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Analysis and Prediction of Influence Imposed on Jiaozhou Bay Tidal Currents and Tidal Energy of M_2 Tidal System by Jiaozhou Bay Reclamation

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Abstract The 3-D ECOMSED ocean model was applied to establish a time-dependent boundary model for Jiaozhou Bay (JZB), in which the operator-splitting technique was used and the 'dry and wet' method was introduced. The influence caused by JZB reclamation on the surface level, residual currents, tidal system and tidal energy of M_2 tidal system were predicted and analyzed. The results show that JZB reclamation has slight impact on the M_2 tidal system, in which the variation of amplitude and phase is less than 1%.The changes of the currents and residual currents in Qian Bay and near the reclamation areas are greater, but in other areas the changes are smaller, in which the currents have a change of around 1%, while the residual currents change ranges from 1.82%–9.61%. After reclamation, the tidal energy fluxes increase by 2.62%–5.24% inside and outside the JZB mouth, but decrease by 20.21%–87.23% near Qian Bay and the reclamation area.

Key words reclamation; tidal energy flux; ECOMSED; hydrodynamics variety; Jiaozhou Bay

1 Introduction

In recent years, with the rapid development of Qingdao's economy and the growing demand for land, the city's authorities are engaged in a reclamation project around Jiaozhou Bay (JZB). According to a survey published by North China Branch of the State Oceanic Administration, the JZB aquatic area has declined 35% in the last 75 years, from 535 km^2 in 1928 to 367 km^2 at present. The pivotal reason for this dramatic decrease is the increasing reclamation activities, especially wanton reclamations (Dai *et al.*, 2007). These activities have caused the changes of coastal line and seabed topography, which might change the hydraulic characteristics and the water exchange capacity of the bay with the coastal sea waters and thus have some impact on marine ecology and sediment transport. In this study, a time-dependent boundary model for JZB was established, in which the operator-splitting technique was adopted and the 'dry and wet' method was introduced (Casulli and stelling, 1995; Lou *et al.*, 2002; Sun and Zhang, 2001; Xu *et al.*, 2001). We mainly focused on the influence of the reclamation on marine hydraulic dynamics, including the effects on sea level, residual currents, and tidal system. Changes due to topographic variations were also compared.

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2 Model Description

2.1 Study Domain and Grid Setting

JZB is located on the west coast of the Yellow Sea (YS), with an average water depth of about 7 m (Fig.1), and is a partly enclosed waterbody with a narrow channel between Xuejia Island and Tuan Island that connects the bay to the YS. The study areas included JZB and its adjacent area (35°54′N–36°18′N, 120°7′E–121°37′E).

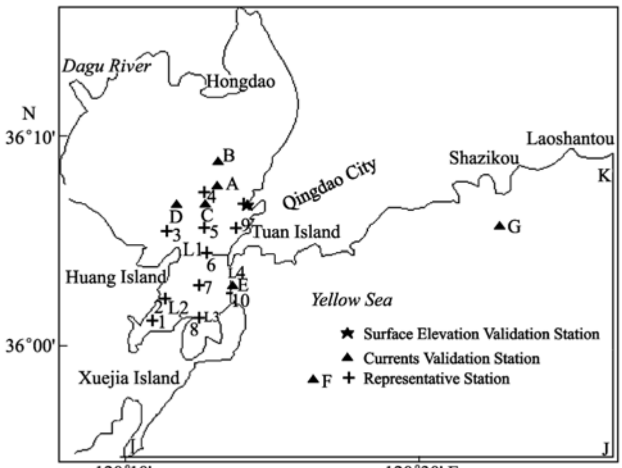

Fig.1 Topographical map and the location of tidal verification stations.

In this study, a rectangular grid with a spatial resolution of 200 m and σ coordinate were adopted horizontally and vertically. C staggered grid finite difference (semi-implicit) method (Blumberg, 2002; Casulli and Cattani, 1994) was used for numerical simulation.

2.2 Boundaries

The coastline boundaries were based on charts Nos.12351 and 12339 published in China in 2000, with reclamation projects related to the construction of ports, express ways *etc.*, taken into consideration. Since JZB is a large tidal zone, a time-dependent 3-D model with the 'dry and wet' method was used. As JZB is dominated by the M_2 tide (Ding, 1986; Chen, 1980), the water boundary was obtained on the basis of M_2 harmonic constants acquired through harmonic analysis of 30 d observed sea level.

