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SIMULATION OF TRANSBOUNDARY POLLUTANT TRANSPORT ACTION IN PEARL RIVER DELTA

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1. Abstract

The rapid economic development in Pearl River Delta Region (PRDR) has exerted serious potential pollution threats to areas in the vicinity, which have complicated the task of environmental protection in Hong Kong and Macau. In this paper, a three-dimensional numerical pollutant transport model coupled with a synchronized numerical hydrodynamic model, is developed and employed to simulate the unsteady transport of a representative water quality variable Chemical Oxygen Demand in Pearl River Estuary. It is demonstrated that there exists a transboundary pollutant transport action between Guangdong Province and Hong Kong for the pollutants in the wastewater discharged from PRDR.

2. Key words

Chemical oxygen demand, numerical simulation, Pearl River delta, pollution transport, transboundary action, water quality

3. Introduction

The Pearl River Estuary (PRE), at which Hong Kong is located, is the largest estuary in Southern China. The Pearl River Delta Region (PRDR) is one of the most quickly developing regions in China and Asia, and covers eight major cities, namely, Guangzhou, Shenzhen, Zhuhai, Foshan, Zhongshan, Dongguan, Huizhou and Jiangmen (Figure 1). The rapid economic growth of this region in the last two decades has exerted a significant pollution impact on the ambient environment. Specifically, the rate of untreated sewage discharge is escalating tremendously. Large quantities of various pollutants have been discharged into the PRE, principally through five outlets, namely, Hu men, Jiao men, Hongqi men, Heng men, and Shenzhen River. This paper delineates a three-dimensional pollutant transport mathematical model, which is integrated with a synchronised hydrodynamic mathematical model (Chau and Jiang 2001), for simulation of the unsteady transport of a representative water quality variable Chemical Oxygen Demand in Manganese (COD_{Mn}) in the PRE. The model employs orthogonal curvilinear co-ordinate in the horizontal direction, sigma co-ordinate in the vertical direction, and a newly developed robust open boundary condition for pollutant transport.

In general, the pollutants in the PRDR are transported from the various outlets of the river network towards its entrance, through the interaction of tidal effects as well as runoff discharge from the rivers. Since Hong Kong Special Administrative Region (HKSAR) and Macau are located on the eastern and western sides of the outlet respectively, the transboundary pollutants from the inner PRE become potentially significant matters of concern. It inevitably adds an additional complexity as well as dimension to the environmental protection tasks in both

HKSAR (Hills et al. 1998) and Macau. As such, it is imperative to determine both qualitatively and quantitatively the impacts of these pollutants from the PRDR on the water quality in the ambient seawaters of HKSAR. In this pollutant transport numerical model, COD_{Mn} is adopted as an index in order to assess the action of pollution transboundary action.

4. Details of the pollutant transport model

The model is developed based on a three-dimensional hydrodynamic numerical model (Chau and Jiang 2001). The curvilinear orthogonal coordinate is employed in the horizontal spatial direction and the sigma coordinate is adopted in the vertical spatial direction. The methodology of the orthogonal curvilinear transformation for hydrodynamics and water quality modeling is similar to those in Chau and Jin (1995) and Chau and Jin (1998). Both the horizontal and vertical time differencing are treated in a semi-implicit manner. Since a time-splitting method is employed in the horizontal time differencing of external model, the allowable time step can be much greater than that acquired from the Courant-Friedrichs-Lewy stability criterion. The model comprises an embedded second moment turbulence closure sub-model in order to cater for vertical mixing coefficients. The model implements complete thermodynamics so that the stratification of salinity and temperature are both taken into accounts. The details of the hydrodynamic model of PRE integrated in the present pollutant transport model can be found in Chau and Jin (2001).

