PERGAMON

Water Research 36 (2002) 2029–2039

WATER RESEARCH

www.elsevier.com/locate/watres

Three-dimensional pollutant transport model for the Pearl River Estuary

K.W. Chau*, Y.W. Jiang

Department of Civil and Structural Engineering, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

Received 18 December 2000; received in revised form 13 August 2001; accepted 22 August 2001

Abstract

In this paper, the development and implementation of a three-dimensional, numerical pollutant transport model, which is based on an orthogonal curvilinear coordinate system in the horizontal direction and a sigma coordinate system in the vertical direction, is delineated. An efficient as well as simple open boundary condition is employed for pollutant transport in this mathematical model. It is then applied to model the distribution and transport of Chemical Oxygen Demand in the Pearl River Estuary. The results from the numerical simulations illustrate that the transboundary or inter-boundary effects of pollutants, between the Guangdong Province and the Hong Kong Special Administrative Region due to the wastewater discharged from the Pearl River Delta Region, are quite strong.

Keywords: COD concentration; Numerical model; Pearl River Estuary; Pollutant transport; Three-dimensional model

1. Introduction

In this paper, the development and implementation of a three-dimensional, numerical pollutant transport model, which is coupled with the orthogonal curvilinear and sigma coordinate system numerical hydrodynamic model [1], is delineated. Besides, an efficient and simple open boundary condition of transport is employed. Application of this model is then made to the largest river system in South China, namely, the Pearl River Estuary (PRE). The Pearl River Delta Region (PRDR), covering eight large cities,namely, Dongguan, Foshan, Guangzhou, Huizhou, Jiangmen, Shenzhen, Zhongshan and Zhuhai, is one of the rapidly developing regions in China as well as in Asia. As a result of this rapid economic development and prosperous activities within the area, an adverse impact on the ambient environment has become inevitable. Amongst various types of pollution, the rate of untreated sewage discharge is escalating at an exceedingly fast rate. During the last decade, an enormous amount of the pollutants has been discharged into the Pearl River Estuary, which are originated from five main outlets, namely, Hu men, Jiao men, Hongqi men, Heng men, and Shenzhen River (see Fig. 1).

The pollutants in the PRDR are transported from the outlets of the Pearl River system to the entrance of the PRE subjected to the coupled physical interaction of the upstream river runoff as well as the tidal effect. Macau is located on the western side of the PRE entrance whereas the Hong Kong Special Administrative Region (HKSAR) is located on the eastern side of the PRE entrance. Whilst nowadays the environment protection issues within the HKSAR and Macau themselves are already a significant matter of concern, the transboundary pollutants from the inner PRE have contributed an additional dimension and complication to their tasks. [2].

As such, there is a strong demand to determine the impact of pollutants from the PRDR to the water quality in the surrounding coastal waters of the HKSAR. A three-dimensional pollutant transport

*Corresponding author. Tel.: +852-2766-6014; fax: +852-2334-6389.

E-mail address: cekwchau@polyu.edu.hk (K.W. Chau).

0043-1354/02/$ - see front matter
PII: S0043-1354(01)00400-6

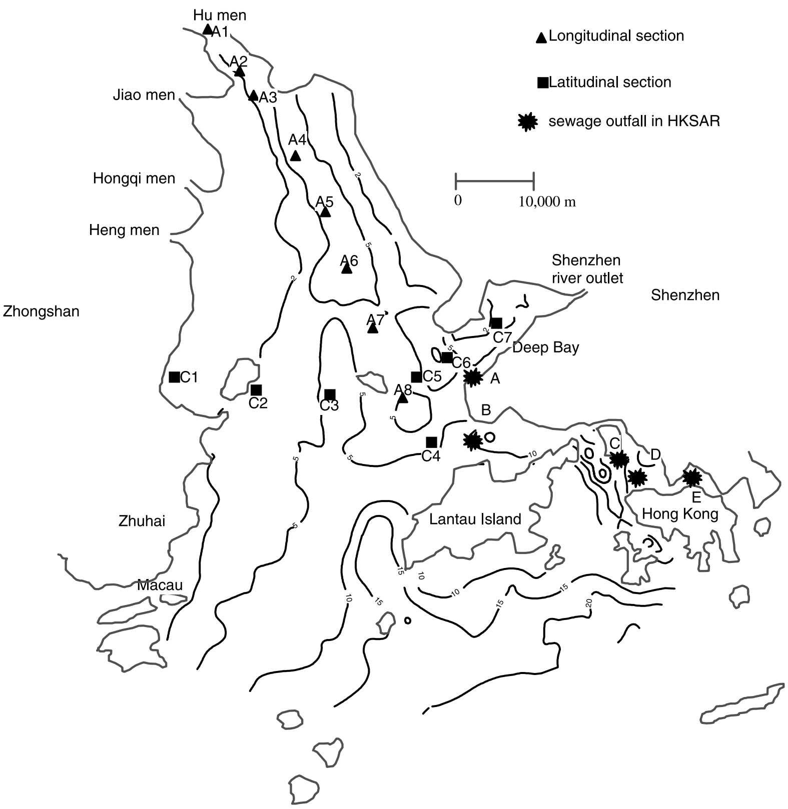

Fig. 1. Topographic map of study area.

numerical model with an advanced open boundary transport condition is developed in this paper. In order to assess the transboundary action of pollutants, the COD is employed as an indicative index to mimic the pollutant transport and distribution pattern in PRE. Another feature, which is quite different from other usual procedure, is that, during the determination of the COD to measure the amount of oxygen required for chemical oxidation of organic matter, instead of employing the more commonly used dichromate solution, permanganate solution is employed in this study. It is because dichromate solution is more appropriate for freshwater such as in the river, whilst permanganate solution is more suitable in a seawater environment, such as in this situation.