2.3 Predicted Results

Four representative stations were selected for tidal currents validation (see Fig.1) with observed current data. The tidal level validation data came from the Dagang Tide Station. The validation of tidal level and currents is illustrated in Figs.2 and 3, respectively. As shown in Figs.2 and 3, the simulated values of M_2 tide agree well with the observed data. In Fig.2, the observed tidal levels of M_2 are those obtained from harmonic analysis of 30 d observed elevations at Dagang Tide Station. In Fig.3, the observed M_2 tidal currents are those obtained from harmonic analysis of 30-day observed surface currents at Stations I, J, K. The harmonic analysis method refers to those of Fang *et al.* (1980) and Huang and Huang (2005).

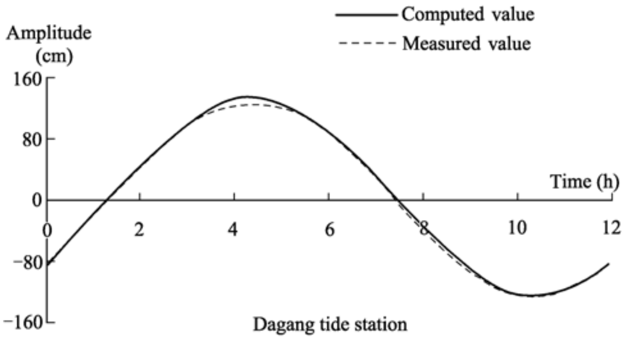

Fig.2 Surface elevation verification curve.

