Modelling study on environmental indicators in an estuary

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This paper reports on an investigation of the spatial and temporal variation of main environmental indicators in the Pearl River estuary using a numerical water quality model. An integrated field survey was undertaken in 2006 and 2007, and the data obtained were used to set up and verify the model. The water quality model was driven by a hydrodynamic model in which the monthly average freshwater discharges from eight major entrances were taken into account and the seaward boundary elevations were specified based on eight major tidal constituents. Two environmental indicators – dissolved inorganic nitrogen and chemical oxygen demand – were chosen as nutrient and pollution indicators, respectively, according to the actual pollution conditions. Both land-based sources (carried by the discharges) and air-based sources (wet and dry atmospheric depositions) were included in the water quality model and the processes of advection, diffusion and degradation were also modelled. The model predictions generally agreed well with the sampling data, and existing field and model results. The present contributions of the main sources were investigated and prospective scenarios of pollution reductions were predicted.

1. Introduction

Estuaries are the areas of interaction between freshwater from precipitation on land and salt water from open oceans (Nielsen, 2009). As it flows into the sea, the freshwater usually carries matter from the feeding river basins. Estuarine waters are characterised by strong gradients in environmental variables such as salinity, nutrients and organic matter, and this environmental heterogeneity constitutes essential conditions for maintaining species diversity (Lohrenz *et al.*, 1990). However, with rapid industrialisation, population growth and intensified agricultural activities, more and more nutrients and organic pollutants are being dumped into the sea through estuaries. As a result, adverse effects on the ambient environment, such as water pollution and eutrophication, have become inevitable. Moreover, elevated nutrient concentrations in river waters often trigger high primary production and algal blooms in the river plume and adjacent estuarine and shelf waters (Dagg and Breed, 2003; Rabouille *et al.*, 2008).

The Pearl River estuary (PRE) is a sub-tropical estuary located along the coast of the South China Sea (Figure 1). This is a complicated system with respect to both geometric and hydrodynamic properties. Over the past few decades, massive economic growth and urban development around this region have led to excessive release of waste into the estuary. Several field surveys

have been conducted to investigate water quality in the estuary, and the results show that nutrients and organic pollutants are two of the major nutrient indicators, especially excess nitrogen over-enrichment (Cai *et al.*, 2004; Harrison *et al.*, 2008; Huang *et al.*, 2003; Xu *et al.*, 2008; Yin and Harrison, 2008; Yin *et al.*, 2000). As a result mainly of the high level of dissolved inorganic nitrogen (DIN) concentration, the water quality in the PRE and some adjacent areas is water quality level 5 (WQL 5, i.e. the worst polluted water (Chen *et al.*, 2007)), according to the Chinese seawater quality standard (GB 3097-1997) in which water quality is divided into five WQLs. It is thus necessary to understand the process of spatial–temporal variation of environmental indicators in order to find a way to solve the environmental problems and develop new tools for building eco-restoration strategies in the PRE (Huang *et al.*, 2003).

Numerical modelling, which can provide details of spatial–temporal variation of water quality indicators, is an effective supplement to field surveys. Chau and Jiang (2002, 2003) simulated the distribution and transport of chemical oxygen demand (COD) in the PRE with decay-type dynamics. Guan *et al.* (2001) designed an ecosystem-based water quality model to estimate the biochemical reaction, and then applied the model to predict the distributions of nutrients and dissolved oxygen. Simplified water quality models, such as decay-type models, are

Figure 1. Topography of the Pearl River estuary and adjacent sea areas showing the eight major entrances, sampling stations (circles) and sluice-controlled rivers (squares: 1, Dalongdong; 2, Qianshanhe; 3, Shenzhenhe)

feasible in the study area for environmental indicators like DIN and COD because the dominant process is mixing (or dilution) and the biochemical reactions are secondary processes (Cai *et al.*, 2004; Yin *et al.*, 2000). To set up and verify this kind of model, adequate field data are still necessary. However, comprehensive investigations that involve pollutant contributions from various sources (such as major entrances and atmospheric depositions) to the distribution and variation of environmental indicators are seldom seen in previously reported studies, as are scenario predictions for planning pollution reductions in the PRE.

The main aim of the current study was thus to gain improved understanding of the distributions of environmental indicators and their seasonal variations in the PRE, and assess the effects of pollution reductions that could be implemented. A field survey in the PRE and adjacent coastal areas was conducted in 2006 and 2007. Assisted by these field exercises, a numerical water quality modelling study was undertaken. In view of the serious problems of eutrophication and industrial organic pollution, and according to the Chinese seawater quality standard (GB 3097-1997), DIN and COD were selected as nutrient indicators and pollution indicators respectively. As this study mainly concerned the horizontal distributions of these indicators, a horizontal two-dimensional (2D) water quality model was employed with a first-order decay equation being used to represent integrated functions of chemical and biological reactions.