COD of wastewater is the measured amount of oxygen needed to chemically oxidize the organic present whilst biochemical oxygen demand (BOD) is the measured amount of oxygen required by acclimated microorganisms to biologically degrade the organic matter in the wastewater. Owing to the relatively simple laboratory procedure, BOD is commonly used in water quality modeling. However, in this case, since the composition of the wastewater from the sources shows that it is mainly constituted by industrial wastewater, it may contain higher proportion of chemical materials, which are not easily degradable biologically. It is thus worthwhile to study the transport effect on COD to truly characterize the organic strength as well as the pollution scenario. Besides, it has been reported that BOD is of limited value in measuring the actual oxygen demand of surface waters since the laboratory environment cannot easily reproduce the ambient physical, chemical and biological condition [3].

2. Description of the model

2.1. Pollutant transport model

This three-dimensional pollutant transport model is coupled together with a hydrodynamic numerical model [1], which was developed and enhanced on the basis of the Ocean Model of Princeton University POM [4]. The following describes the primary features of this model:

(a) The sigma coordinate system is used in the vertical spatial direction whilst the curvilinear orthogonal coordinate system is used in the horizontal spatial direction.

(b) Similar to treatment by Casulli and Cheng [5], the time differencing in both horizontal and vertical directions is represented in a semi-implicit manner. In this case, during the time integration of the governing equation, the vertical flux term and the decay term are treated implicitly whilst all the other terms in the equation are treated in an explicit fashion. A time-splitting method is used for the horizontal time differencing of external mode. As such, the allowable time step is much greater than that determined from the Courant-Friendrichs-Lewy (CFL) stability criterion, which stipulates that $dt < dx/(\sqrt{2gh} + U_{MAX}/\sqrt{2})$.

(c) Thermodynamics are completely implemented and thus the thermal structure of the estuary is considered. Both the density and salinity stratification are expressed as functions of temperature variation in both horizontal and vertical direction.

(d) A second moment turbulence closure sub-model is embedded to accommodate for vertical mixing coefficients.

Mellor [4] furnishes the details of the hydrodynamic equations and the corresponding solution method employed in this model whilst the details of the equations for the orthogonal curvilinear transformation are delineated in Chau and Jin [6]. The hydrodynamic model of the PRE that is employed in this pollutant transport study has been detailed in Chau and Jiang [1]. By fulfilling the momentum equations, the temperature as well as salinity transport equations subjected to the appropriate initial and boundary conditions, the density structure of the conveying seawater is computed as a spatial and temporal function in the hydrodynamic model. Various issues regarding the POM including the level of confidence, accuracy, previous calibrations and the model usage can be found in Blumberg and Mellor [7] and Quamrul and Blumberg [8].

Amongst others, the most significant distinction between this model and the POM is in the second point mentioned above. The horizontal time differencing is totally explicit in the POM and hence the time step is subjected to the CFL condition. On the contrary, in this model, the horizontal time differencing is treated in a semi-implicit fashion through the use of a time-splitting method. As such, the maximum allowable time step of this model is much larger than that available in the POM. This characteristic is particularly beneficial to the application to some domains in which complex flow patterns and large currents are caused by both river discharges as well as tidal forcing, such as the Pearl River estuary in this case.

2.2. Governing equation

The governing equation on the phenomenon of pollutant transport in this model can be expressed as

$$\frac{\partial \mathrm{SD}}{\partial t} + \frac{\partial \mathrm{SUD}}{\partial x} + \frac{\partial \mathrm{SVD}}{\partial y} + \frac{\partial S\omega}{\partial \sigma} = \frac{\partial}{\partial x}\left(A_s H \frac{\partial S}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_s H \frac{\partial S}{\partial y}\right) + \frac{\partial}{\partial \sigma}\left[\frac{K_H \partial S}{D\, \partial \sigma}\right] - K_s \mathrm{DS} + S_s, \quad (1)$$

where S is the pollutant concentration as a function of x, y, σ, t, which in this study is the concentration of the COD; t is the time; U, V, ω are the mean fluid velocities in the x, y, σ directions; $D = \eta + H$, where η is the elevation of the sea surface above the mean water level, H is the mean water depth; and K_H is the vertical turbulent flux coefficient, which can be derived from the second moment ($q^2 \sim q^2\ell$) turbulence energy model [4]. The term $q^2/2$ is the turbulent kinetic energy and ℓ is the turbulence length scale. For this type of model, one equation is written for q^2, representing turbulent kinetic energy, whilst another equation is written for $q^2\ell$, representing turbulent dissipation. K_s is the rate of decay of the pollutant and S_s is the source of the pollutant. A_s is the horizontal turbulence coefficient, which can be obtained from the Smagorinsky formula [9]:

$$A_s = C\,\Delta x\,\Delta y \left[\left(\frac{\partial U}{\partial x}\right)^2 + \frac{1}{2}\left(\frac{\partial V}{\partial x} + \frac{\partial U}{\partial y}\right)^2 + \left(\frac{\partial V}{\partial y}\right)^2\right]^{1/2}, \quad (2)$$

where C is a coefficient between 0.1 and 0.2. In this model, a constant of 0.12 is adopted which has been proved to work well in the calibration against several standard idealized tests for verification of the accuracy of this model.