In this model, the governing equation of pollutant transport is written as:

$$\frac{\partial SD}{\partial t}+\frac{\partial SUD}{\partial x}+\frac{\partial SVD}{\partial y}+\frac{\partial S\omega}{\partial \sigma}=\frac{\partial}{\partial x}(A_S H\frac{\partial S}{\partial x})+\frac{\partial}{\partial y}(A_S H\frac{\partial S}{\partial y})+\frac{\partial}{\partial \sigma}\left[\frac{K_H}{D}\frac{\partial S}{\partial \sigma}\right]-K_S DS+S_S \qquad (1)$$

where (U,V,ω) are mean fluid velocities in the (x,y,σ) direction; S is the density of the pollutant, which in our case is the density of COD_{Mn}; $D=\eta+H$, η is the water surface elevation above the undisturbed mean sea level and H is the undisturbed mean water depth; K_H is the vertical turbulent flux coefficient, which can be derived from the second moment $q^2 \sim q^2 l$ turbulence energy model (Mellor 1996); K_s is the decay rate of pollutant; S_s is the source of pollutant; A_s is horizontal turbulent coefficient, which can be acquired from the following Smagorinsky formula (Oey et al 1985)

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

where C is a coefficient ranged from 0.1 to 0.2. In this model, a value of 0.12 is adopted after a number of thorough trials.

The above governing pollutant transport equation is then written in finite difference equation under the "Arakawa C" grids as follows:

$$\begin{aligned}&\delta_t(SD)+\delta_x(\overline{S}^x\overline{D}^x U)+\delta_y(\overline{S}^y\overline{D}^y V)+\delta_\sigma(\overline{S}^\sigma\omega)=\delta_x(\overline{H}^x\overline{A}_s^x\delta_x S)+\delta_y(\overline{H}^y\overline{A}_s^y\delta_y S)\\&+\delta_\sigma(\overline{K}_H^\sigma\delta_\sigma S_+/D)-K_S DS_+ + S_s\end{aligned} \qquad (3)$$

where for any parameter $F=F(x,y,\sigma,t)$ with spatial and temporal property x,y,σ,t ,

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

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

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

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

Except unknowns $S(x,y,\sigma,t+\Delta t)$, $S(x,y,\sigma+\Delta\sigma,t+\Delta t)$, and $S(x,y,\sigma-\Delta\sigma,t+\Delta t)$ in the first term of left hand side and the third and fourth term of right hand side of the discretized equation (3), all the other components can be acquired either from the hydrodynamic model or from the previous time steps. Therefore, the equation can be re-arranged as:

$$AS(x,y,\sigma-\Delta\sigma,t+\Delta t)+BS(x,y,\sigma,t+\Delta t)+CS(x,y,\sigma+\Delta\sigma,t+\Delta t)=D \qquad (8)$$

where A, B, C and D are some known coefficients. It is obvious that equation (8) is a tri-diagonal matrix in the vertical direction, which can be solved by the technique depicted in Richtmeyer and Morton (1967).

5. The Pearl River Delta Region

5.1 HYDROLOGICAL CONDITIONS

The PRDR is a delta estuary comprising four main outlets, namely, Hu men, Jiao men, Hongqi men, Heng men, in the northwest of PRE and Shenzhen River outlet at the Deep Bay. The annually averaged net discharges of the four main outlets during different seasons are evaluated and estimated based on Pang and Li (1998). The data of 1998 are the most recent information that are available. Nevertheless, the situation is not changing drastically within these few years. The tide in PRE is predominately of semi-diurnal and irregular nature with the mean tidal range being 1.0m or so. The mean tidal range is 0.85-0.9m at the entrance of the estuary. However, the range is higher in the inner estuary. When it arrives Hu men, the mean range becomes 1.6m (Kot and Hu 1995). During the wet season, which is roughly from May to September, the river runoffs are so significant that they become the predominant hydrodynamic force in the PRE. On the other hand, during the dry season, which is from December to March, the tide is the principal force. As such, in order to capture the whole picture of the transport pattern, the distribution of pollutant during different seasons shall be investigated.

5.2 MODEL PARAMETERS

In this model, the total number of horizontal grids within the entire computing domain is 3400 whilst the number of layers in the vertical direction is six. Each layer has the same $\delta\sigma$, with a value of *1/6*. The initial conditions are set such that the density of pollutants for all grid points are zero. After running for 100 tidal periods or so, which is about 50 days, a steady state condition is obtained.

