstream direction of transport (Case 1) and coarser, better sorted, and more positively skewed in the downstream direction (Case 2). A detailed explanation of the method can be found in Gao and Collins (1994).

4 Results

4.1 *Sediment grain size features*

4.1.1 *Sediment type distribution*

Surficial sediment type distribution in the Jiulongjiang Estuary and Xiamen Bay is shown in Fig. 3. According to the classification of CSOA (1992) and Folk (1970), eight sediment types for samples are presented including gravel (G), gravel coarse sand (G–CS), coarse medium sand (C–MS), coarse sand (CS), medium sand (MS), silt (T), sand–silt–clay (STY), and clayey silt (YT). Clayey silt is the most widely occurring type (65.22%) found in the study area (Table 1). The percentages of coarse medium sand and gravel coarse sand are 15.42% and 11.07%, respectively. Those of other sediment types including gravel, coarse sand, medium sand, silt, and sand–silt–clay are 0.4%, 1.98%, 1.58%, 2.77%, and 1.58% respectively.

Table 1. Sediment components

Sediment type	YT	G–CS	T	CS
Percentage/%	65.22	11.07	2.77	1.98
Sediment type	MS	STY	C-MS	G
Percentage/%	1.58	1.58	15.42	0.40

Fine particulate matters have the largest proportion in clayey silt at more than 60%. The dominant sedimentary characteristic in the area is fine particulate matter deposition.

According to the sediment type distribution graph in Fig. 3, the sediment distributions in the six areas are shown below:

(1) The bottom sediments of the branch area of Jiulongjiang Estuary are mainly coarse medium sand (C–MS), and the eastern seabed of the Humaozhou (i.e., Dachengping shoal) is floored by clayey silt (YT).

(2) In the Jiulongjiang Estuary area, the seabed is mainly floored by coarse medium sand (C–MS) and clayey silt (YT). Medium sand is distributed around the Haimen Island owing to local island effects, and clayey silt is mainly distributed in Haicang Harbor and Zhaoyin Harbor districts of the Xiamen Bay.

(3) The bottom sediments in the western sea area of Xiamen Island (i.e., Dongdu Harbor District of Xiamen Bay) and those in the Tong'an Bay are mainly clayey silt (YT).

(4) The eastern sea area of Xiamen Island is composed mainly of coarse particles including gravel–coarse sand (G–CS), gravel–coarse medium sand (G–CMS), coarse medium sand (C–MS), and medium sand (MS). Gravel–coarse sand is main sediment. In the Liuwudian Harbor District of Xiamen Bay, the main sediment is clayey silt with a small amount of coarse medium sand.

(5) The Xiamen Bay mouth area is composed mainly of clayey silt. Some coarse particles such as coarse medium sand (C–MS) and coarse sand (CS) are distributed near islands.