Section 2 gives a brief introduction to the key geographic features of the PRE and its adjacent coastal areas. Section 3 presents some details of the field survey exercises and the numerical model. Section 4 details the model predictions and observed data,

and the results are analysed in Section 5. Finally, the main conclusions from the study are outlined in Section 6.

2. Study area

This study is focused on the water quality in the PRE and adjacent coastal areas, within a square area defined by 21°30'–23°00'N and 112°30'–115°00'E (Figure 1). The coastal line of the study area stretches from northeast to southwest, with the South China Sea located at the south side and the Pearl River delta at the north side. Hong Kong is located at the east bank of the PRE. The water depth is less than 20 m for most part of the estuary and bays. The total area of water surface in this domain is about 30 000 km².

The PRE is the biggest estuary of the Pearl River, which is the second largest river in China and the thirteenth largest river in the world in terms of mean annual water discharge (PRWRC, 1991). Located at about 22°N latitude, the Pearl River is a typical subtropical river (Rabouille *et al.*, 2008). The total annual discharge is about 330×10^9 m³, according to historic data (Zhang *et al.*, 2008). Passing through a complex river network in the Pearl River delta, freshwater discharge flows into the PRE and coastal areas mainly through eight major entrances – Hu-men, Jiao-men, Hongqi-men, Heng-men, Medao-men, Jiti-men, Hutiao-men and Ya-men from northeast to southwest respectively (Figure 1); the word ‘men’ means major entrance in Chinese. Apart from these major entrances, three rivers controlled by sluices (Dalongdong, Qianshanhe and Shenzhenhe) are located near Guanghai Bay, Medao-men and PRE respectively.

As a typical tidal river network, the hydrological processes in the

Pearl River are rather complicated with regard to both the spatial and temporal distributions of the freshwater discharge. It is well known that there is a large seasonal variation in freshwater discharge, with about 80% of the total volume being discharged in the wet season and 20% in the dry season (Cai *et al.*, 2004; Dong *et al.*, 2004). The mean tidal range in the PRE varies between 0.8 and 1.7 m (Wong *et al.*, 2003; Zhao, 1990). The tidal cycle is mainly a semi-diurnal mixed tidal regime with daily inequality in range and time between the highs and lows (Mao *et al.*, 2004). M2 is the dominant tidal constituent, followed by K1, O1 and S2.

3. Data and methods

3.1 Data acquisition

An integrated field survey, which included field sampling in the study area, determination of pollution load and so on, had already been conducted as part of this study. In addition, historic data (e.g. freshwater discharge) were collected to support the modelling study.

3.1.1 Sampling data

Several cruise surveys were undertaken to investigate the horizontal distributions of environmental indicators, including salinity, DIN and COD, and their seasonal variations. As shown in Figure 1, 25 sampling stations were designated in the PRE and adjacent coastal areas. In order to cover the coastal area near Hong Kong, four of the routine stations (NM6, SM6, EM3, MM15) of the Environmental Protection Department of Hong Kong were also selected. The cruise surveys covered three typical periods: 5–16 July 2006 as the summer wet season; 17–24 September 2006 as the mean-flow season; 14–25 March 2007 as the spring dry season.

3.1.2 Freshwater discharge data

Freshwater discharge data were estimated based on records obtained from 1945 to 2004 by the Guangdong Research Institute of Water Research and Hydropower. Figure 2 shows the monthly average values of combined discharges of the two main channels. The discharge across these two rivers accounts for 84% of the

Figure 2. Monthly average values of combined discharges of two main rivers (Xijiang and Beijing rivers)

total freshwater volume, which is consistent with previous studies (Cai *et al.*, 2004; Kot and Hu, 1995; PRWRC, 1991; Rabouille *et al.*, 2008; Zhang *et al.*, 2008). Table 1 lists the annual discharges and proportion of freshwater contributions from the eight major entrances, which are also consistent with results from previous studies (Hou *et al.*, 2004; Kot and Hu, 1995). It can be seen that, among the entrances, the discharge from Medao-men is the largest, followed by those from Hu-men and Jiao-men.