In total, two open boundaries are encountered in this model, namely, the eastern open boundary and the southern open boundary. In most previous models, the open boundary condition for pollutant transport is usually treated in a simple fashion (Leedertse and Crittion 1971). For instance, for grids in the vicinity of the eastern open boundary, the treatment employed by Leedertse and Crittion (1971) is as follows:

$$P_{i,j}^{n+1}=P_{set} \qquad U_{i-\frac{1}{2},j}^{n+1}<0 \qquad (9)$$

$$\frac{dP}{dt}=0 \quad that \quad is\,\frac{P_{i,j}^{n+1}-P_{i,j}^{n-1}}{2\Delta t}+U_{i-\frac{1}{2},j}^{n+1}\frac{P_{i,j}^{n}-P_{i-1,j}^{n}}{\Delta x}=0 \qquad U_{i-\frac{1}{2},j}^{n+1}>0 \qquad (10)$$

where P_{set} denotes the prescribed along-boundary component of the pollutant density. Of course, if the value is known, it can be applied directly. However, it is more often an unknown value. In such cases, a value of zero has to be set. Hence, the captioned open boundary condition represents the real situation only when the boundary value is known or there exists strong capacity of water exchange along the open boundary. In this case for the PRE, such boundary data are not available. Moreover, the exchange capacity at the entrance of PRE is not strong enough for the condition $P_{set}=0$ to be justifiable. As such, in this model, a simple but efficient open transport condition is developed as follows:

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

$$\frac{dP}{dt}=0 \quad that \quad is\,\frac{P_{i,j}^{n+1}-P_{i,j}^{n-1}}{2\Delta t}+U_{i-\frac{1}{2},j}^{n+1}\frac{P_{i,j}^{n}-P_{i-1,j}^{n}}{\Delta x}=0 \qquad U_{i-\frac{1}{2},j}^{n+1}>0 \tag{12}$$

With this boundary condition, the ebb tide condition remains the same, as shown in equation (10) and equation (12). However, during the flood tide, equation (11) replaces equation (9). The parameter a in equation (11) is a constant coefficient, whose range is between 0 and 1, with value depending on the capacity of water exchange outside the open boundary. If the exchange capacity is strong, a small value of a should be employed. On the other hand, if it is weak, a large value should be used. For this model in the PRE, after a number of trials, $a=0.9$ is adopted, which is able to provide the best-fit result comparison with the measured field data.

5.3 POLLUTANT SOURCES AND LOADING

The main source of pollutants discharged to PRE are mainly from the four outlets at the northwestern side of the PRDR and Shenzhen River outlet at Deep Bay. Since no direct COD data discharged from different outlets are available, the loading of COD at different outlets is evaluated as follows. The volume flow rates of domestic and industrial wastewater discharged from Guangdong Province are firstly calculated based on Wen et al. (1994). From these data, a relationship between discharge rate of COD and the discharge rates of domestic and industrial wastewater can then be derived:

$$Q_{COD}=0.00027Q_d+0.000305Q_i \tag{13}$$

where Q_{COD} is the discharge rate of COD, Q_i is the discharge rate of industrial wastewater, Q_d is the discharge rate of domestic wastewater. The coefficient of regression of this relationship is 0.93.

By employing this relationship, the quantity of the COD discharged from the eight major cities in the PRDR can be derived from the corresponding wastewater discharges. Since the PRE is a river network system, the COD loading data can be approximated by the COD discharge of these eight major cities, together with the net discharge flow rates of the corresponding river outlet. The assigned value of the decay rate of pollutants is 0.25 day^{-1}.

6. Model results

In this study, the COD loading of PRDR in different seasons are evaluated and applied. As such, the numerical model can be employed to simulate the effect and distribution of incremental COD_{Mn} caused by these pollutant sources. The impacts of the pollutant sources from the PRDR on Hong Kong ambient seawaters can thus be assessed using this method. Besides, since the vertical mixing is found to be quite well, it is noted that the differences of vertical averaged COD_{Mn} densities in different layers are negligible.