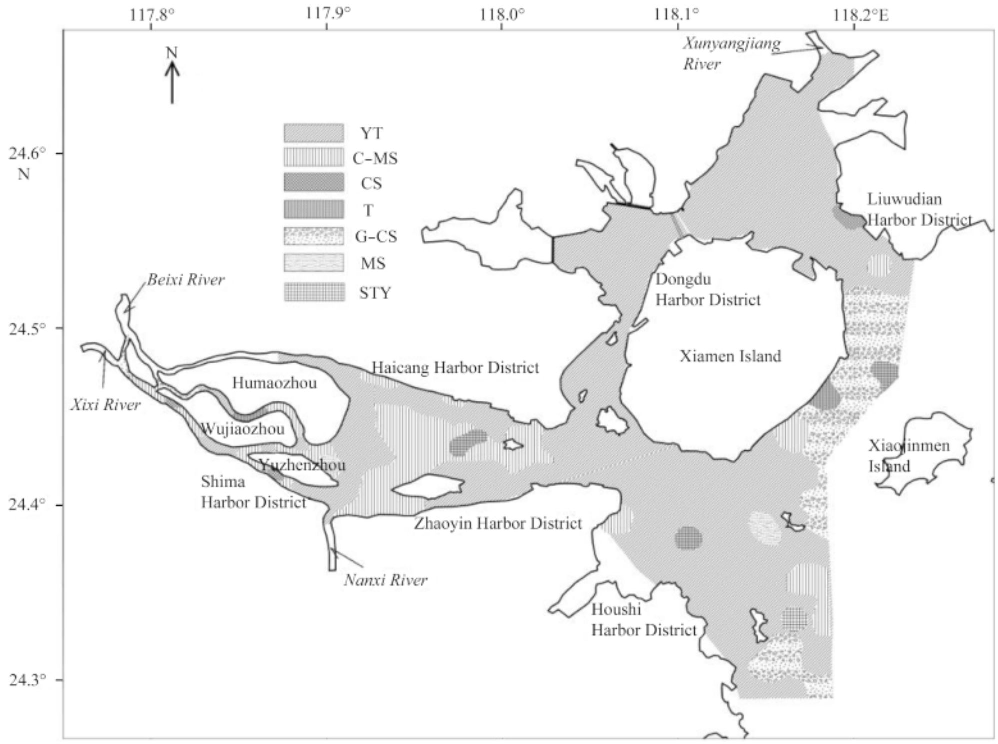

Fig. 3. Sediment type distribution in the Xiamen Bay sea area.

4.1.2 *Median size distribution*

Figure 4 shows the horizontal distribution of the sediment median size. The average median size is 0.254 mm; the approximate maximum and minimum sizes are 1.5 mm and 0.005 mm, respectively.

The median size is coarsest, 1.5 mm, in the branches area of the Jiulongjiang Estuary.

In the Jiulongjiang Estuary, the median size at Haicang Harbor District is generally 0.005–0.010 mm; that at Zhaoyin Harbor District is very fine, between 0.006 mm and 0.008 mm; and that at the north and south waters of Haimen Island is relatively coarse, between 0.100 mm and 0.500 mm. The coarser particle distribution area on the Haimen Island north side spreads eastward near the Jiyu Island with a median size of 0.100–0.500 mm.

In the Xiamen west sea area, water and sediment are exchanged between Xiamen western waters and open sea mainly through Song-Gu and Xia-Gu waterways. The bottom sediments are mainly deposited from suspended sediment water; therefore, the median grain size is relatively small, ranging from 0.005 mm to 0.010 mm.

In the Tong'an Bay, the median grain size is fine, at approximately 0.006 mm.

In the Xiamen eastern waters, the median size is generally from 0.04 mm to 1.5 mm. The sediment is relatively coarse and generally greater than 0.100 mm in Liuwudian Harbor District. In the channel between Xiaojinmen Island and Xiamen Island, the diameters are approximately 1.0 mm.

The median size is generally from 0.005 mm to 0.02 mm in the Xiamen Bay mouth waters. The sediment median size is between 0.005 mm and 0.010 mm in the CDE section waters of Xiamen Port Channel.

4.1.3 *Clay content distribution*

The clay content of the bottom sediment has an important influence in the sediment incipient motion, settling velocity, and dredging capacity of a dock basin or channel. According to the isograms of clay content shown in Fig. 5, the clay fraction is less than 20% at the Jiulongjiang Estuary branches area and in the eastern waters of Xiamen Island. That in other waters is more than 20%, particularly at the western sea area of Xiamen and the Tong'an Bay, which is approximately 40%. Due to the larger amount of unexposed features and no available sediment sources in this area, bottom sediments are mainly deposited from suspended sediment in water body with flood and ebb tides; therefore, the clay content is obviously high and the sediment particle size is fine.

In the Jiulongjiang Estuary, the clay content is less than 10% from Haimen Island south and north waters to the Jiyu Island waters. That at Haicang Harbor and Zhaoyin Harbor Districts is generally 30%. The maximum clay fraction is 40% at the west seabed of Xiamen Island (i.e., Dongdu Harbor District).

The clay fraction at Liuwudian Harbor District and the Xiamen Bay mouth area is approximately 30%; however, that at the Liuwudian channel between Xiamen and Xiaojinmen is approximatively zero.

4.2 ***Sorting coefficients***

The sorting coefficient of bottom sediment in the Xiamen sea area ranges from 0.29 to 2.18; that in the six sampling areas is 1.10–1.55 on average (Fig. 6). These relatively high values indicate that the sediment was poorly sorted.

In general, the sorting coefficient distribution corresponds strongly with the median grain size distribution, in which the sorting is relatively good at the coarse particles region. The sorting coefficients are mostly 1.0–2.5 for fine particle sediment and 0–1.0 for coarser particle sediment.