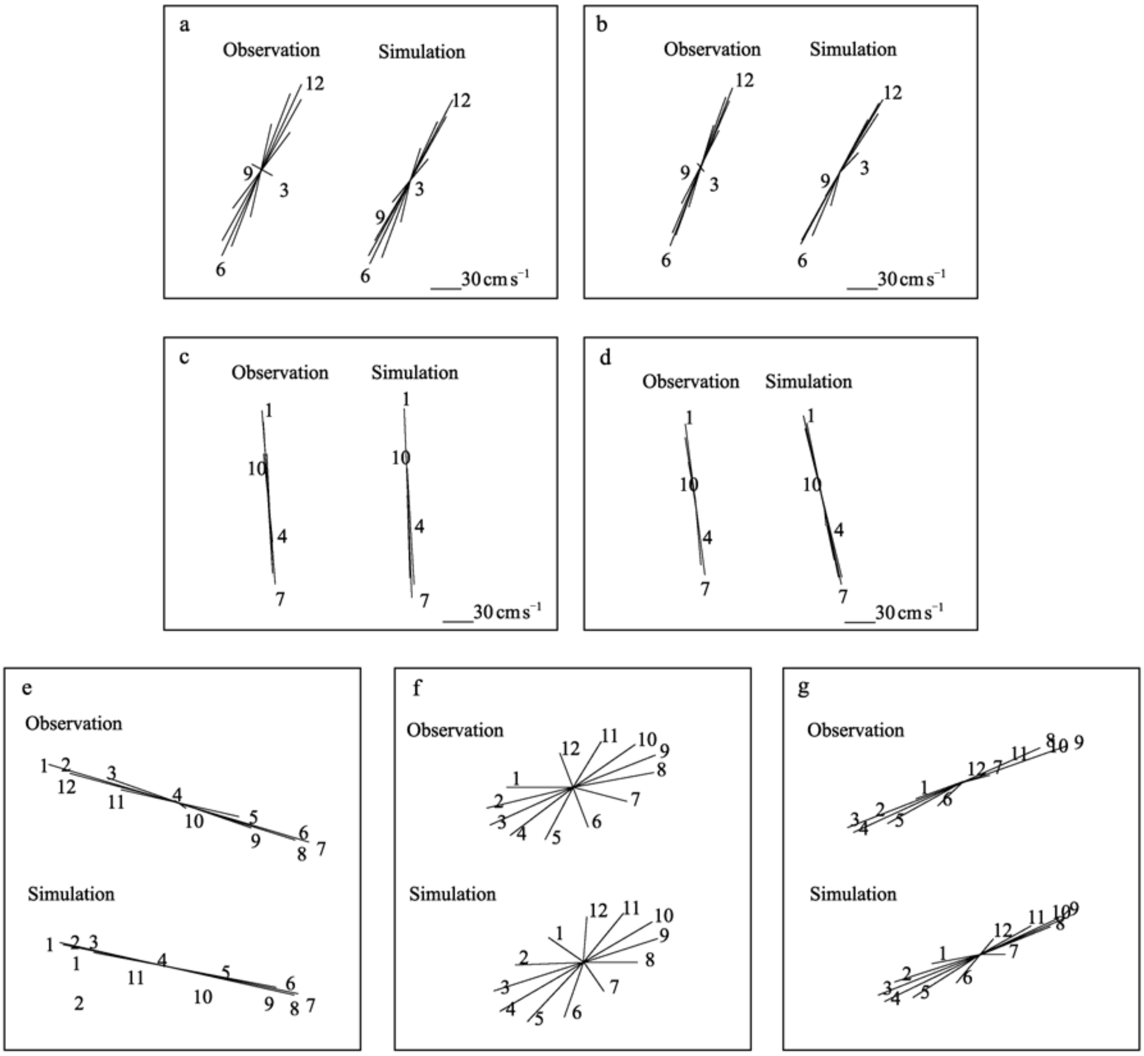

Fig.3 Validation of current roses.

The M_2 cotidal chart of JZB in Fig.4 shows that the tide propagates from northeast to southwest outside JZB and constitutes a counterclockwise tidal system; after the tidal wave enters JZB, it travels inward. The amplitude adjacent to the southeast corner of Fig.4 is less than 100 cm, and it increases as the tidal wave travels inside JZB, with a maximal value of 130 cm at the northern end of the bay. These results agree well with the historical data (Sun and Zhang, 2001; Zhang and Sun, 2005).

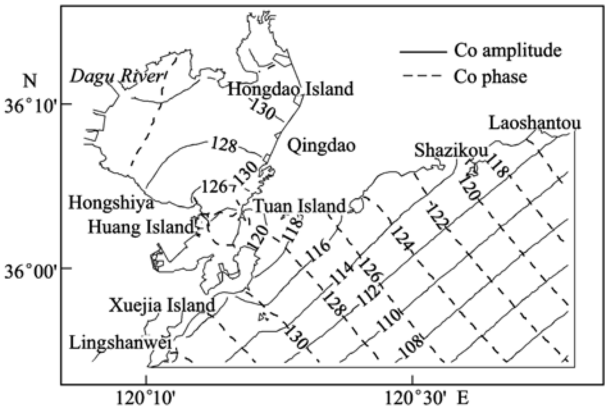

Fig.4 M_2 cotidal chart.

3 Influences on the Tidal Currents, Tidal Level, and Tidal System by Reclamation

In this study, the variation in the tidal currents, tidal level and tidal system caused by reclamation was studied based on the present and future topography (Fig.5).

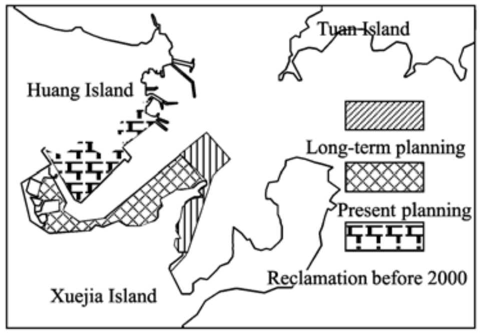

Fig.5 Illustration of future and present topography.

3.1 Influence on the Tidal Currents

Ten representative stations (see Fig.1) were chosen to make a comparison between tidal currents at mid-flood and mid-ebb tides before and after reclamation. The results are shown in Table 1.

3.1.1 Impact inside JZB

Table 1 shows that the currents at Stations 3, 4, 5 and 9 are changed by less than 1.3% in velocity and direction. The velocity is increased at Stations 5 and 6, while decreased at Stations 4 and 9. However, on the whole, the reclamation in Qian Bay causes the velocity in inner JZB to diminish and the impact is smaller during the ebb tide than during the flood tide.