The incremental distribution of COD_{Mn} due to sewage loading from the PRDR in different seasons, namely, dry season, mean season and wet season, during the ebb tide are shown in Figure 2 to Figure 4. It can be observed from these figures that the influence of COD loading from the five outlets is significant up to the northern part of the Lantau Island, and that its effect becomes less in the other areas of Hong Kong ambient seawaters. It is found that the maximum value of incremental density of COD_{Mn} caused by the loadings of the five outlets is about 0.75 mg/L adjacent to the Lantau Island. During the wet season, the COD_{Mn} is transporting to its largest extent, and its impact on the quality of Hong Kong seawaters is more significant. However, the density change of COD_{Mn} in the inner estuary is not as high as during the mean season or the dry season. The most probable reason is that the conveyance capacity is highest under the largest net discharge. On the other hand, during the dry season, the density of COD_{Mn} is relatively high in the inner PRE, yet at the entrance of the PRE, especially at Hong Kong seawaters, COD_{Mn} is much more dilute. The virtual zero value near Macau means that they have minimum effect there. The background COD value near Macau is about 1.9 mg/L, which is consistent with the measured data.

It is also found that the pollutants from the Hu men outlet and Shenzhen River outlet exert higher impacts on the PRE and Hong Kong ambient seawaters, when compared with the other river outlets. It is because the pollutant loading in the Hu men outlet is the largest, whilst the hydrodynamic transport capacity of Shenzhen River is quite limited by its location and the small net water discharge. Table 1 shows the verification of the simulation results at some monitoring stations in wet season during ebb tide. Since the proposed relationship on the discharge rate of COD has a high regression coefficient, the input values will not be subjected to large variation. Nevertheless, it is still worthwhile to explore how the changes of these values affect the results. Sensitivity tests have been carried out with the variations on the basis of the above regression coefficient. It is found that the changes in the results are unnoticeable.

7. Conclusions

A three-dimensional pollutant transport model for the simulation of transboundary effect in Pearl River delta is implemented, based on orthogonal curvilinear grid in the horizontal direction and sigma coordinate in the vertical direction. A simple but robust open boundary condition for pollutant transport is adopted. Although the pollutant load data at these five main outlets in the PRE are not directly available, the COD_{Mn} discharge rates at different outlets are evaluated and estimated for input as the pollutant sources into the water quality model. The simulated results illustrate that the pollutants from the PRDR affect the Hong Kong ambient seawaters significantly, especially during wet season under large net runoff discharge condition. It is also found that the pollutants discharged from the Hu men outlet and Shenzhen River outlet exert higher impacts on the water quality in the PRE and Hong Kong ambient seawaters, when compared with other outlets of the PRE.

8. Acknowledgements

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Figure captions

Figure 1. Bathymetry of Pearl River Delta Region

Figure 2. Simulated incremental distribution of COD_{Mn} (in mg/L) due to sewage loading from the PRDR in dry season during ebb tide

Figure 3. Simulated incremental distribution of COD_{Mn} (in mg/L) due to sewage loading from the PRDR in mean season during ebb tide

Figure 4. Simulated incremental distribution of COD_{Mn} (in mg/L) due to sewage loading from the PRDR in wet season during ebb tide

Table 1. Verification of simulation results in wet season during ebb tide

Location	Simulated COD_{Mn} (mg/L)	Observed COD_{Mn} (mg/L)
Jiao men	4.5	4.6
Hongqi men	4.1	4
Heng men	3.3	3.4
Deep Bay	3.9	3.8
Lantau Island	2.5	2.4
Macau	1.9	1.8