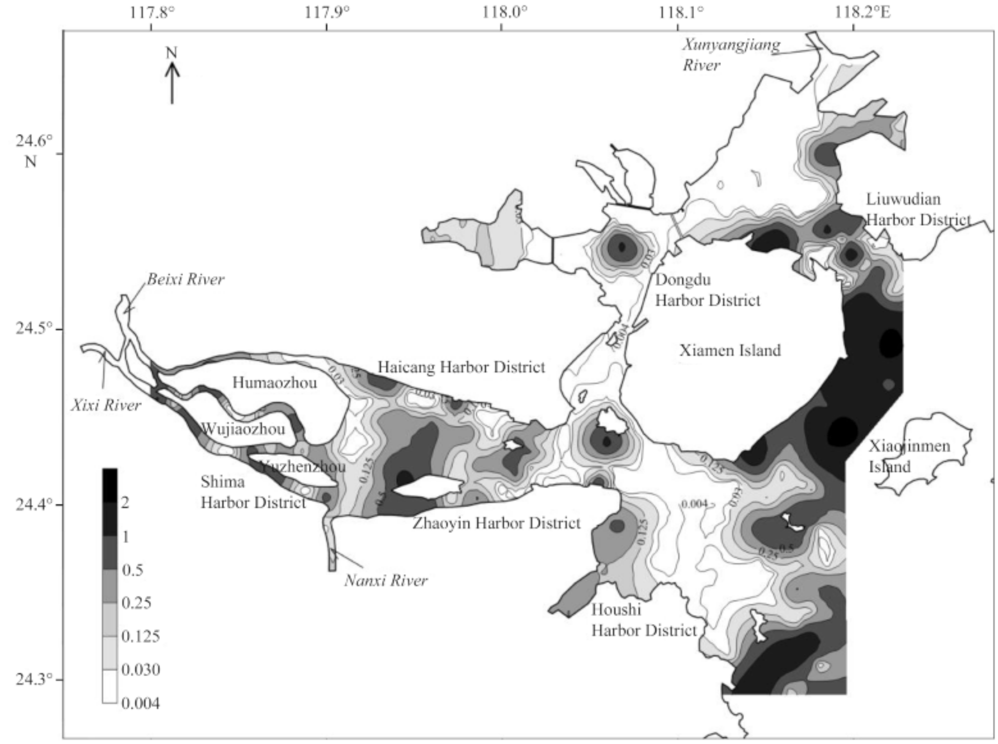

Fig. 4. Median particle diameter (mm) distribution in the Xiamen Bay sea area.

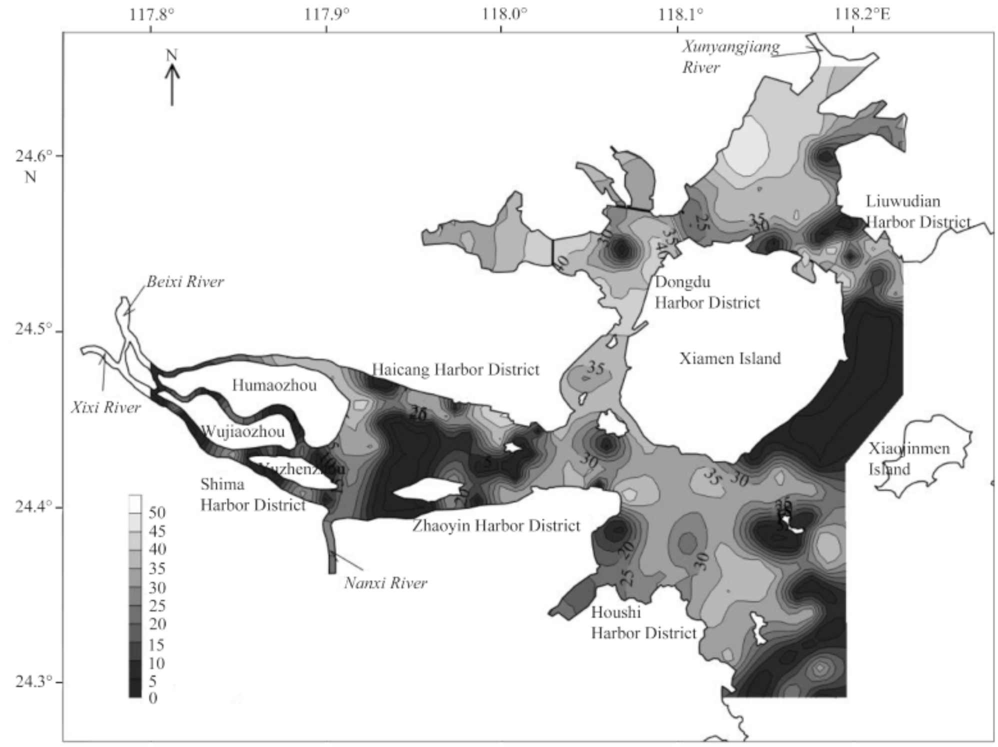

Fig. 5. Clay content (%) distribution in the Xiamen Bay sea area.