By using the "Arakawa C" grids as shown in Fig. 2, the governing equation on pollutant transport can be discretized in following differencing form:

$$\delta_t(\mathrm{SD}) + \delta_x(\bar{S}^x \bar{D}^x U) + \delta_y(\bar{S}^y \bar{D}^y V) + \delta_\sigma(\bar{S}^\sigma \omega) = \delta_x(\bar{H}^x \bar{A}_s^x \delta_x S) + \delta_y(\bar{H}^y \bar{A}_s^y \delta_y S) + \delta_\sigma(\bar{K}_H^\sigma \delta_\sigma S_+/D) - K_s \mathrm{DS}_+ + S_s. \quad (3)$$

For any parameter F which is a function of x, y, σ, t, namely, $F = F(x, y, \sigma, t)$, various operators on F in the above Eq. (3) are defined as follows:

$$\delta_t F = \frac{1}{2\Delta t}(F(x, y, \sigma, t + \Delta t) - F(x, y, \sigma, t - \Delta t)), \quad (4)$$

$$\bar{F}^x = \frac{1}{2}\left[F\left(x + \frac{\Delta x}{2}, y, \sigma, t\right) + F\left(x - \frac{\Delta x}{2}, y, \sigma, t\right)\right], \quad (5)$$

$$\delta_x F = \frac{1}{\Delta x}\left[F\left(x + \frac{\Delta x}{2}, y, \sigma, t\right) - F\left(x - \frac{\Delta x}{2}, y, \sigma, t\right)\right], \quad (6)$$

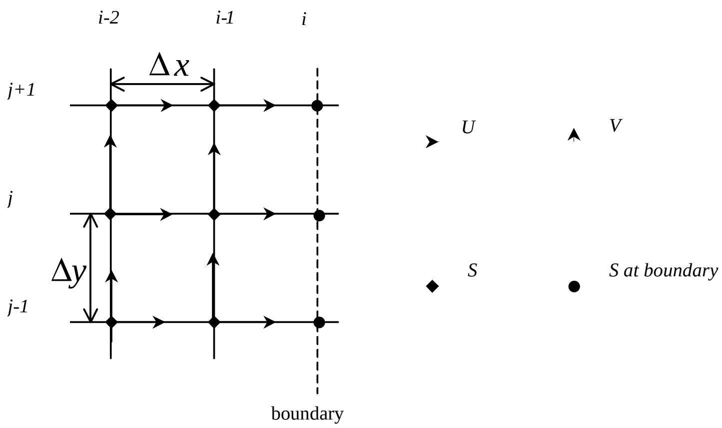

Fig. 2. Arakawa C grids with eastern open boundary.

$$S_+ = S(x, y, \sigma, t + \Delta t). \quad (7)$$

By substituting the above expressions into the finite difference Eq. (3), it can be noted that all the parameter values can be acquired from the previous time step of the hydrodynamic model except three unknowns. They are namely, $S(x, y, \sigma, t + \Delta t)$, $S(x, y, \sigma + \Delta\sigma, t + \Delta t)$, and $S(x, y, \sigma - \Delta\sigma, t + \Delta t)$ in the first term of the left hand side and the third and fourth term of the right hand side, respectively. As such, Eq. (3) can be expressed in the following form:

$$\mathrm{AS}(x, y, \sigma - \Delta\sigma, t + \Delta t) + \mathrm{BS}(x, y, \sigma, t + \Delta t) + \mathrm{CS}(x, y, \sigma + \Delta\sigma, t + \Delta t) = D, \quad (8)$$

where A, B, C, D are some known coefficients. It can be seen that Eq. (8) is a tri-diagonal matrix in the vertical direction, which can be solved with the algorithm by Richtmeyer and Morton [10].

Some verification tests involving several idealized geometries and forcing functions, which have also been previously performed to the POM, have been conducted in order to establish the veracity of this model. These tests cover simple tests concerning its capability in conserving different components as well as a few more rigorous tests dealing with baroclinic and barotropic responses of a hypothetical coastal basin with or without topography in reproducing a variety of large scale oceanographic phenomena [7]. Chau and Jiang [1] have illustrated that the model is able to mimic the physics and to generate output results identical to its counterpart of the well-established POM. It furnishes a high degree of confidence in a consistently high numerical accuracy of the scheme together with the same order of magnitude of numerical diffusion as the actual physical diffusion.

3. The Pearl River Estuary

3.1. Bathymetry and flow conditions

There are in total five main river outlets in the studied delta estuary, namely, four main river outlets (Hu men, Jiao men, Hongqi men, Heng men) in the north-western side of the PRE and the Shenzhen River outlet flowing into the Deep Bay in the eastern side (Fig. 1). From Pang and Li [11], the averaged net discharges of the former four outlets during the mean season years between 1985 and 1995 are 1788, 1650, 581 and 1021 m^3/s, respectively. The tidal forcing in the PRE is primarily irregular semi-diurnal with a mean tidal range of 1.0 m or so. The mean tidal range is found to be 0.85–0.9 m at the entrance to the estuary, which gradually increases its magnitude towards the inner estuary up to 1.6 m at the Hu men River mouth [12].

Fig. 3 shows the transformed rectilinear grid adopted for this model. There are in total 3400 horizontal model segments and six layers with equal $\delta\sigma$ values in the vertical direction. Whilst during the dry season from December to March, the tidal current is the predominant driving force for flow circulation, during the wet season from May to September, the river runoff becomes significant and dominates the hydrodynamic behavior in the PRE. As such, the distribution of pollutants during different seasons will be studied so as to examine and discern different phenomena of pollutant transport in the PRE.