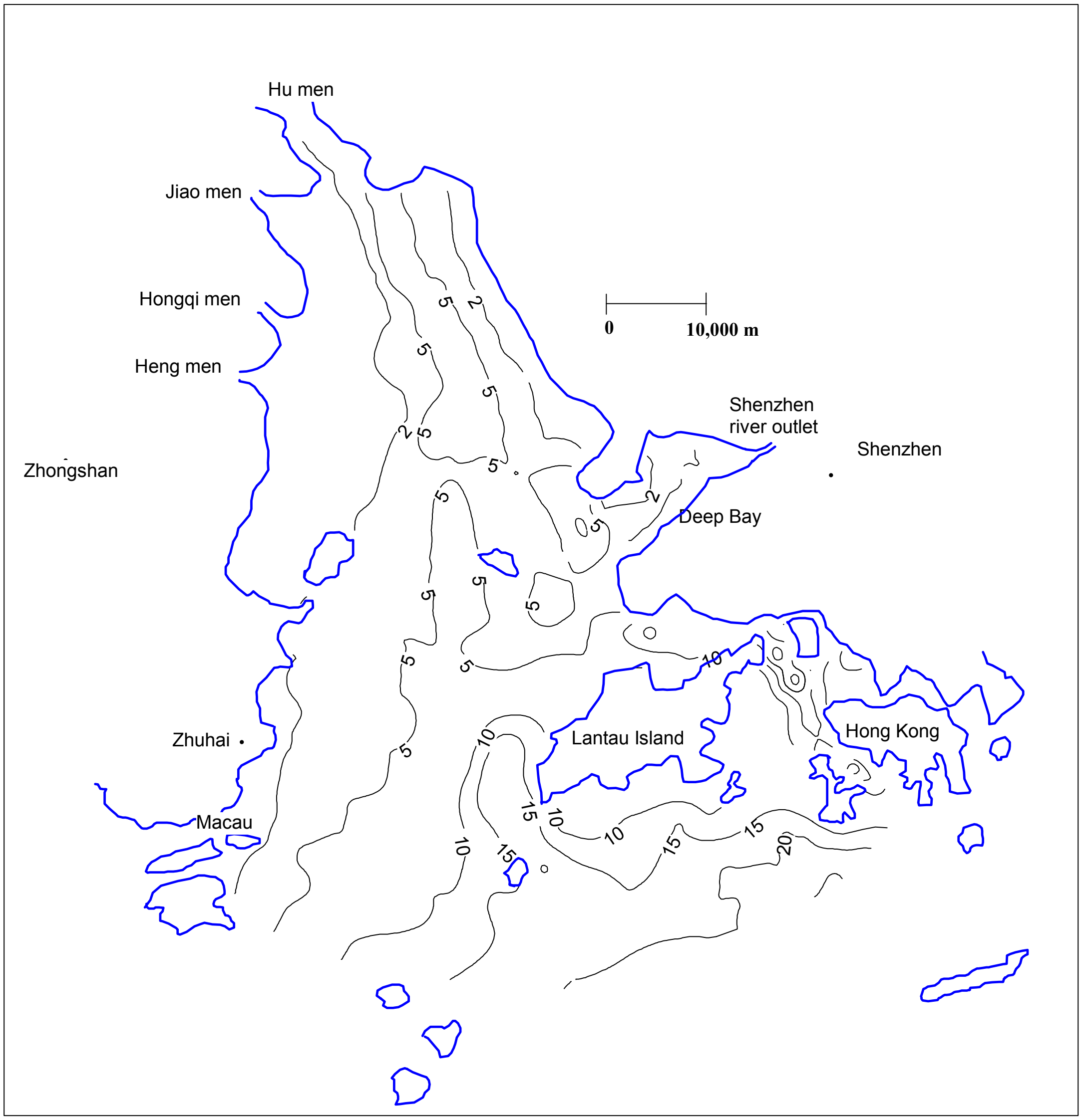
Hu men
Jiao men
Hongqi men
Heng men
Zhongshan
0
10,000 m
Shenzhen river outlet
Shenzhen
Deep Bay
Lantau Island
Hong Kong
Zhuhai
Macau
2
5
10
15
20

Figure 1.

