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Research on the numerical simulations of marine hydrodynamics and pollutant diffusion in Bohai Bay

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ABSTRACT

In this paper, the two-dimensional hydrodynamic mathematical model of Delft 3D was used to evaluate the hydrodynamic behaviour of Beidaihe Bay, and also to simulate the diffusion of pollutants in the Beidaihe bay. The chemical oxygen demand, nitrite nitrogen, total phosphorus content and heavy metal content in Bohai bay was analyzed, and the present situation of shallow water quality was also analyzed. Coupled simulation of coastal water quality with flow module and WAQ module in Delft 3D, the diffusion characteristics of pollutant emission were obtained. The study of impact from land-source pollution in Beidaihe Bay helps in further understanding the existing pollution status and provides a better view of land-source pollution to the general public.

Keywords: Water quality testing; Hydrodynamics; Pollutant diffusion; Delft 3D

1. Introduction

Bohai is the largest closed inland sea in China, so that the water quality is affected greatly by the coastal human activities. The seawater exchange cycle in Bohai Bay is long and the renewal ability is relatively weak. With the rapid development of coastal economic and aquaculture around Bohai Bay area, pollutants entering the Bay are increasing rapidly and water pollution is getting more and more serious in the area, and the marine environment problems are becoming more and more prominent [1]. Beidaihe district is one of the four municipal districts of Qinhuangdao city, which is located in the middle of the north coast of Bohai Bay. Beidaihe district faces Bohai Bay in the east and south sides. It is 11.2 km long from the east to the west, and 10.15 km wide from the north to the south, with the total area of 70.14 km^2. In the district, Daihe River and Xinhe River enter the Bohai Bay in the west and east sides, respectively [2,3]. With the deterioration of sea water quality in Bohai Bay, the inshore water quality of Beidaihe district has been decreasing year by year. The discharge of pollutants from Beidaihe district and its surrounding land areas caused sea water eutrophication around the Beidaihe and its adjacent coastal areas, which resulting in the occurrence of red tide disasters increasingly frequent, and the scale and duration of continuous also expanse. The pollution of oil and heavy metals caused by economic activities such as sewerage and port transportation along the coast is becoming more and more serious [4]. The deterioration of water quality in Beidaihe district and its adjacent sea areas has become a restricting factor affecting the sustainable development of people's

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livelihood and economy. Therefore, it is of great significance to study the hydrodynamics and pollutant dispersion in the coastal Bohai Bay of Beidaihe [5].

Delft 3D [6] is a software package for water flow and water quality, developed by the Delft Hydraulic Research Institute in Holland. It is used to simulate the two-dimensional (depth averaged) or three-dimensional unsteady flow and material transport properties. Its general idea is to generate grid and grid nodes on the depth of the document. And according to the calculated results of the data processing, the corresponding water flow problem can be calculated through the corresponding module. So this software includes the grid generation part of the grid and the depth of water on the grid node. In the module, it includes 3D flow calculation, wave, water quality, ecology, sediment transport and terrain evolution modules. It plays a very important role on the research of hydrodynamic behaviour and pollutants diffusion processions of rivers and marines.

The integral modelling of Delft 3D is based on the flow model (hydrodynamic module), and the other models are extended and configured on the basis of the flow model, which include water environment, water ecology, topographic evolution, sediment transport and so on. Based on the Navier-Stokes equations, the hydrodynamic model is established. And the model is simplified for the shallow waters. The governing equations of the coordinate system are discretized by the alternating direction method (ADI).

According to the characteristics of Beidaihe and coastal waters, this paper uses Delft 3D to simulate the hydrodynamics and pollutant migration. Based on the analysis of hydrodynamic behaviour and pollutants diffusion processions of, it can help us understand the origin of the land-source pollution in Beidaihe area and provide solution to control the problems from legislation, implementation and maintenance aspects.