4.3 *Sediment grain size trend*

The grain size trend analysis model of Gao and Collins (1992) has been widely used in many coastal areas, such as the littoral area of Huanghe River (Yellow River) Delta (Ren et al., 2012) and Bohai Strait (Cheng et al., 2004) in China, the Bay of Seine in France (Poizot et al., 2006), and Izmir Bay (Duman et al., 2004) in Turkey. In the section, this model is applied to analyze the sediment data to further understand the behavior of sediment transport.

In the grain size trend calculations, the sampling interval and

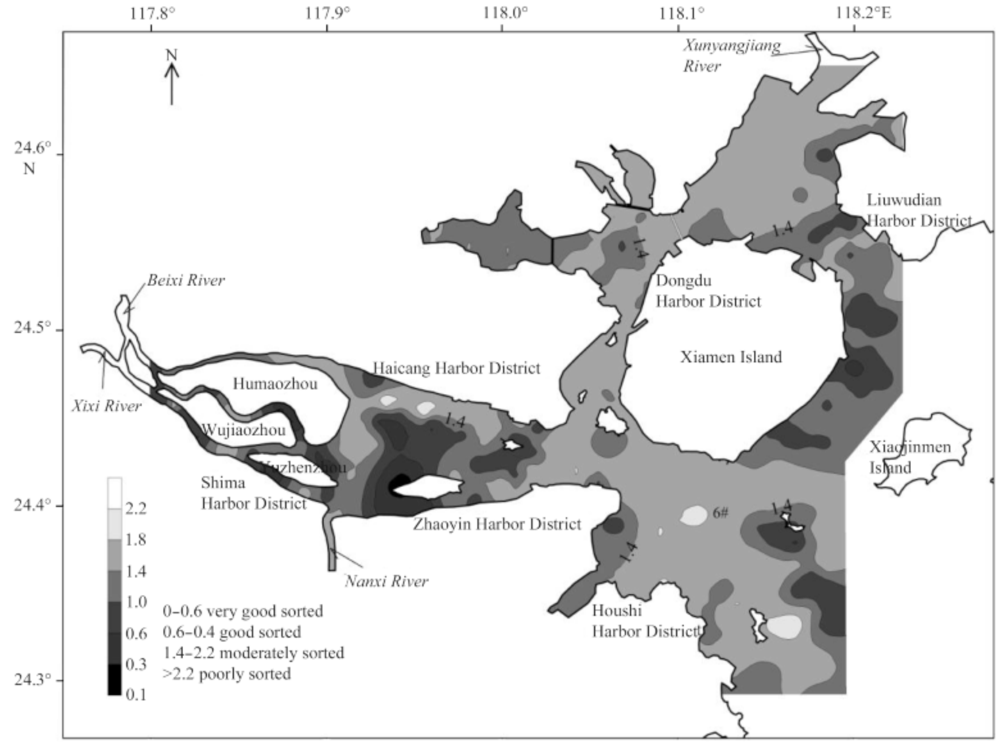

Fig. 6. Sorting coefficient distribution in the Xiamen Bay sea area.

the mean range values of the three grain size parameters of mean size, sorting coefficient, and skewness were separately used to calculate the net sediment transport trend vectors in the Xiamen sea area. The results are shown in Fig. 7.

The figure shows a trend of eastward sediment transport in Jiulongjiang Estuary and at the bay mouth. Sediment material from Jiulongjiang River is deposited in the estuary, and a portion is transported to the Xiamen Bay outside. A small amount is