3.1.3 Pollution load of DIN and COD

Regarding coastal water quality, two types of pollution load are potentially important – the land-based load and the air-based load. Pollution loads were calculated based on the field surveys undertaken in 2006 and 2007. The annual land-based loads (including those from point sources (M_P) and those from non-point sources (M_N)) from the eight major entrances are shown in Figure 3. It can be seen that Hu-men, Medao-men and Jiao-men are the three largest contributors of DIN and COD, which is related to the large freshwater discharge from these three

Entrance	Annual discharge: 10^9 m^3	Proportion: %
Hu-men	60.31	18.50
Jiao-men	56.50	17.33
Hongqi-men	20.88	6.41
Heng-men	36.58	11.22
Medao-men	92.24	28.30
Jiti-men	19.69	6.04
Hutiao-men	20.21	6.20
Ya-men	19.57	6.00
Total	325.98	100.00

Table 1. Annual discharges of eight major entrances to the Pearl River estuary

Figure 3. Annual land-based load of COD and DIN from the major entrances

entrances. The temporal fluxes (F) of DIN and COD loads are given as

$$1. \quad F(t) = \frac{M_P}{T} + \frac{M_N Q_{\text{River}}(t)}{\int_0^T Q_{\text{River}}(t) dt}$$

where T is the time period (1 year) and $Q_{\text{River}}(t)$ is the temporal river freshwater discharge. In this study, the monthly average DIN and COD loads were used together with the monthly average freshwater discharges.

Wet and dry atmospheric depositions were measured to estimate the air-based loads (Fan *et al.*, 2010; He *et al.*, 2008). The monthly variation of the wet and dry atmospheric depositions of DIN shown in Figure 4 indicates that atmospheric deposition is generally more intensive in the wet season than in the dry season. An exception is seen in July, which is thought to be related to this specific year of measurements; the deposition value for August was used for the wet season in the simulation thereafter.

3.2 Model description

3.2.1 Hydrodynamic model

A depth-integrated 2D numerical model was used to calculate the water level and velocity distributions. In this model, the study domain was discretised in a space-staggered grid, with the water elevation located at the centre of a grid cell and the flux at the side of the cell. The alternating direction implicit finite-difference scheme was used to solve the governing equations (Lin and Falconer, 1995). This scheme is essentially second-order accurate both in time and space with no stability constraints owing to the time-centred implicit characteristics. This hydrodynamic model has been successfully used in Chinese coastal areas (Nie and Tao, 2009a, 2009b; Sun and Tao, 2006; Sun *et al.*, 2009; Tao *et al.*, 2001) and is able to deal with complex topography, such as various tidal flats (Sun and Tao, 2010).

Figure 4. Monthly variation of wet and dry atmospheric depositions of DIN

At the seaward boundary, the temporal variation of water elevation was specified, which was calculated based on constants obtained from harmonic analysis. Eight tidal constituents were taken into account, including four main constituents (M2, S2, K1 and O1) and four minor constituents (N2, P2, K2 and Q2). The harmonic constants are given by a global tidal model named TPXO6-2 (Egbert and Erofeeva, 2002). At the riverward boundary, the eight major entrances were treated as flow boundaries, while other discharges are small and regarded as point source inputs.

3.2.2 Water quality model

The following solute transport equation is used in the water quality model

$$2. \quad \frac{\partial(H\phi)}{\partial t} + \frac{\partial(HU\phi)}{\partial x} + \frac{\partial(HV\phi)}{\partial y} = \frac{\partial}{\partial x} \left(HD_x \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left(HD_y \frac{\partial \phi}{\partial y} \right) + q_{\text{River}} \phi_{\text{River}} + \Phi_{\text{Air}} - \alpha H \phi$$

where ϕ is the concentration of environmental indicators (salinity, DIN or COD), H is the total depth, U and V are the velocity components in the x and y directions, respectively, D_x and D_y are dispersion–diffusion coefficients, q_{River} and ϕ_{River} are the river discharge per unit area and the input concentration, respectively, Φ_{Air} is the (wet and dry) atmospheric deposition, and α is the first-order decay coefficient (per day) representing integrated functions of chemical and biological reactions.

It can be seen from Equation 2 that both land-based sources and air-based sources were taken into account, as were the processes of advection, dispersion and decay. The seawater boundary conditions of water quality were specified according to observed properties

- at the boundary line where the water column is deeper than 50 m, concentrations of COD and DIN are set to zero and the salinity level is set to be 35
- at other boundary positions, a zero-gradient of indicators is used.

Equation 2 was discretised and solved with a space step of 1 km and a time step of 30 s. The total simulation period was 2 years, from 1 January 2006 to 31 December 2007, and the spin-up time was 2 months.