2. Theory

2.1. Hydrodynamic model description

The continuity equation in the curvilinear coordinate system is given as follows [7,8]:

$$\frac{\partial\zeta}{\partial t}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\left(\frac{\partial[(d+\zeta)u\sqrt{G_{\eta\eta}}]}{\partial\xi}+\frac{\partial[(d+\zeta)v\sqrt{G_{\xi\xi}}]}{\partial\eta}\right)=0 \quad (1)$$

The equations of motion in the ξ and η directions are as follows:

$$\begin{aligned}&\frac{\partial u}{\partial t}+\frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial u}{\partial\xi}+\frac{u}{\sqrt{G_{\eta\eta}}}\frac{\partial u}{\partial\eta}+\frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial\eta}\\&-\frac{v^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial\xi}-fv=\\&-\frac{1}{\rho_0\sqrt{G_{\xi\xi}}}P_\xi-\frac{gu\sqrt{u^2+v^2}}{(d+\zeta)C^2}+F_\xi+M_\xi\end{aligned} \quad (2)$$

$$\begin{aligned}&\frac{\partial v}{\partial t}+\frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial v}{\partial\xi}+\frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial v}{\partial\eta}+\frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial\xi}\\&-\frac{u^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial\eta}+fu=\\&-\frac{1}{\rho_0\sqrt{G_{\eta\eta}}}P_\eta-\frac{gu\sqrt{u^2+v^2}}{(d+\zeta)C^2}+F_\eta+M_\eta\end{aligned} \quad (3)$$

In the above equations, u is the ξ directional velocity component; v is the η directional velocity component; $G_{\xi\xi}$ and $G_{\eta\eta}$ are the coordinate transformation coefficients; P_ξ and P_η are the pressure gradient forces; ρ_0 is the density of water; ζ is the water level above the datum level; d is the water depth below the datum plane; $d + \zeta = H$ is the actual depth; F_ξ and F_η are Reynolds stress terms; M_ξ and M_η are subsidiary loads affecting the secondary flow; f is Coriolis force.

The coastline near the estuary is used as the closed boundary of the simulated region, and the free slip condition is adopted to the closed boundary. Flow transport analysis uses alternating direction explicit and implicit mixed schemes based on finite difference method (ADI). The grid of the format is square or rectangle, and the variables ξ, u, v are arranged alternately on both sides or center of the grid [9].

We focus our study on the lower river course of Yanghe River as shown in Fig. 1. The computational area of the numerical simulation is the sea area within 5 km offshore. The minimum width of the grid near the outfall is about 20 m, the width of the offshore grid is relatively large, which is about 500 m. A total of 740 curvilinear grids and 798 nodes are generated in all the computational regions.

In this model, the geographical coordinates are in the north latitude 39°47'45.12", East 119°24'08" to 119°31'58" [10], with a precision of 12.96″. The main driving forces are earth gravity, rotation force, river driving force, tide, wave and so on; gravity acceleration is 9.81 m^2/s; sea water density is 1,024 kg/m^3; the atmospheric density is 1 kg/m^3; the tidal type is irregular semidiurnal tide; the temperature is set according to the climate conditions of the simulated area; turbulence model is $k-\varepsilon$; eddy viscous coefficient are 10 m^2/s and 10^{-6} m^2/s in horizontal and vertical directions; when the water temperature range is 10°C – 28°C, the coefficient of degradation is generally between 0.02 and 0.07 d^{-1}; the highest salinity in Beidaihe sea appeared around June, which is about 32 psu, the minimum peak occurred around August, which is about 25 psu; the lowest value of dissolved oxygen appeared around July, which is about 6 mg/L, and the highest value appeared around September, which is 9 mg/L; the seawater temperature begin to rise from May, the highest value appeared around August, and the highest value is about 26°C; the water temperature begins to decline in September, and the water temperature is about 17°C in October.

2.2. Pollutant diffusion model description

The transport equation of pollutant diffusion is:

$$\frac{\partial(HP)}{\partial t}+\frac{\partial(HUP)}{\partial x}+\frac{\partial(HVP)}{\partial y}=\frac{\partial}{\partial x}\left(HD_x\frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial y}\left(HD_y\frac{\partial P}{\partial y}\right)+HS \quad (4)$$

where U, V and P are the propagation velocities and concentration in x, y space. Dx and Dy are dispersion coefficient, H is the depth of water.

2.2.1. Boundary condition

When the terrigenous input is taken into account without considering the atmospheric subsidence and submarine exudation, the mass flux of sea surface and sea floor is zero.