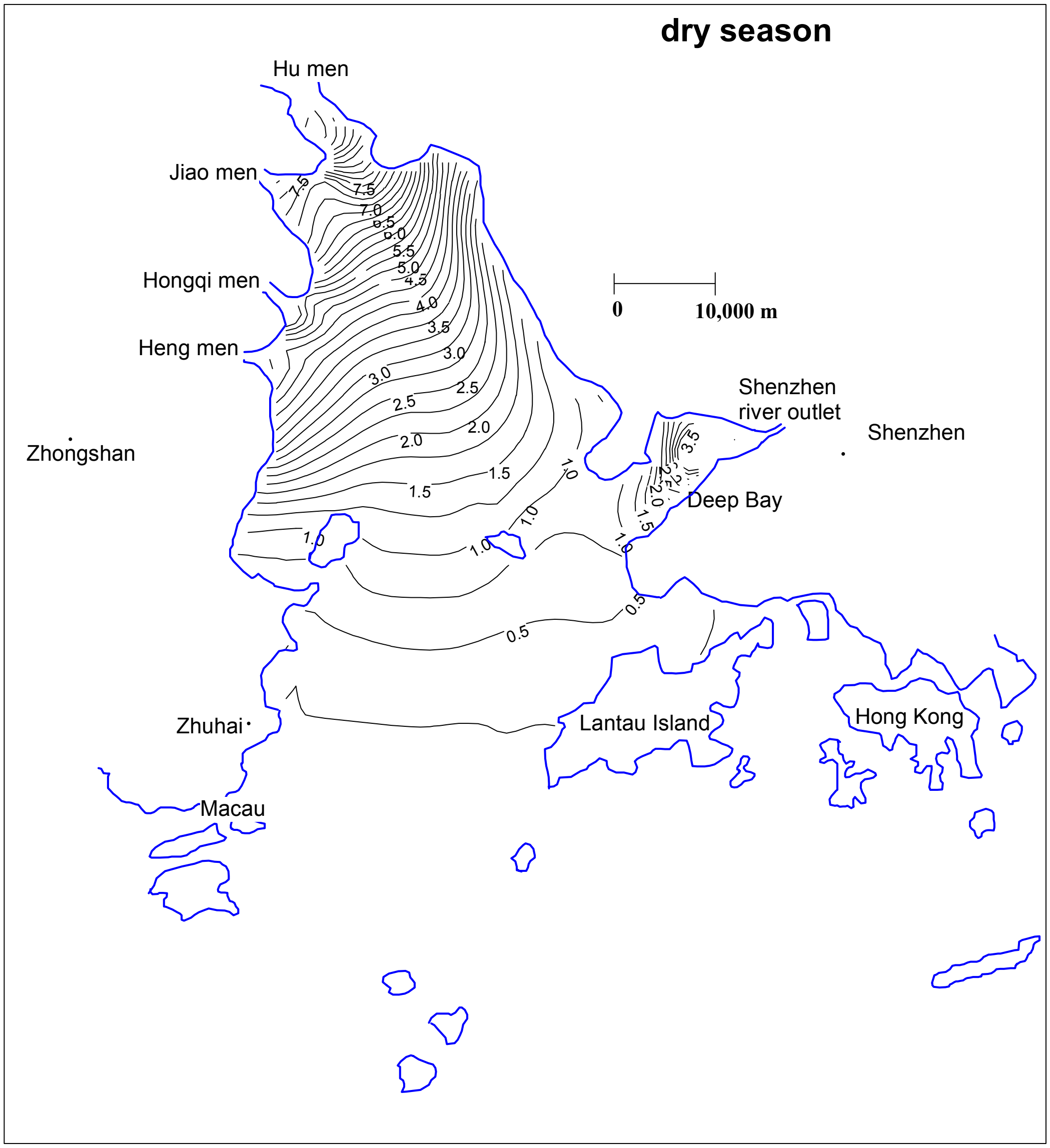
dry season
Hu men
Jiao men
Hongqi men
Heng men
Zhongshan
Zhuhai
Macau
Lantau Island
Hong Kong
Shenzhen
Shenzhen river outlet
Deep Bay
0
10,000 m
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5

Figure 2.