3.2. Boundary and initial conditions

Within the model domain, there are two open boundaries, namely, the southern open boundary at South China Sea and the eastern open boundary at Lei Yu Mun. In the literature, a simple open boundary condition is usually employed for pollutant transport

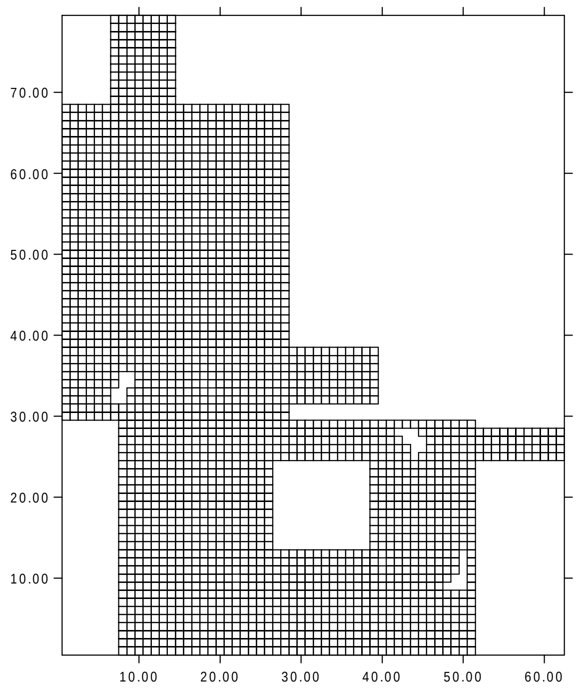

Fig. 3. The transformed rectilinear plane of PRE.

phenomenon. If the method of Leendertse and Crittion [13], for instances, is adopted on the grids in the vicinity to the eastern open boundary, the boundary conditions can be expressed as

$$P_{i,j}^{n+1} = P_{\text{set}}, \quad U_{i-1/2,j}^{n+1} < 0, \tag{9}$$

$$\frac{\mathrm{d}P}{\mathrm{d}t} = 0$$

that is

$$\frac{P_{i,j}^{n+1} - P_{i,j}^{n-1}}{2\Delta t} + U_{i-1/2,j}^{n+1} \frac{P_{i,j}^{n} - P_{i-1,j}^{n}}{\Delta x} = 0, \quad U_{i-1/2,j}^{n+1} > 0, \tag{10}$$

where P represents the pollutant concentration and P_{set}denotes the prescribed along-boundary component of pollutant concentration. In these two equations, Eqs. (9) and (10) apply for the flood and ebb tide conditions, respectively. Eq. (10) represents the condition that there is no spatial gradient in concentration. However, sometimes an appropriate value of P_{set} cannot be established. In such circumstance, a value has to be assumed according to all the data available. As such, the aforementioned open boundary condition is only reasonable when the boundary condition is known or in cases the level of water exchange/flushing outside of the model domain is so strong that no internal pollutant will build up at the open boundary.

In the PRE, COD data are not available and the exchange capacity at the entrance of the PRE is not strong enough so as to use the $P_{\text{set}} = 0$ approach. Hence, in this model, instead of the above approach, an efficient and simple open boundary condition is adopted for pollutant transport under flood condition as follows:

$$\frac{P_{i,j}^{n+1} - P_{i,j}^{n-1}}{2\Delta t} + U_{i-1/2,j}^{n+1} \frac{(a-1)P_{i-1,j}^{n}}{\Delta x} = 0, \quad U_{i-1/2,j}^{n+1} < 0, \tag{11}$$

where a is a coefficient ranging from 0 to 1, which relies upon the level of water exchange/flushing outside the model domain. If the level of flushing is strong, the value of a is small, and otherwise the value approaches 1. Fig. 4 displays the steady-state boundary COD concentration under different a values. Besides, there is a lower limit imposed on the boundary condition in Eq. (11), i.e., $P_{i,j} = 0$ if $P_{i,j} < 0$ which, as shown in Fig. 4, occurred during certain time intervals of the tidal periods at small a values.

Now, under this approach, Eq. (11) is used instead of Eq. (9) during the flood tide, representing the proportion of pollutant concentration brought back by the flood tide, whilst the same Eq. (10) is used during the ebb tide. In this model, a value of 0.9 is adopted for the coefficient a, which works well according to the internal COD calibration. Besides, whenever the COD concentration at the boundary is less than 1.8 mg/L, it is set to become 1.8 mg/L in accordance with the initial background condition of COD.

The background data or the initial pollutant concentration of COD in the model domain was set to a fixed value of 1.8 mg/L. After the computation runs for 100 tidal periods or so, which is about 50 calendar days, a steady state concentration gradient will be accomplished.

3.3. Pollutant sources

The five main river outlets are the main sources of discharge pollutants to the PRE. Since no direct COD data are available from the different river outlets, the loading of COD at different river outlets in this model is computed based on the characteristics of the wastewater together with the discharge volume.

The domestic and industrial wastewater flow generated in the Guangdong Province, as shown in Table 1, are acquired from the Guangdong Yearbook Editorial Committee (1996), from which the following relationship between the COD loading rate and the domestic and industrial wastewater flow rates is established:

$$W_{\text{COD}} = 0.00027Q_{\text{d}} + 0.000305Q_{i}, \tag{12}$$

where W_{COD} is the loading rate of COD, Q_{d} is the domestic wastewater flow rate and Q_i is the industrial