Sea surface:

$$q_s = A_v\left(\frac{\partial c}{\partial z}\right)_s = 0 \tag{5}$$

Seabed:

$$q_b = A_v\left(\frac{\partial c}{\partial z}\right)_b = 0 \tag{6}$$

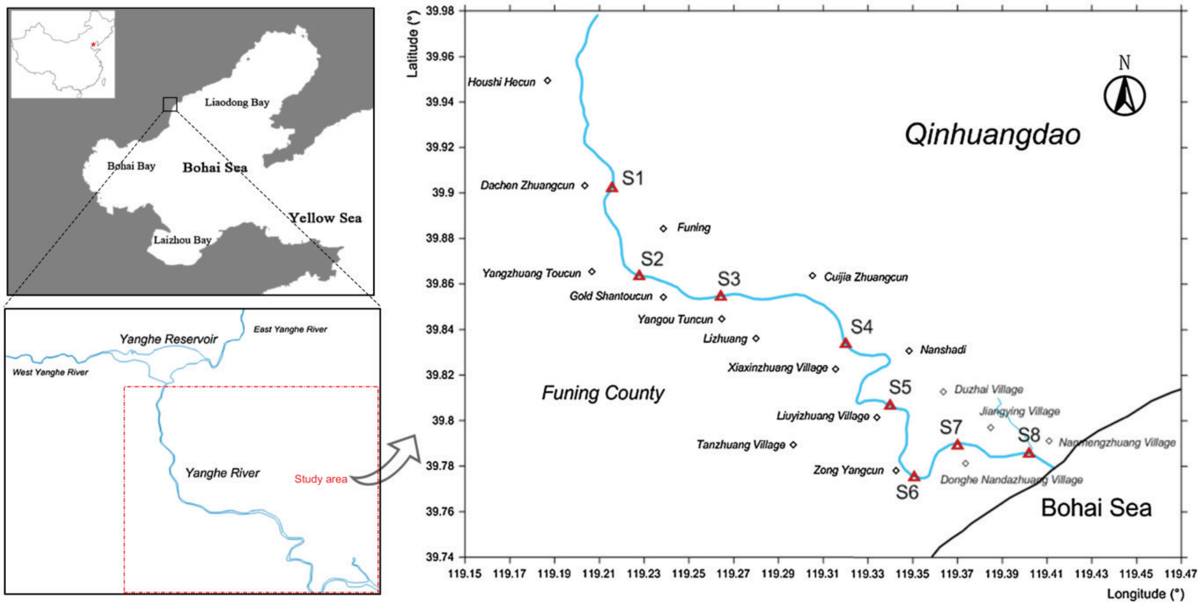

Fig. 1. Location of the study area.

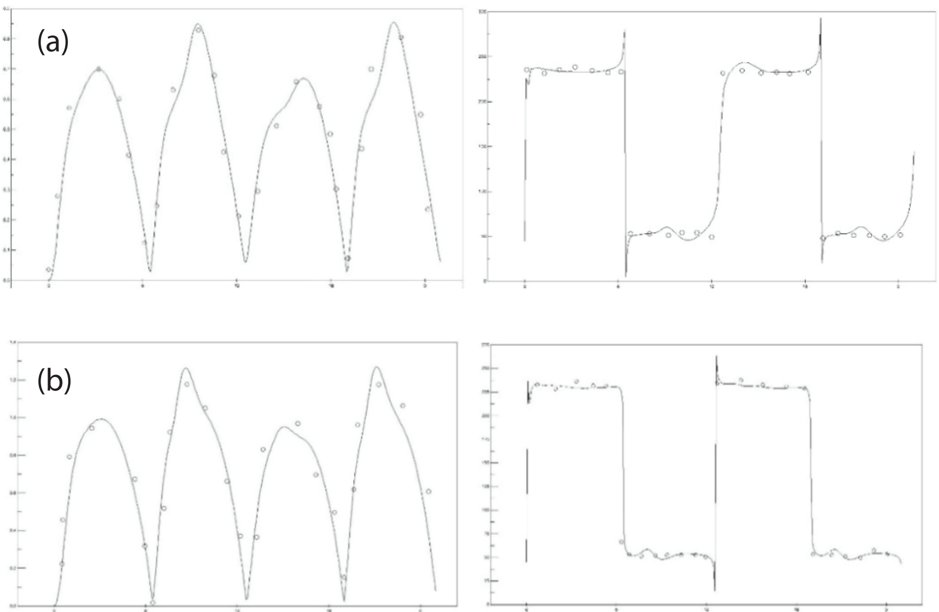

Fig. 2. Tidal flow direction and velocity verification. (a) Flow velocity and direction of estuary observation points in Yanghe River. (b) Flow velocity and direction of estuary observation points in Yanghe River.