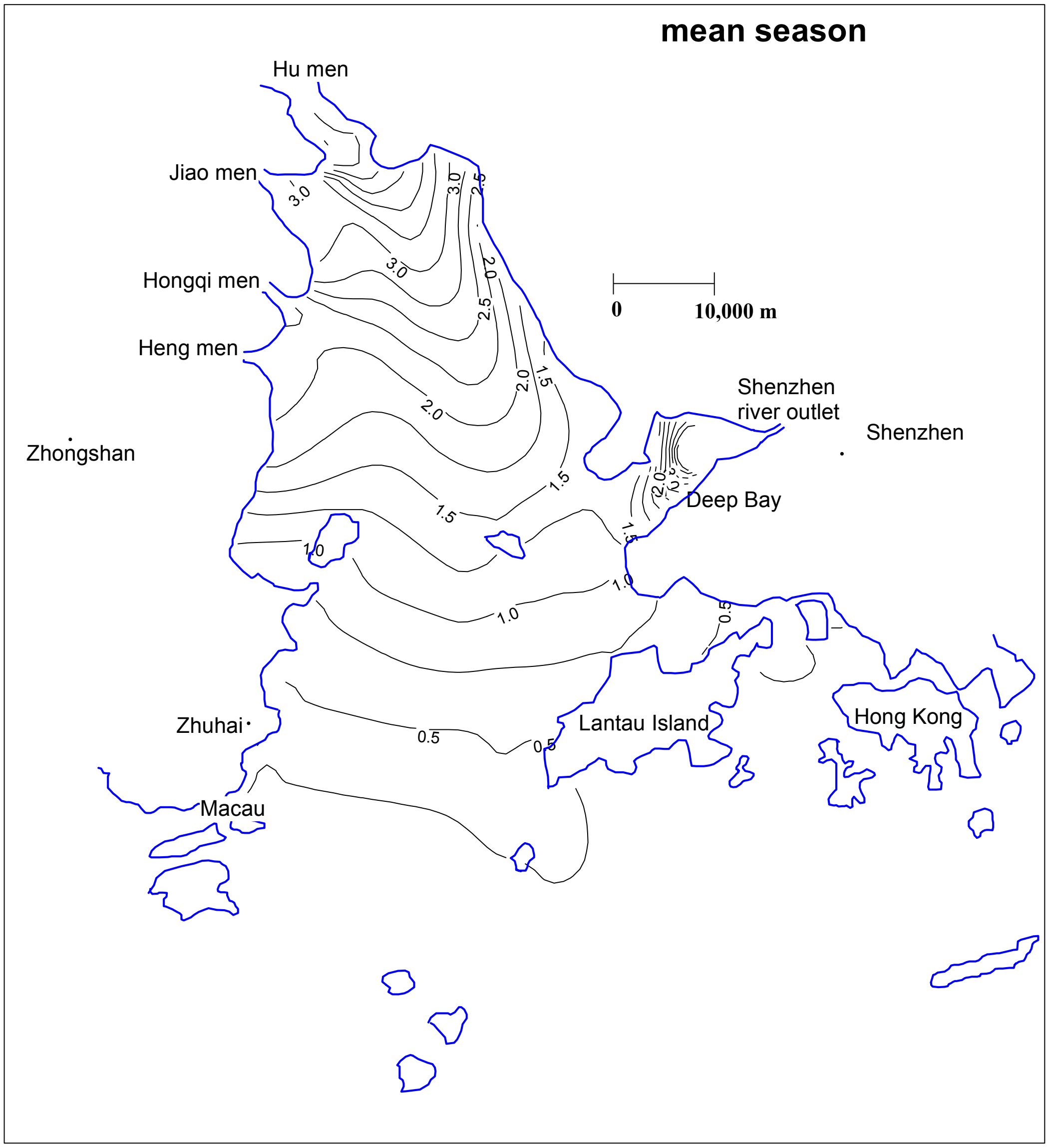
mean season
Hu men
Jiao men
Hongqi men
Heng men
Zhongshan
Zhuhai
Macau
Lantau Island
Hong Kong
Deep Bay
Shenzhen river outlet
Shenzhen
0
10,000 m
3.0
2.5
2.0
1.5
1.0
0.5

Figure 3.