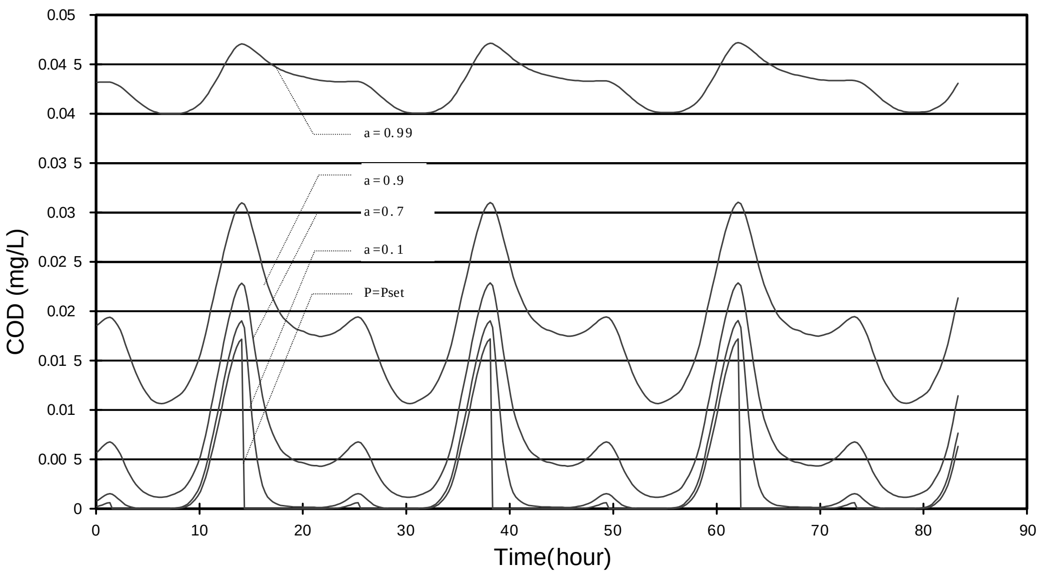

Fig. 4. COD concentration at the eastern open boundary corresponding to different a values.

Table 1
Summary statistics of wastewater flow and COD load from Guangdong Province (unit: million ton)[a]

Source	1990	1991	1992	1993	1994	1995	1996
Domestic	1110.12	1058.47	1310.49	1492.91	1981.31	2123.69	2122.22
Industrial	1402.5	1392.24	1419.39	1397.62	1315.31	1609.79	1508.74
Total wastewater	2512.62	2510.9	2801.03	2959.9	3372.07	3816.57	3714.05
COD	0.69	0.72	0.78	0.8	0.94	1.12	1.06

[a] Source: Guangdong Province Yearbook Editorial Committee (1996).

Table 2
Average water discharge rates for the five main river outlets during different seasons

(10^8 m^3/day)	Hu men	Jiao men	Hongqi men	Heng men	Shenzhen
Wet	2.09	1.99	0.77	1.31	0.06[a]
Mean	1.56	1.44	0.51	0.89	0.06[a]
Dry	0.68	0.59	0.17	0.37	0.06[a]

[a] Accurate flow data is not available and therefore an estimate is made from local flow gauge and drainage area ratio.

wastewater flow rate. Thus, the COD loading rate discharged from the eight major cities around the PRDR can be calculated by employing this equation and the corresponding wastewater flows.

Table 2 shows the net averaged water discharge rates of the five main river outlets during wet season (May to September), mean season (April, October and November) and dry season (December to March). Since the Pearl River Estuary is primarily a river network system, the COD loading data at different main river outlets can be approximated from the COD loading of the eight major cities. Based on these, the daily COD loading at the five main river outlets, namely, Hu men, Jiao men, Hongqi men, Heng men, Shenzhen are 671 307, 479 390, 123 661, 210 365 and 89 877 kg/day, respectively.

Besides, the COD loading data from sewage outfalls A, B, C, D and E in the HKSAR are 84 237, 55 200, 114 452, 131 675 and 242 101 kg/day, respectively, which are derived from the Hong Kong strategic sewage disposal plan [14]. The locations of these sewage outfalls or discharges are also shown in Fig. 1.