Shore boundary:

$$q_l = 0 \tag{7}$$

Open boundary:

$$C = 0 \tag{8}$$

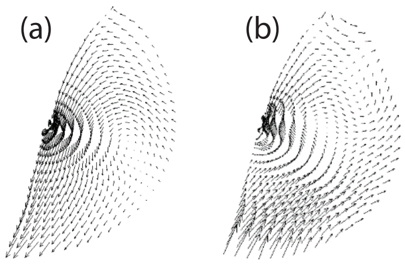

Fig. 3. Simulation results of Yanghe River estuary area: (a) northeasterly wind and (b) southwest wind.

3. Experiments and discussion

3.1. Hydrodynamic model validation

In order to verify the accuracy of the calculation results, we use electronic drift card system to monitor the water quality change characteristics of Beidaihe sea area. The measured data of velocity and flow direction are validated. The measured data are derived from experimental measurements of Yanghe River.

The power flow verification is shown in Fig. 2, the line represents the calculation result, and the point represents the measured result. From the verification, the calculated values of velocity and direction of the tidal stations are in good agreement with the measured values, the error is controlled within 20%. The parameters of that model is reasonable, the calculation method is reliable and can accurately depict the situation of tide and ebb. Therefore, the model is reliable and reasonable in the simulation process of the Bay, and its simulation results can correctly reflect the flow field characteristics of the bay.

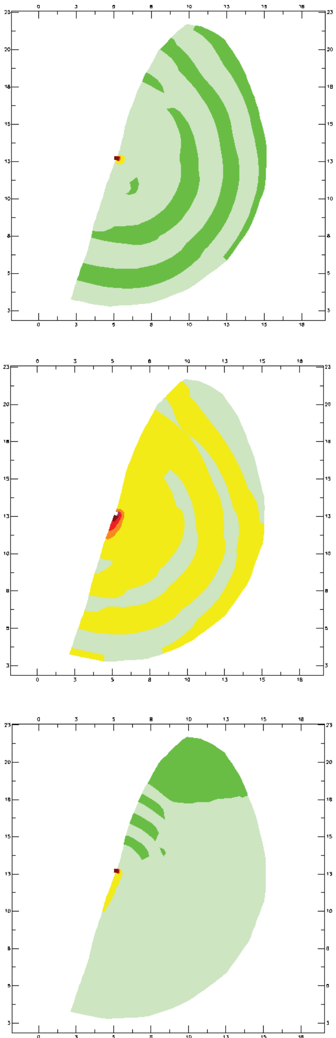

Fig. 4. Yanghe River estuary flow diffusion of pollutant effects in high water period.

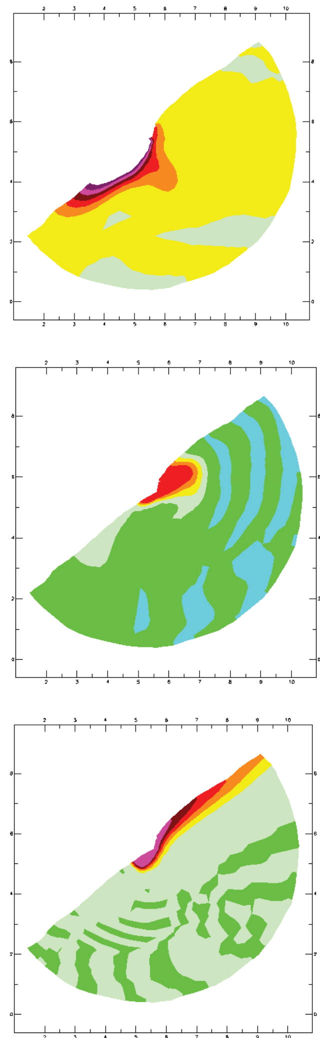

Fig. 5. Yanghe River estuary flow diffusion of pollutant effects in low water period.

Fig. 6. Changes of COD_{MN} and PO_4 concentration of Yanghe River in high water period.