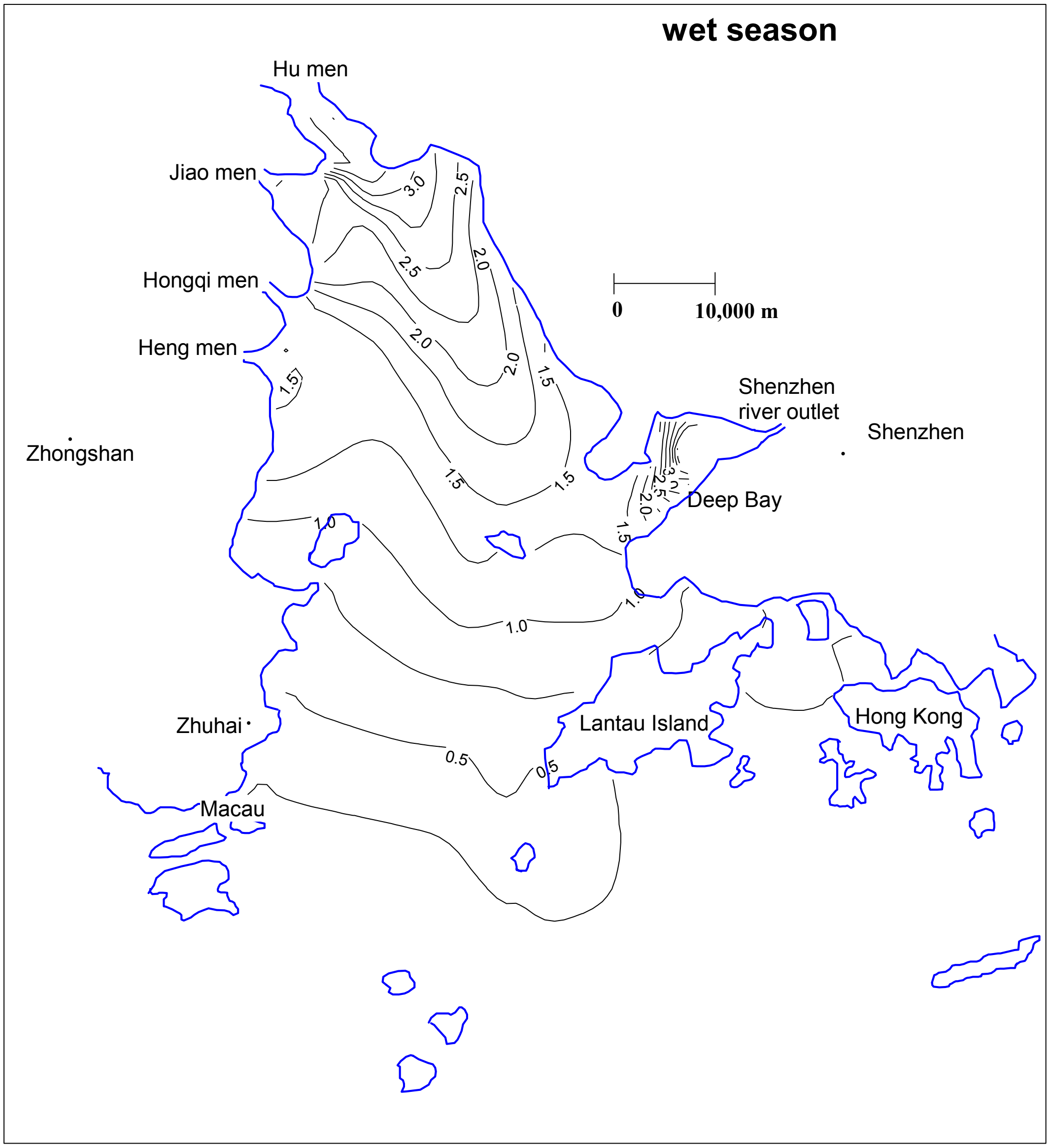
wet season
Hu men
Jiao men
Hongqi men
Heng men
Zhongshan
Zhuhai
Macau
Lantau Island
Hong Kong
Deep Bay
Shenzhen river outlet
Shenzhen
0
10,000 m
3.0
2.5
2.5
2.0
2.0
2.0
1.5
1.5
1.5
1.5
1.5
1.0
1.0
1.0
0.5
0.5
3.0
2.5
2.0
1.5

Figure 4.