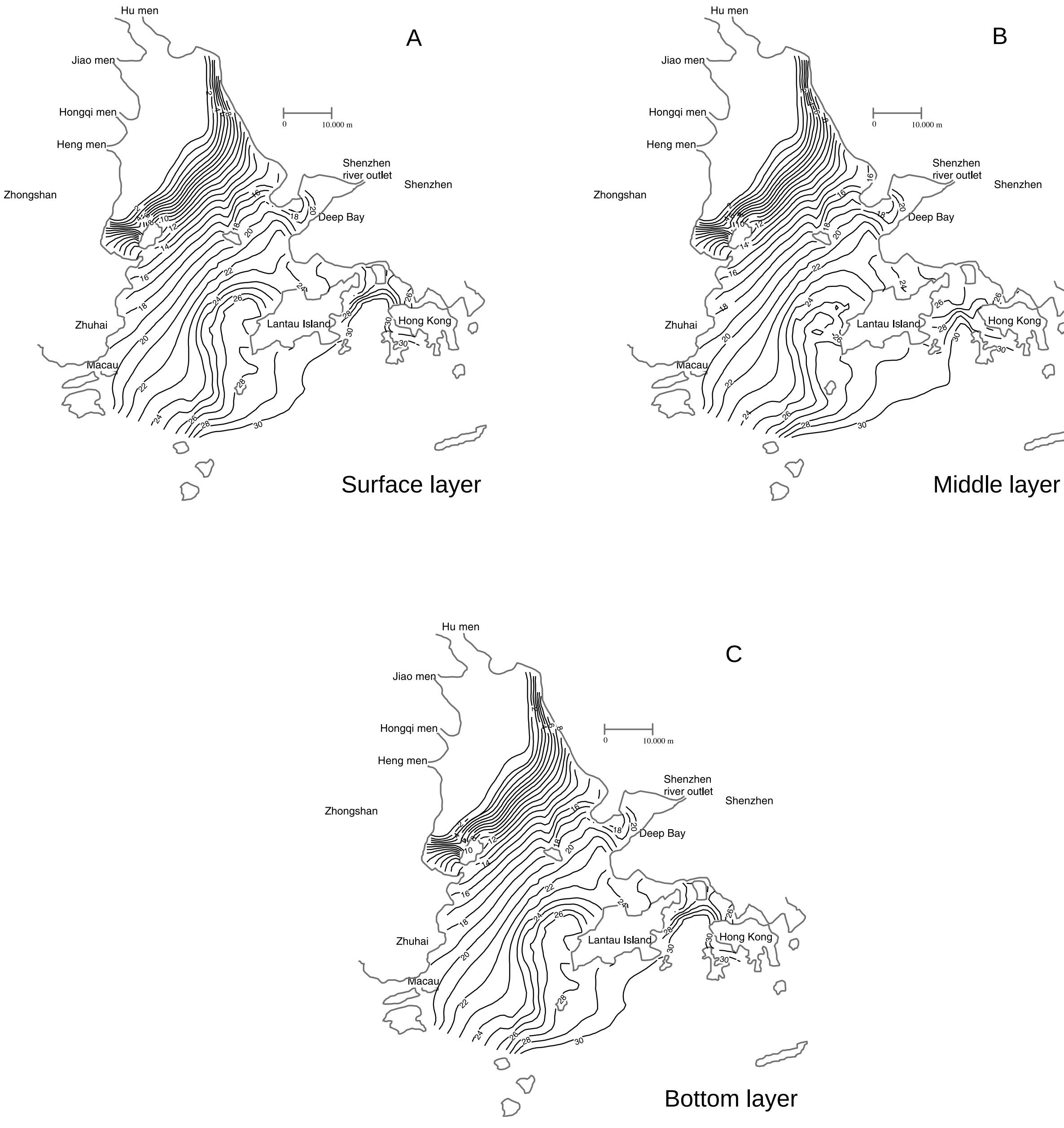

Fig. 5. The computed salinity contour of three layers in wet season: (A) surface, (B) middle and (C) bottom.

These estimated COD loadings are treated as continuous point sources and there are no sink terms or losses of COD in this case study.

4. Results and discussions

The distribution of COD caused by the pollutant sources and also from background sources is simulated through applying the estimated COD loadings from both the PRDR and the HKSAR during different seasons in this numerical model. Besides, a sensitivity analysis is performed to evaluate the impact of the pollutant sources from the PRDR on the coastal seawaters in Hong Kong.

As shown in Fig. 5, from the hydrodynamic model calibrations, the computed salinity contours of the surface layer, middle layer and bottom layer during the wet season indicate very slight vertical density stratification. Since the vertical mixing is quite well,