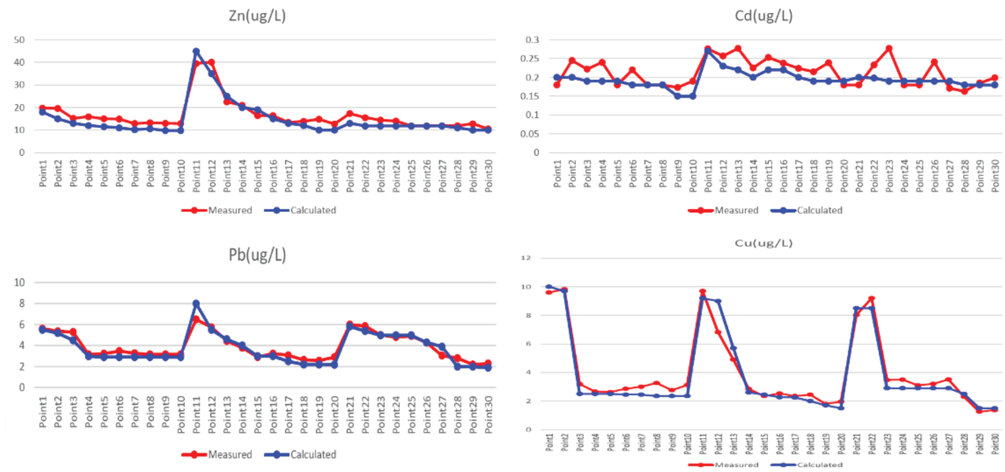

Fig. 7. Changes of heavy metals concentration of Yanghe River in high water period.

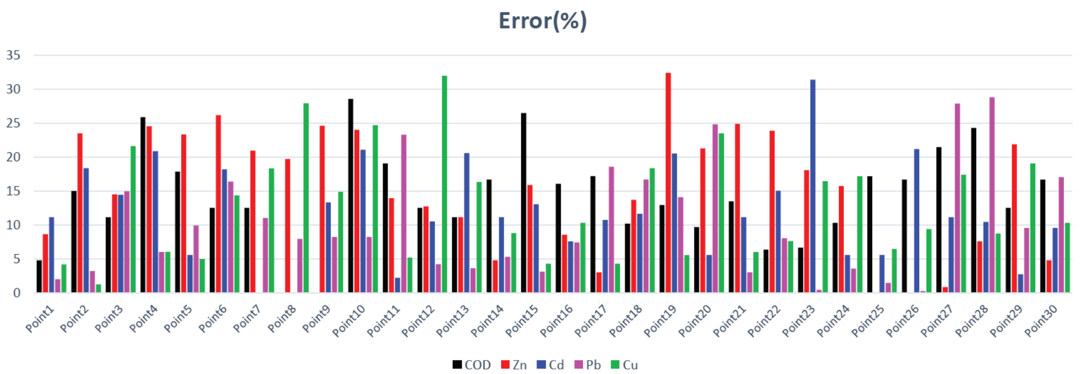

Fig. 8. Yanghe River error rate distribution of pollutants in high water period.

3.2. Simulation results of flow field

Simulation results of flow field are shown in Figs. 3 and 4. Arrow direction indicates flow field direction, and arrow size indicates flow velocity. According to the analysis of flow field simulation results, we can see that the sea near the Yanghe River estuary is shallow water, so the flow of Yanghe River estuary flow is mainly affected by wind direction. In addition, the wind direction along the land boundary plays an important role in the convection field, and the far away from the land area shows a counter-clockwise trend.

3.3. Pollutant diffusion model validation

We use the Delft 3D to couple model the water and use water quality modules to simulate pollutant diffusion in the computational domains. Then we get the diffusion characteristics of pollutant emissions, and the results are shown in Figs. 4 and 5. Simulation results indicate the pollutants in coastal waters move obviously along with the wind direction, the influence of wind force is an important factor of pollutant dispersion in shallow sea.

In order to effectively analyze the change rules and feature of the near sea water environment quality, this project selects typical water quality indicators in offshore water quality management: chemical oxygen demand (COD), nitrite, total phosphorus and the concentration of copper, lead, zinc and chromium ions are studied. We choose 30 actual monitoring sites as the monitoring points of the simulation area.