Table 1 Variation of tidal currents due to topographical change

Location	Station		Absolute velocity change Δu (cm s^{-1})	Relative velocity change (%)	Absolute direction change (°)	Relative direction change (%)
Inside the bay	3	flood	0.0	0.2	0.2	0.1
		ebb	0.0	0.1	–0.1	0.3
	4	flood	–0.1	0.2	–0.2	0.2
		ebb	–0.2	0.6	–0.1	0.1
	5	flood	0.2	0.6	–0.4	0.4
		ebb	–0.1	0.5	0.9	1.3
	6	flood	3.9	6.2	2.2	2.0
		ebb	0.4	1.4	2.6	3.9
	9	flood	–0.4	1.2	–0.3	0.5
		ebb	–0.1	0.3	0.1	0.0
Near the mouth	1	flood	–6.1	53.8	15.8	7.3
		ebb	–6.6	55.7	17.8	49.7
	2	flood	–7.9	54.8	71.4	46.5
		ebb	–1.8	16.9	48.1	209.0
	7	flood	2.8	7.7	–5.9	4.1
		ebb	18.2	65.6	–1.8	5.8
	8	flood	–9.2	46.0	7.1	3.4
		ebb	–10.4	44.7	27.4	180.0
Outside the bay	10	flood	–0.7	0.9	–0.7	0.5
		ebb	1.2	1.1	–1.0	3.7

3.1.2 Impact near the mouth of JZB

Table 1 shows that the reclamation imposes more impact on outer JZB, where the relative velocity changes at Stations 1, 2, 7 and 8 range from 7.7% to 65.6%; the relative direction changes are even greater, especially at Stations 2 and 8. The current turns to the right during the flood tide in the northeast and adjacent region of the reclamation area, while in the northwest and north of the reclamation region, it turns left. The situation is reversed during the ebb tide. The cause of this phenomenon is the change of tidal energy due to reclamation.

3.1.3 Impact outside of JZB

It can be seen by comparing the data for Station 10 that the reclamation has slight impact outside JZB.

In summary, the changes of coastline will have some impact on JZB hydrodynamics, especially in outer JZB and the reclamation area.

3.2 Impact on Residual Currents

In this study, the residual currents were calculated via current averaged over a complete tital cycle. And the residual currents in the surface and bottom layers are illustrated in Figs.6 and 7.

The magnitude of tidal residual currents is much smaller than that of tidal currents; however, the pivotal factors in mass transport in the ocean environment are tidal residual currents and sea water mixing processes. Table 2 shows that the changes in tidal residual currents are much more evident than those in currents.

3.2.1 Impact inside JZB

Table 2 shows that the changes at Stations 3, 4, 5, 6, and 9 are greater than those at the other stations, where the absolute velocity changes are less than 1 cm s^{-1}, and the relative velocity change ranges from 1.82%–9.61%, except that the relative velocity change at Station 3 is less than 1%. At all the representative stations, the variation of direction is much smaller.

3.2.2 Impact near the mouth of JZB

Table 2 reveals that significant changes occur mostly near the mouth of JZB, where the absolute velocity changes at the surface are in the range from −4.55 to −0.34 cm s^{-1}, the relative velocity changes are from 29.50% to 70.05%, and the changes in direction are much greater.

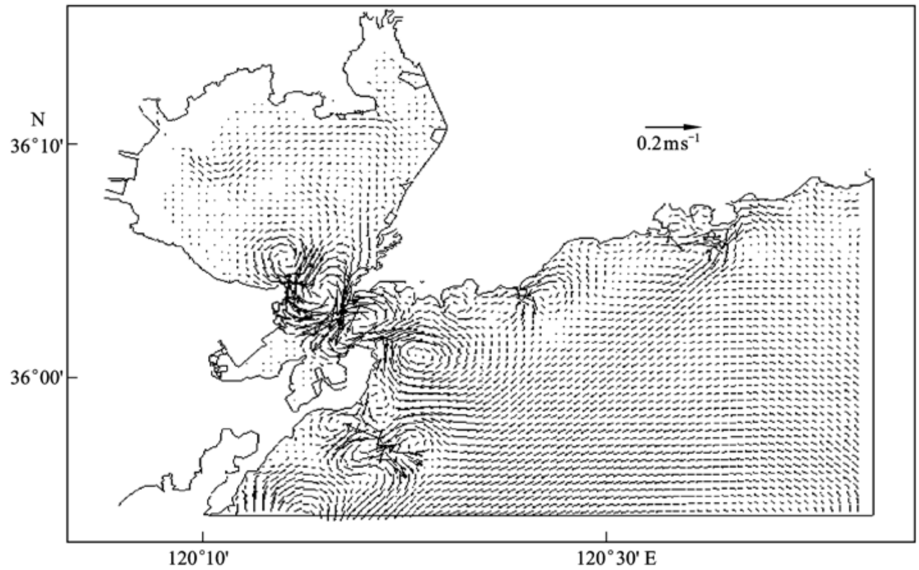

Fig.6 M_2 residual current (surface layer).