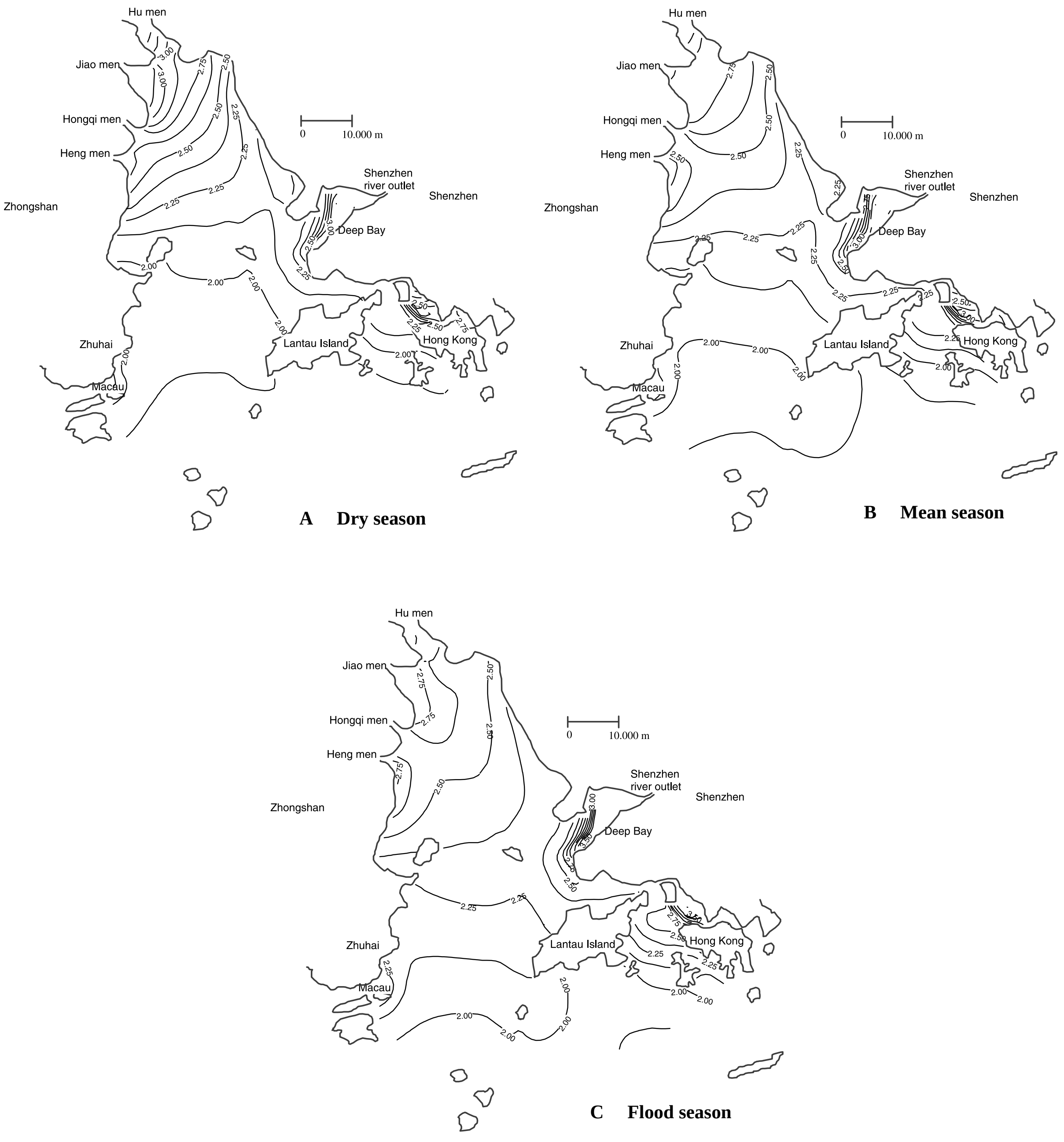

Fig. 6. The average COD distribution (in mg/L) during different seasons: (A) dry season, (B) mean season and (C) wet season.

the difference of COD concentrations between the top and the bottom can be considered negligible and, as such, a vertically averaged value is adopted here.

The average distribution of COD at the ebb tide during different seasons is shown Fig. 6. From this figure, it can be observed that the COD concentration in the western PRE varies at different season. The COD concentration in northwestern PRE during the wet season is lower than its counterparts during the dry season. The reason may be attributed to the higher dilution ratio corresponding to the greater average discharge flow. On the other hand, owing to the higher conveyance in the wet season, the concentration in southwestern PRE during the wet season is higher than its counterparts during the dry season. Since in the eastern PRE the hydrodynamic forcing is mainly

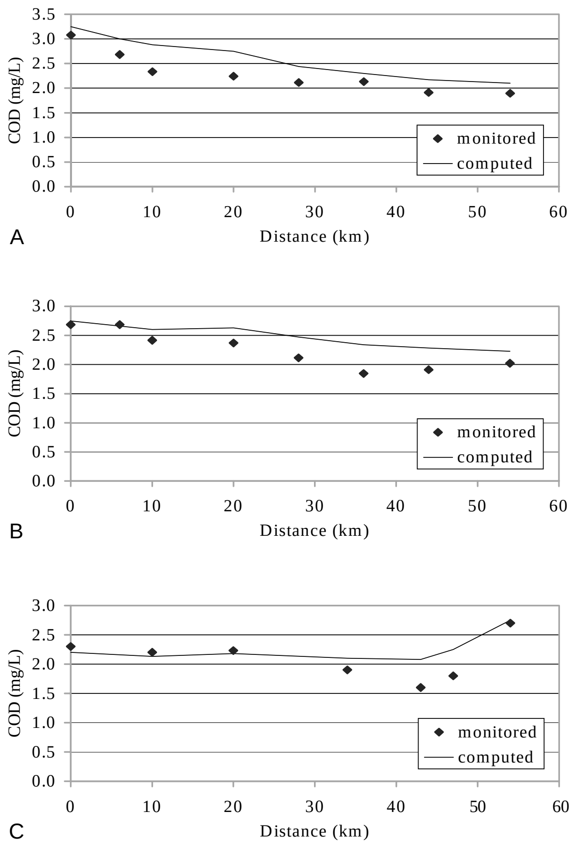

Fig. 7. Model verification of the COD concentration: (A) the longitudinal section in dry season, (B) the longitudinal section in wet season and (C) the latitudinal section in mean season.

dominated by the tidal current and the boundary condition does not vary much with the season, only slight seasonal variation is observed on the COD concentration.

As shown in Fig. 1, two sections, namely, the longitudinal section A_1–A_8 and the latitudinal section C_1–C_7, with the observed data monitored by Wen et al. [15], are used for model calibration. Both the computed and measured COD data during different seasons along these two sections are shown in Fig. 7. In general, it is noted that, with the exception at the western side of the estuary, the model outputs tend to over-compute when compared with the actual field data. Nevertheless, under the current condition that accurate COD loading data from different river outlets are not available, it anyhow demonstrates satisfactory results. If the actual COD loading from all the river outlets can be obtained, it is believed that the accuracy of the results can be improved.

Besides, a model sensitivity analysis was performed so as to assess the impact of sewage pollutants, such as COD, that are discharged from the PRDR, on the water quality in the coastal seawaters of HKSAR. In this hypothetical case, only the COD sewage loading from the PRDR is included and the background COD value is pre-set to 0 mg/L. Fig. 8 shows the results from the wet season, which has the largest amount of pollutant transport. It can be seen that the extent of the impact of COD from the five river outlets in the PRDR is significant only up to the northwestern part of Lantau Island whilst it has less effect on other areas of Hong Kong seawaters. The increase in COD concentration due to the loadings of the five river outlets is greater than 0.25 mg/L near Lantau Island. Besides, since the COD is transported over a wider area and the flow is greatest during the wet season, the effects on the water quality of Hong Kong seawaters is higher during this period.

5. Conclusions

In this paper, a three-dimensional, numerical model based on an orthogonal curvilinear grid system in the horizontal direction and a sigma coordinate system in the vertical direction for the prediction of water quality constituents has been developed and implemented. In this model, an efficient as well as simple open boundary condition is adopted for the pollutant transport phenomenon. It is then applied to a complicated estuary domain, the PRE, in order to model the distribution of COD within the PRE and, furthermore, to evaluate any possible transbounday pollution action between the Pearl River Delta Region and Hong Kong Special Administrative Region. This region is known to be the most quickly developing in China, thus causing enormous amount of pollution problems during the last decade, with Hong Kong and Macau at its entrance.

In this model, with the use of a time-splitting method, the horizontal time differencing algorithm is semi-implicit. As such, the allowable time step is much larger than POM and less computational time is needed to keep the computation stable. This characteristic is particularly useful in domain problems with complicated flow patterns and large currents caused by river discharges as well as tidal forcing, such as in PRE here.