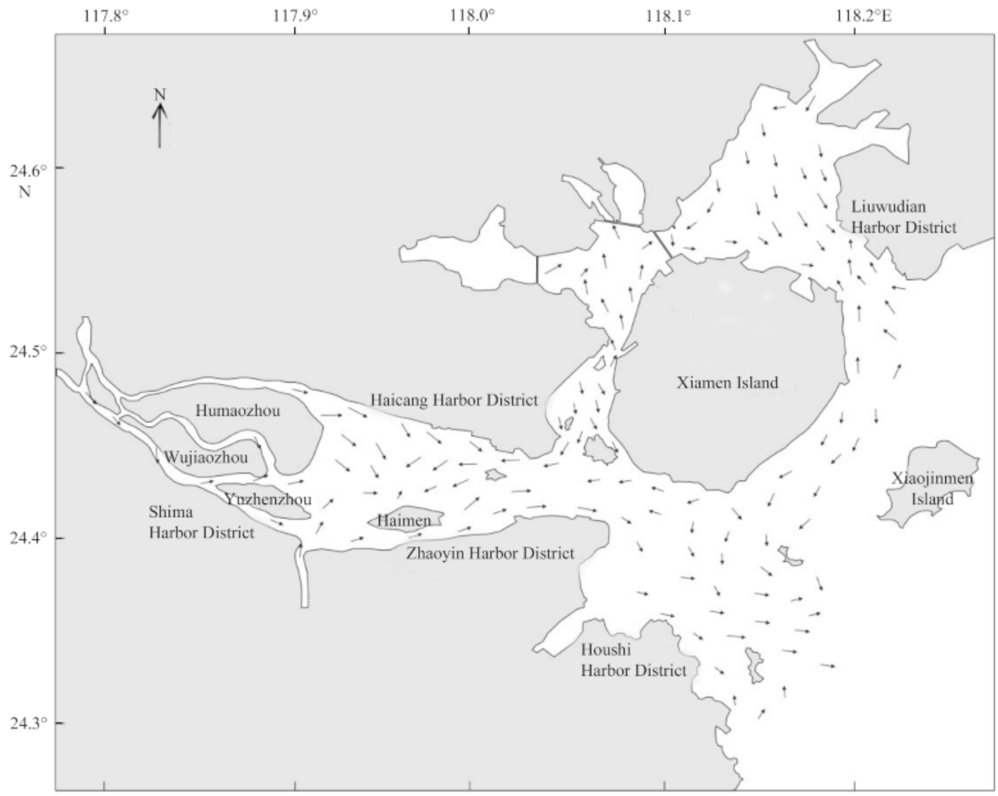

Fig. 7. Surface sediment migration trend in the Xiamen sea area.

transported and deposited on south of the Xiamen western waters under the action of flood currents.

The trends of outward sediment transport from the inside to the outside of Tong'an Bay are believed to be controlled by residual tidal currents and wind waves.

These sediments are transported toward the Gao-Ji seawall and accumulated at the shoals of the eastern side of the seawall. As a result, the sediments can be easily deposited with a continuous supply at the east side of the shoals. These phenomena reflect the depositional environment with the primary effects of tidal currents and secondary functions of waves and runoff.

In the Xiamen eastern waters, sediment transport trends are to the north. This result occurs because the flood duration is longer than the ebb duration, and the average and maximum flood velocities are slightly greater than the ebb velocities in the waterway between Xiamen and Xiaojinmen Islands.

5 Discussion

5.1 *Sedimentary dynamic processes*

Each area has different sedimentary characteristics at the Jiulongjiang Estuary and Xiamen Bay, owing mainly to differences in sediment source and hydrodynamic processes. Runoff, tides, and wave are the main forces dominating the sediment dynamics on the seabed and tidal flats.

Area I is the branches area of Jiulongjiang Estuary, which is affected mainly by upstream runoff. Sediment carried by upstream runoff settles as the discharge cross-section gradually widens; however, fine sediment continues to be transported downstream under the action of water flow. Therefore, the sediment of the area is relatively coarse, and the sediment types are mainly CS and C–MS.

Area II is the estuary, where coarse and fine sediments of mainly C–MS and YT are distributed. The area is affected by the water and sediment from upstream, flood tidal currents, and the mixing of saltwater and freshwater. Islands are present, and their local waters have relatively strong hydrodynamic changes. The port areas, Haicang Harbor District and Zhaoyin Harbor District, are composed mainly of fine particle matter.

Area III includes Xiamen western waters sheltered against strong wind waves and tidal currents; the average flow velocity of the spring tide is 0.3–0.4 m/s. Because there is no outer sediment source, sediment sources include the surface sediment of the seabed and tidal flats in addition to repeated transport under current action. The sediment here is composed mainly of fine particles settled from suspended sediment.

Area IV is the bay mouth area, which is affected mainly by tides. The sediment types are relatively single, which is mainly YT. Local has coarse particle by the island effects. In addition, the sediment frequency curve and its peak shape are normal, which shows that the sedimentary environment is relatively stable.