The comparison between the simulation results of main pollutants and the measured values in Yanghe River are shown in Figs. 6 and 7. Error rate analysis is shown in Fig. 8. The error rate of COD_{MN} is less than 28%, among which the error rate is less than 20%, accounting for 83% of the total point; the error rate of heavy metal zinc is less than 31%, among which the error rate is less than 30%, accounting for 97% of the total point and the error rate is less than 20% accounting for 63% of the total point; the error rate of heavy metal cadmium is less than 31%, among which the error rate is less than 30%, accounting for 97% of the total point and the error rate is less than 20% accounting for 60% of the total point; the error rate of heavy metal lead is less than 29%, among which the error rate is less than 20%, accounting for 87% of the total point; the error rate of heavy metal copper is less than 31%, among which the error rate is less than 30%, accounting for 97% of the total point and the error rate is less than 20% accounting for 83% of the total point.

The comparison between the simulation results of main pollutants and the measured values in Yanghe River is shown in Fig. 9. Error rate analysis is shown in Fig. 10. The error rate of COD_{MN} is less than 33%, among which the error rate is less than 20%, accounting for 83% of the total point; the error rate of heavy metal zinc is less than 35%, among which the error rate is less than 30%, accounting for 97% of the total point and the error rate is less than 20% accounting for 77% of the total point;