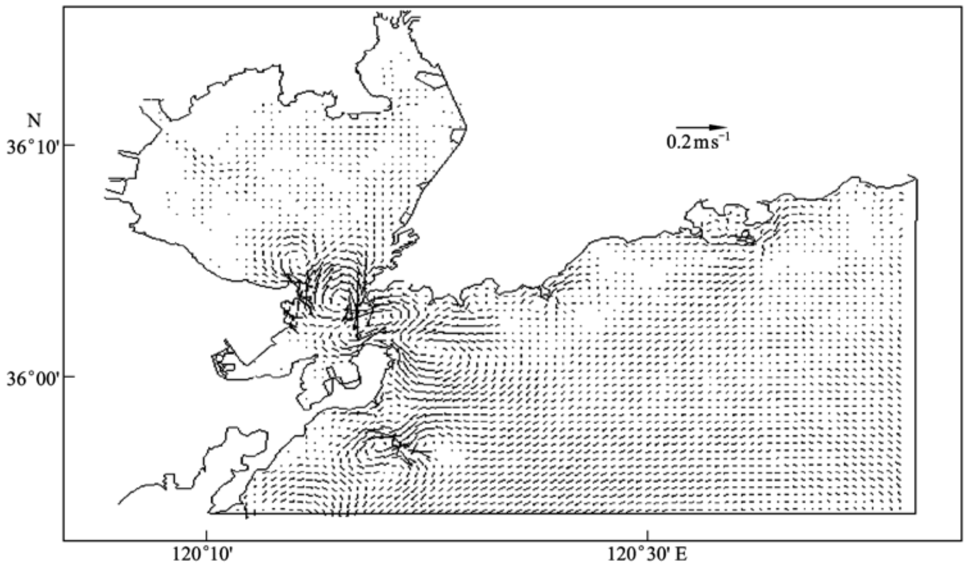

Fig.7 M_2 residual current (bottom layer).

3.2.3 Impact outside JZB

This can also be seen from Table 2. For instance, the absolute and relative velocity changes at the surface at Station 10 are 1.41 cm s^{-1} and 33.04%, respectively; while the changes of absolute and relative velocity at the bottom are 0.83 cm s^{-1}, and 14.89%, respectively.

Comparing the results of changes in currents, we can find that the reclamation will make a much greater impact on tidal residual currents, for both the residual velocity and direction can be changed significantly.

3.3 Impact on the Tidal System

Table 3 shows that reclamation activities have only a slight impact on JZB M_2 tidal system. The amplitudes at the ten stations decrease by 0.05–0.30 cm after reclamation, though the amplitudes increase by 0.26 cm at Stations 1 and 2. While the phases increase by 0.02°–0.15°, they decrease by 0.14° and 0.5° at Stations 8 and 10, respectively.

Table 2 Variation of residual currents due to topographical change

Location	Layer		Absolute velocity change Δu (cm s^{-1})	Relative velocity change (%)	Absolute direction change (°)	Relative direction change (%)
Inside the bay	3	surface	–0.05	0.86	0.29	0.10
		bottom	–0.04	0.73	0.09	0.03
	4	surface	0.06	3.14	–3.95	3.12
		bottom	0.05	5.13	–3.86	3.44
	5	surface	0.45	5.40	–0.21	0.34
		bottom	0.31	7.86	0.01	0.03
	6	surface	0.75	8.33	2.30	1.83
		bottom	0.15	1.82	4.61	6.91
	9	surface	0.50	9.61	–0.87	0.33
		bottom	0.33	8.07	0.12	0.05
Near the mouth	1	surface	–0.34	55.88	31.34	38.20
		bottom	–0.07	35.14	22.50	46.14
	2	surface	–1.15	45.16	209.12	142.69
		bottom	0.75	67.74	–140.72	96.93
	7	surface	–2.93	29.50	18.24	8.36
		bottom	–1.34	30.21	43.19	17.39
	8	surface	–4.55	70.05	–28.50	8.40
		bottom	–3.12	72.08	–33.88	9.82
Outside the bay	10	surface	1.41	33.04	–5.30	1.62
		bottom	0.83	14.89	–6.24	48.67