Area V includes Xiamen eastern waters. The sediment grain size is generally coarse in this area, besides local area related to geological conditions. Hydrodynamic forces in this area are stronger than those in other areas. Influenced by wind waves, the average flow velocity of the spring tide is approximately 1.0 m/s.

Area VI includes Tong'an Bay waters, in which sediment particles are fine and the sediment type is YT. These features indicate relatively weak hydrodynamic conditions and a stable sedimentary environment. These conditions are related to the area's close location to the Xunyangjiang Estuary area and the poor water exchange owing to Gao-Ji seawall blocking.

5.2 *Effects of hydrodynamic factors*

5.2.1 *Effects of run-off*

The Jiulongjiang River is the largest river discharging into the research area. Beixi River and Xixi River are two main streams with average annual water discharges of 81.9×10^8 m^3 and 39.2×10^8 m^3, respectively. Their average annual sediment discharges from 1991 to 2009 were 183.7×10^4 t and 55.5×10^4 t, respectively. The Nanxi River is a small tributary with a short drainage process and low water yield. There are no available hydrologic statistics on the tributary.

Sediment carried by runoff is main sediment source of the Xiamen Port waters. Sediment discharge is closely related to sediment concentration, which have important effects on the surficial sediment distribution (Fig. 8).

5.2.2 *Effects of tidal current*

The Xiamen sea sedimentary features are mainly developed by combined effects of open-sea tidal currents and runoff from the Jiulongjiang River. The tidal current strengths of different parts play important roles in sediment distribution. Near Shima Harbor District, south of Wujiaozhou Island, the starting velocity of sediment particles is generally about 0.9 m/s, but the flow ve-

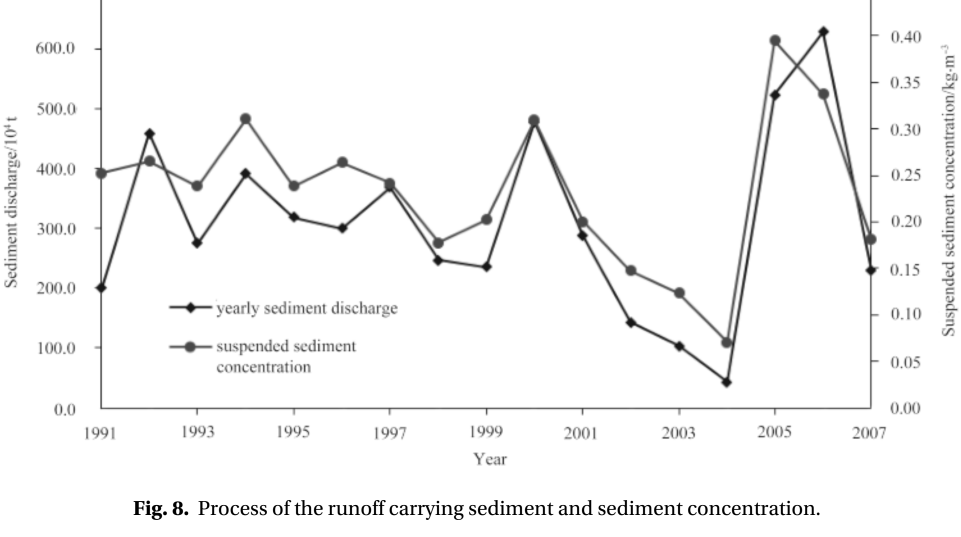

Fig. 8. Process of the runoff carrying sediment and sediment concentration.

locity is approximately 0.6 m/s. The flow does not have sufficient power to start coarse sediment particles on bed; therefore, surficial sediments near Shima Harbor District are composed of coarse particles. Fine sediment friction can be transported to downstream reach under the flow velocity. As the discharge cross-section gradually widens, the current velocity decreases in Jiulongjiang Estuary with an average velocity 0.5 m/s (Table 2). Under these conditions, the fine particles in suspended load easy settle on the seabed.

In the Xiamen western sea area, the average and maximum velocities are less than 0.5 m/s and 0.8 m/s respectively, which enables the suspended sediment to deposit under the low-velocity conditions of flow diffusion, leading to relatively small particle sizes at the west part of Xiamen Island. The Xiamen mouth areas have a certain extent increase in current velocity with a maximum value of more than 1.1 m/s (Table 2, Fig. 9), which may enhance the sediment transport ability and wash away the fine bed-load.