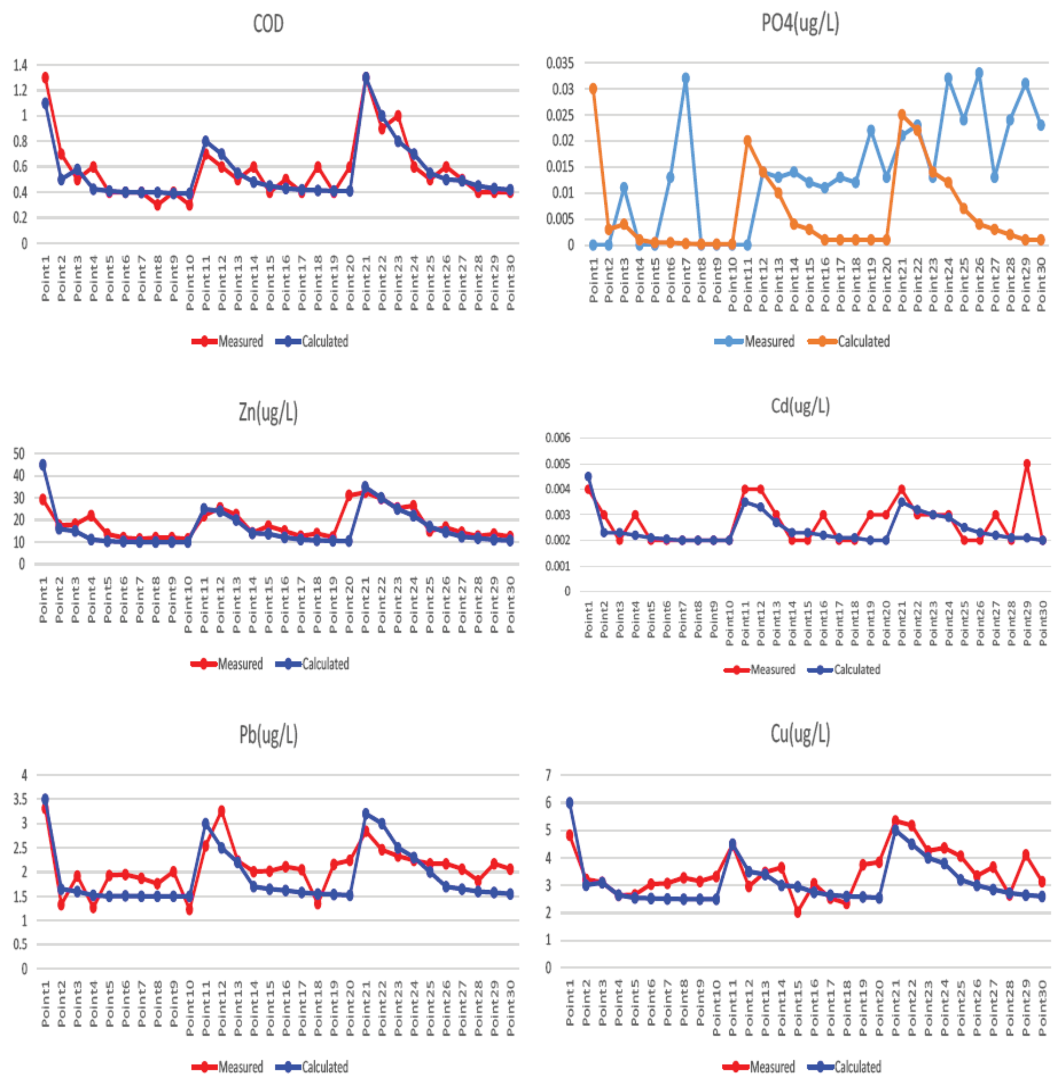

Fig. 9. Changes of COD_{MN}, PO_4, and heavy metals concentration of Yanghe River in low water period.

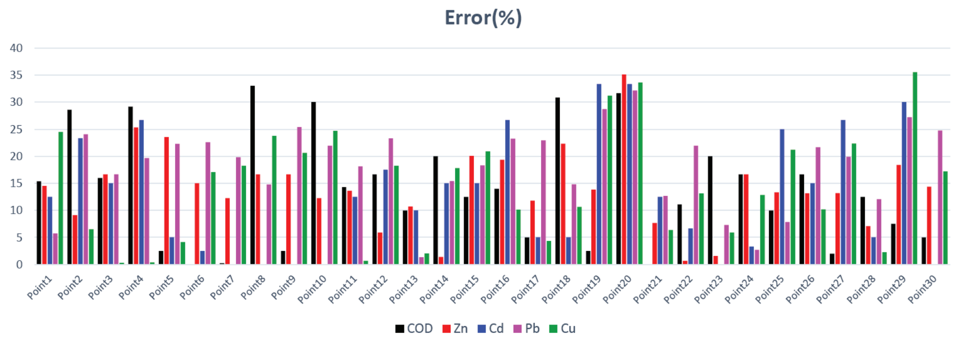

Fig. 10. Yanghe River error rate distribution of pollutants in low water period.

the error rate of heavy metal cadmium is less than 33%, among which the error rate is less than 30%, accounting for 90% of the total point and the error rate is less than 20% accounting for 67% of the total point; the error rate of heavy metal lead is less than 30%, among which the error rate is less than 20%, accounting for 53% of the total point; the error rate of heavy metal copper is less than 33%, among which the error rate is less than 30%, accounting for 93% of the total point and the error rate is less than 20% accounting for 73% of the total point.

From the above simulation results, it can be seen that the direction of the COD_{MN} transport is in line with the direction of ebb and flow. The distribution of COD_{MN} concentration decreases from the estuary to the sea, the dilution of channel COD_{MN} is higher after discharging into sea area; the gradient of the concentration field is smaller in the estuary than that of the offshore area. When the tide rises, the high concentration area of COD_{MN} moves towards the river course, the high concentration area of COD_{MN} in offshore is the smallest. When the tide falls, the COD_{MN} high concentration zone goes towards offshore area, the high concentration area of COD_{MN} in offshore is the largest.

4. Conclusion

From simulation of flow field and influence of flow field on pollutant diffusion in Beidaihe district, we can see that the pollutants are mainly diffused and transferred near the estuary, and have little effects on the high sea area [11]. In conclusion, the distribution of heavy metals in sea water at each observation point shows that the distributions of copper, zinc, cadmium and lead are similar, they are all decreased from offshore to high seas. The heavy metal concentration areas are mainly located in the coastal waters near the estuary. The concentration of simulation area near high seas is relatively low. At the same time, the simulation of COD_{MN}, total phosphorus and inorganic nitrogen contents also confirmed this conclusion. It shows that the pollution areas caused by land-based pollutants are mainly distributed in the coastal waters of the Beidaihe district. The COD_{MN} N range of the surveyed sea area is between 1 and 3 mg/L. The value of COD_{MN} meets second-class water quality standards in wet period, most of the COD_{MN} values in dry season and normal water period meet first-class water quality standards. Heavy metals are below the second-class water quality standards and basically do not cause pollution. The study of impact from land-source pollution in Qinhuangdao area can help us further understand the existing pollution status and provide a better view of land-source pollution to the general public. It will also provide government basic data to analyze the side effect. The pollution brings to the economic development for Qinhuangdao city, and helps to put forward an optimized suggestion from both corporate and government levels to help sustainable development of Qinhuangdao city and its surrounding areas.

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