Since the pollutant load data at the five main river outlets to the PRE is not directly available, the COD loading rates at the pollutant sources in the water quality model are derived mainly based on the characteristics of the wastewater and the discharge rates. The output results illustrate that the pollutants from the PRDR have certain impact on the Hong Kong seawaters, especially during the wet season when the discharge rates are high at the upstream ends. Nevertheless, if more actual COD loading can be obtained

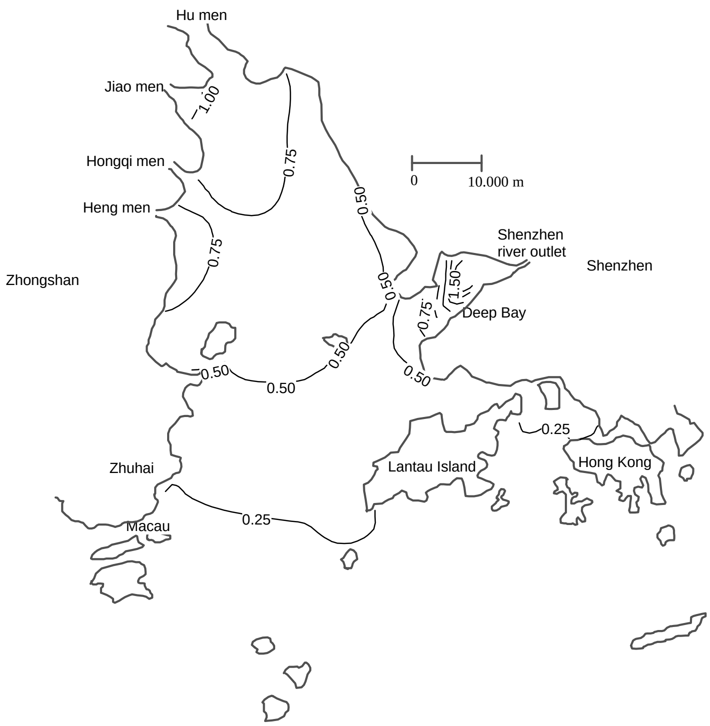

Fig. 8. Increased COD distribution (mg/L) over background due to sewage loading from the PRDR during wet season: (A) dry season, (B) mean season and (C) wet season.

from all the river outlets, it is believed that the accuracy of the results can be further improved.

Above all, a complicated and efficient three-dimensional pollutant transport has been developed and applied, which is found to works well when applied to the PRE.

Acknowledgements

The work described in this paper was substantially supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region (Project No. *PolyU 5084/97E*).

References

[1] Chau KW, Jiang YW. 3D numerical model for Pearl River Estuary. J Hydraulic Eng ASCE 2001;127(1):72–82.

[2] Hills P, Zhang L, Liu JH. Transboundary pollution between Guangdong province and Hong Kong: threats to water quality in the Pearl River Estuary and their implications for environmental policy and planning. J Environ Plann Manage 1998;41(3):375–96.

[3] Hammer MJ, Hammer Jr MJ. Water and wastewater technology. Upper Saddle River, NJ: Prentice-Hall International, Inc., 1996.

[4] Mellor GL. User's guide for a three-dimensional, primitive equation, numerical ocean model. Princeton, NJ: Princeton University Rep. Princeton University, 1996.

[5] Casulli V, Cheng RT. Semi-implicit finite difference methods for three-dimensional shallow water flow. Int J Numer Methods Fluids 1992;15(6):629–48.

[6] Chau KW, Jin HS. Numerical solution of two-layered, two-dimensional tidal flow in boundary-fitted orthogonal curvilinear coordinate System. Int J Numer Methods Fluids 1995;21(11):1087–107.

[7] Blumberg AF, Mellor G. A description of a three-dimensional coastal ocean circulation model. In: Heaps NS, editor. Three-dimensional coastal ocean models. Washington, DC: American Geophysical Union, 1987. p. 1–16.

[8] Quamrul AKM, Blumberg AF. Three-dimensional model of Onondaga Lake, New York. J Hydraulic Eng ASCE, 1999;125(9):912–23.

[9] Oey LY, Mellor GL, Hires RI. A three-dimensional simulation of the Hudson Raritan estuary. Part I; Description of model and model simulation. J Phys Oceanogr 1985;15(12):1693–709.

[10] Richtmyer RD, Morton KW. Difference methods for initial-value problems, 2nd ed. NewYork: Interscience, 1967.

[11] Pang Y, Li XL. Study of pollutants passing through the four east outlets of Pearl River Delta to Lingding sea. In: Li YS, editor. Proceedings of the Workshop on Hydraulics of the Pearl River Estuary, 1998. p. 85–98.

[12] Kot SC, Hu SL. Water flows and sediment transport in Pearl River Estuary and wave in South China Sea near Hong Kong. Coastal infrastructure development in Hong Kong—a review, Hong Kong Government, Hong Kong, 1995. p. 13–32.

[13] Leendertse JJ, Crittion EC. A water quality simulation model for well-mixed estuaries and coastal seas computation procedures. R-708-NYC.11, Rand Corp, New York, 1971.

[14] Sin WS, Chan PK, Chan KM. Sewage and stormwater disposal. Coastal infrastructure development in Hong Kong—a review, Hong Kong Government, Hong Kong, 1995. p. 343–359.

[15] Wen WY, Zhang GX, Du WC. A study on water pollution in the Zhujiang Estuary. Environmental research of Pearl River Delta Region, Guangdong Province Government, Guangzhou, 1994. p. 99–151.