5.2.3 *Effects of waves*

In addition to flow currents, wind waves maybe a major dynamical factor in the temporal distribution. The uplifted effects of wind waves can result in a large amount of bed-load re-suspension.

Due to the coastline and terrain effects, there is a great difference between outside and inside waters in the waves. Wave height gradually reduces from outside to inside (Figs 10 and 11). At the bay mouth, the maximum wave height was more than 6.9 m during the Typhoon 7309 (Zheng et al., 2006); in the west sea area, the wave height was only 1.4 m. This indicates that the dynamical erosion and deposition differ among areas because of seasonal and regional changes in wind waves.

Fine particles such as silt and clay can be uplifted and moved away under the action of normal waves and then back-deposited with no wave effects, which results in a clayey silt sediment zone with poor sorting features. In addition, the mean wave effective depth can reach a value of 6 m at the mouth of Xiamen Bay, facing intense wave action from the open sea.

During the past year, this area was mainly impacted by peripheral typhoons Dan (199914), Bilis (200604), and Fanapi (201011), with 35 m/s maximum wind speed. Therefore, a high amount of coarse sediment can be uplifted near the coastal

Table 2. Average and maximum values of the measured vertical tidal velocity during spring tide in September 2008

			Station							
			1#	2#	3#	4#	5#	6#	7#	8#
Mean velocity	flood tide	velocity/m·s^{-1}	0.56	0.54	0.61	0.66	0.44	0.69	0.59	0.42
		direction/(°)	303	278	274	302	18	318	25	316
	ebb tide	velocity/m·s^{-1}	0.56	0.39	0.59	0.74	0.38	0.68	0.49	0.41
		direction/(°)	119	64	96	122	203	146	214	138
Max velocity	flood tide	velocity/m·s^{-1}	0.87	0.85	0.84	1.09	0.68	1.03	1.01	0.71
		direction/(°)	305	281	274	310	21	317	24	318
	ebb tide	velocity/m·s^{-1}	0.92	0.55	1.05	1.27	0.87	1.11	0.85	0.65
		direction/(°)	117	72	100	116	216	147	212	137

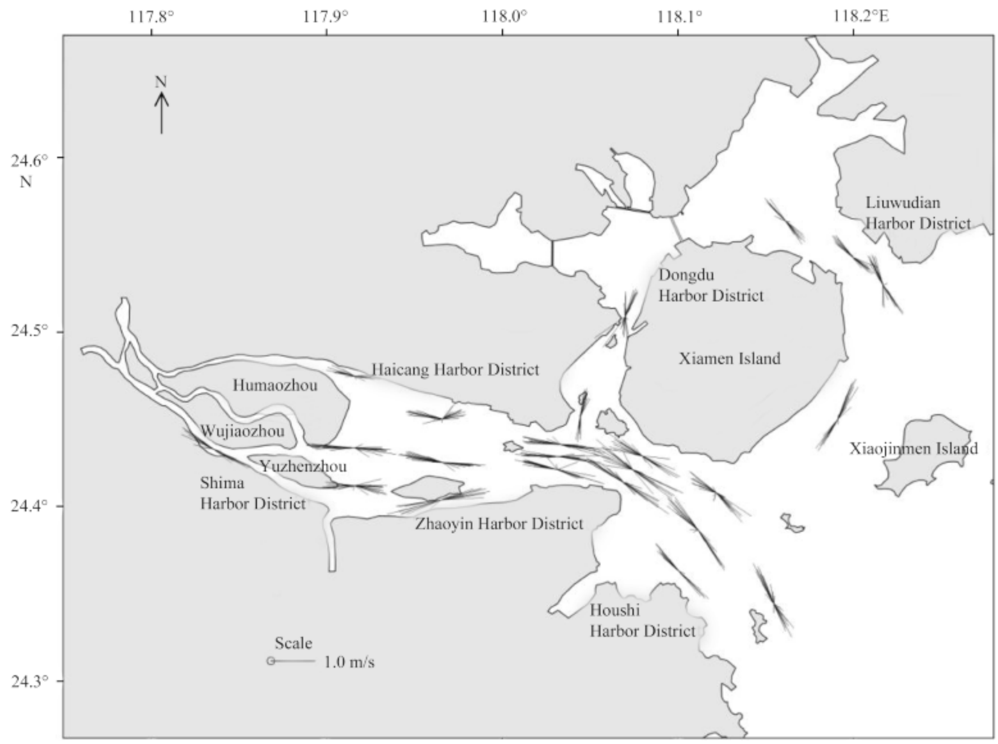

Fig. 9. Sketch of the vector plot of tidal currents.