Table 3 Variation of tidal system at the representative stations

Location	Station	Absolute amplitude change ΔS (cm)	Relative amplitude change (%)	Absolute phase change Δd (°)	Relative phase change (%)
Inside the bay	3	–0.06	0.05	0.03	0.02
	4	–0.05	0.04	0.03	0.02
	5	–0.06	0.05	0.03	0.02
	6	–0.07	0.06	0.03	0.02
	9	–0.06	0.05	0.03	0.03
Near the mouth	1	0.26	0.21	0.08	0.06
	2	0.26	0.21	0.15	0.11
	7	–0.08	0.07	0.02	0.02
	8	–0.30	0.25	–0.14	0.10
Outside the bay	10	–0.05	0.04	–0.5	0.04

4 Impact on Tidal Energy Flux

In this study, the concept of tidal energy flux and the dynamic effects due to topographical changes were analyzed. Generally speaking, topographical changes are caused by the deposition and erosion of sediments near the seabed and the coastlines. This is a process of sediment transport, which in turn is in essence a process of energy release and constraint. Therefore, the variation of tidal energy flux will cause erosion of sediments and siltation, which corresponds to sediment transportation and energy transmission. Analyzing the tidal energy flux variation caused by the reclamation is of great significance in understanding the impact of Qian Bay reclamation on the JZB environment.

4.1 Definition of Tidal Energy Flux

When a tidal wave travels from the ocean to the coastal sea, the process is accompanied by energy propagation. Across every vertical section between the ocean and the sea, there is a continuous flow of energy to maintain the tidal motion. The transfer of energy across the section in unit time should equal to the work done by water particles on the outer side of section on those on the other side. Let the y-axis be in the direction of the section and the *x*-axis be normal to the section and point to the inside of the area. Let the pressure on a unit area in tidal motion be *p*, and the distance water particles travel along the *x*-axis in time internal Δt be Δx, then the work done by the outer water particles on the adjacent inner ones is $p\Delta x$, and the work done in unit time is $p\Delta x/\Delta t = pu$. Denote the mean water depth at the section by *h*, then the work done in unit time by the outer water particles for unit width of the section is *hpu*. The virtual pressure being $pg\zeta$, the work done on unit width is $pghu\zeta$, which is the energy flow rate. The tidal energy flux should be calculated based on appropriate simulation of tidal currents fields. According to an article (Li *et al.*, 2005), the tidal energy flux components in the *x*- and *y*- directions E_{fx}, E_{fy} can be defined as

$$(E_{fx}, E_{fy}) = \frac{\rho}{T}\int_0^T\int_{-1}^0 (u,v)h[g\zeta + \frac{u^2+v^2}{2}]\mathrm{d}\sigma\mathrm{d}t\,,$$

where ρ is the water density; *u, v* are the velocities in the *x* and *y* directions, respectively; *T* is the period of M_2 tidal cycle; *g* is the gravitational acceleration; and ζ is tidal level.

4.2 Tidal Energy Flux of JZB

The M_2 tidal energy flux in JZB was simulated and shown in Fig.8. M_2 tidal energy travels from northeast to southwest outside the bay. During the propagation process some energy dissipates while entering JZB, some moves into Qian Bay, some travels into west JZB, and the remaining enters directly into the interior of JZB. The total tidal energy flux crossing the section outside JZB (Section L4 in Fig.1) is 58477 kW, while the energy flux crossing the section inside JZB (Section L1 in Fig.1) is 43801 kW, and the energy flux consumed by topographical friction outside JZB is 14676 kW.