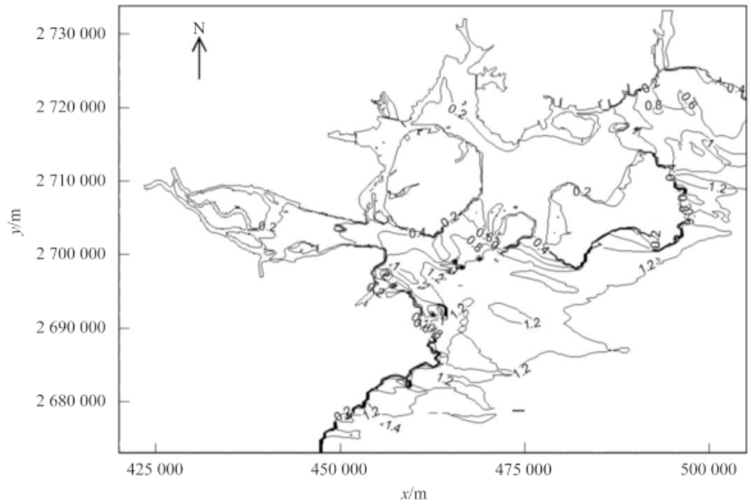

Fig. 10. Average wave height distribution (m) of ESE by numerical model.

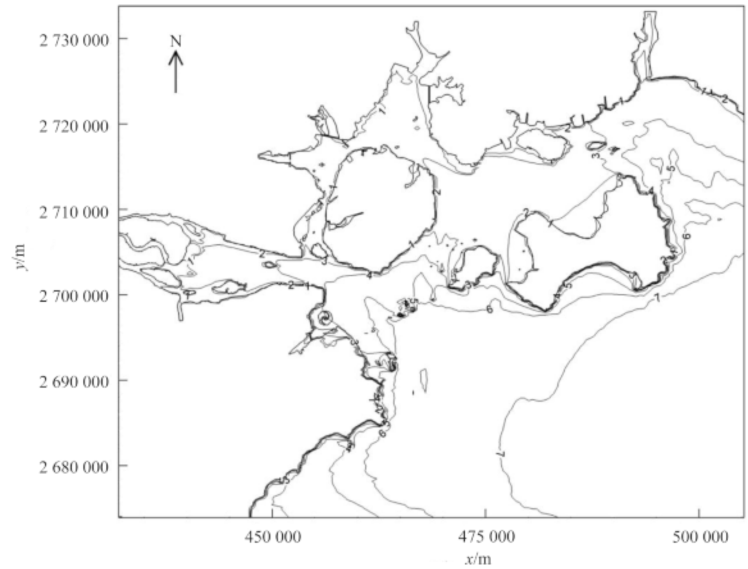

Fig. 11. Wave height distribution (m) during the Typhoon 9914 by numerical model.

shoal, where the water is very turbid, to form a large shoal of coarse sand in the Houshi Harbor District. This mechanism could explain why the sediment samples collected in this area were relatively coarse and better sorted.

6 Conclusions

The grain size distribution of surficial sediments in the Xiamen Bay area is clearly shown in the paper. The results of this study are shown in the following points:

(1) Eight sediment types are represented in the samples, with clayey silt most prevalent in the study area at 65.22%. The results show that dominant sedimentary characteristics in this area are of those of deposited fine particulate matter.

(2) In the Jiulongjiang Estuary, the median size in Haicang Harbor District is generally from 0.005 mm to 0.010 mm; the median grain size is relatively small, ranging from 0.005 mm to 0.010 mm in the western waters of Xiamen Island. The median grain size is fine, approximately 0.006 mm at the Tong'an Bay; in the Xiamen eastern and Xiamen Bay mouth waters, the median sizes are generally from 0.04 mm to 1.5 mm and from 0.005 mm to 0.02 mm, respectively.

(3) The sedimentary characteristics in the Xiamen sea region vary among specific areas, owing mainly to differences in sediment source and hydrodynamic processes. Runoff, tides, and waves are the main forces dominating the sediment dynamics on the seabed and tidal flats.

(4) Grain size analysis reveals a net sediment transport trend at the Jiulongjiang Estuary and the bay mouth. The results are broadly consistent with the combined action of runoff, residual tidal current, and wave hydrodynamics and are confirmed by the temporal and spatial changes in sediment distribution.

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