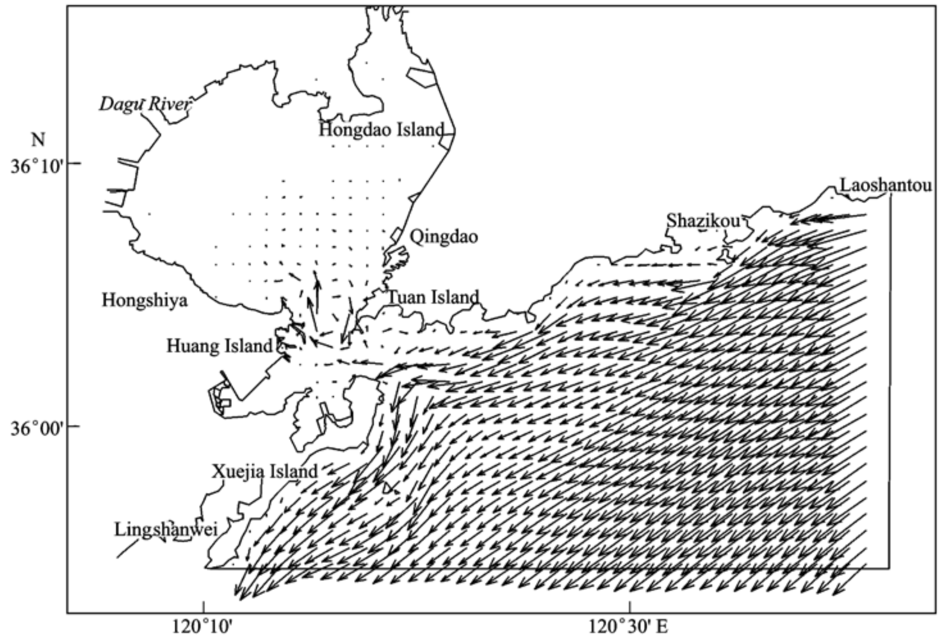

Fig.8 Distribution of Jiaozhou Bay tidal energy flux.

4.3 Impact on the Tidal Energy Flux by Qian Bay Reclamation

The variation of tidal energy flux at the representative stations is shown in Table 4. For the stations inside JZB, the tidal energy flux increases by 2.62% to 4.91%, except for Station 3, where it decreases slightly. For the representative stations near the mouth of JZB, the tidal energy flux decreases by 20.21% to 87.23% at Stations 1, 2, 7 and 8. For Station 10, which is outside the bay, the energy flux increases, the relative change being 5.24%.

In this study, four sections L1, L2, L3 and L4 (see Fig.1), were chosen to study the variation of tidal energy fluxes of Qian Bay, west JZB and inner JZB.

The energy fluxes crossing Sections L1 and L4 before the reclamation are 43801 kW and 58477 kW, respectively, while they increase to 44159 kW and 58734 kW, respectively, after the reclamation. The energy flux increase will cause more sediment erosion. But since the increase is not significant, its influence is not serious.

However, the energy flux crossing Section L2 diminishes from 791 kW to 570 kW because of the reclamation, which may cause more sediment deposition near Qian Bay ports.

Thus, it can be concluded that from the perspective of energy change, the reclamation activities have great impact on the project sea area, as they will cause changes in hydrodynamics and topography due to more erosion and sediment deposition.

Table 4 Variation of tidal energy flux at the representative stations

Location	Station	Absolute change (kW)	Relative change (%)	Absolute direction change (kW)	Relative direction change (%)
Inside the bay	3	–51.25	1.02	0.02	0.01
	4	182.91	4.91	–0.05	–0.07
	5	924.42	4.52	–1.41	1.81
	6	1046.95	2.93	4.09	4.16
	9	188.47	2.62	0.01	0.01
Near the mouth	1	–223.63	87.23	–35.84	14.10
	2	–248.05	20.21	75.73	26.83
	7	–4675.46	29.70	5.20	3.37
	8	–1169.45	39.60	–74.89	22.58
Outside the bay	10	1357.37	5.24	–2.00	1.27

5 Conclusions

The reclamation activities have a slight effect on the tidal system, whose variation in amplitude and phase is less than 1%. While they have a much greater impact on Qian Bay hydrodynamics, where the tidal current velocity decreases by 16.9% to 55.7%, and the residual velocity decreases by 29.50%–72.08%. In this study, the impact of Qian Bay reclamation on JZB was also studied from the perspective of the tidal energy change. The energy flux through the inner mouth and outer mouth of JZB will increase by 2.62% to 5.24%, which has some impact on sediment erosion; on the other hand, the energy flux through Qian Bay and the project area will decrease by 20.21% to 87.23%, which has some impact on the siltation. And from the perspective of energy change, the reclamation of Qian Bay has a great influence on the sediment erosion and deposition in some areas of JZB, which will cause the change of topography, especially near the project waters.

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