4. Verification

4.1 Hydrodynamic model

The hydrodynamic model was verified against the data from this survey and previous studies. Figure 5 shows comparisons of water

Figure 5. Comparison of predicted (curves) and measured (circles) hydrodynamic factors for station E38, 12:00 19 October 2006 to 12:00 20 October 2006

depth and velocity variations between the model prediction and field survey at station E38 from 12:00 19 October 2006 to 12:00 20 October 2006. It can be seen that the model-predicted water depth and velocity distributions agree closely with the data measured in real flows. Figure 6 shows a comparison of predicted and measured tidal harmonic constants; the measured data were obtained from Admiralty tidal tables (HoN, 1990) and a survey carried out by Mao *et al.* (2004) during both dry and wet seasons in 1998. The close agreement between the model-predicted and measured tidal amplitudes indicates the reliability of the model prediction for long-term hydrodynamic processes.

4.2 Water quality model

The water quality model consists of two main sub-models: the advection–diffusion model and the source model. The advection–diffusion model was first verified against the salinity distribution, for which the source term was zero. The two environmental indicators (DIN and COD) were then predicted. The model-predicted distributions of salinity level and DIN and COD concentrations in three typical seasons are shown in Figure 7. The salinity level shows a decreasing trend from the outer estuary to the inner estuary, while a generally increasing trend can be seen for DIN and COD. These trends show that the DIN and COD carried by freshwater from rivers are diluted by seawater.

Comparisons with measurements are shown in Figure 8. The

Figure 6. Comparison of predicted and measured tide amplitudes; measured data from HoN (1990) and Mao *et al.* (2004)

predicted salinity level and DIN and COD concentrations generally agree well with the observed values, which is also positively supported by previous field observations (Dai *et al.*, 2006; Qiu *et al.*, 2010; Yin *et al.*, 2000; Zhang *et al.*, 1999).

The agreement between the predicted COD and field data is not as close as that of DIN. This is thought to be related to the low level of COD concentration in this area. In such conditions, the complex chemical–biological reaction is important, to some degree, for the variation of COD concentration. This is also supported by the statistical results that DIN has a closer relationship with salinity than COD. However, the major environmental factor is DIN rather than COD because the DIN is at such a high level and the COD at a low level. The prediction accuracy is, however, appropriate for COD with the simple decay-type model as the main purpose of this study was to provide information to local environmental managers to help them plan for integrated pollution reduction.

5. Results and discussion

5.1 Sensitivity analysis of decay coefficients

The decay process is an important factor influencing the distribution of environmental indicators, together with the dilution process. Considering the range of measured decay coefficients, a sensitivity analysis was undertaken. Figure 9 shows that the error in COD reached the minimum value when the decay coefficient was between 0.05/day and 0.10/day. This range is approximately at the mean level of the measured decay rates. Wang *et al.* (2004) estimated the mean decay coefficient to be about 0.052/day with in situ incubation experiments in Bohai Bay, which is close to the present result. Chau and Jiang (2003) set up their water quality model with a decay coefficient of 0.25/day, which is thought to be

Figure 7. Horizontal distribution of model-predicted salinity level and dissolved inorganic nitrogen (DIN) (mg/l) and chemical oxygen demand (COD) concentrations (mg/l). The contour is plotted by the monthly average values

rather high. For DIN, the error is maintained at the same level (i.e. it is not sensitive to the decay coefficient). This is because the magnitude of the DIN decay coefficient is rather small (about one fifth of the value of the COD decay coefficient) and so the DIN can be regarded as conservative. In other words, DIN will be flushed out of the inner estuary before it has a chance to decay substantially. It should be noted that the value of the decay coefficient may have seasonal variations, but this cannot be confirmed by the present study owing to a lack of more extensive data. The use of a constant decay coefficient can be considered acceptable given the generally good agreement shown in Figure 9.

5.2 Source reconciliation

The actual distributions of DIN and COD concentrations in the PRE are influenced by all of the input pollution sources discharging

into the estuary. It is important to identify the independent contributions of individual sources to enable reliable assessment of the environmental state and regional environmental management planning for future improvements.

In this study, the contribution of a specified source to the spatial-temporal distribution of a water quality indicator is represented by the single source response (SSR) relationship (i.e. the concentration distribution under the effect of a single pollution source). This method can be used to assess the contribution of every source. Figure 10 shows the predicted SSR distributions of DIN concentrations, which are related to atmospheric deposition and the DIN loads from major entrances in the wet season.

Figure 10(a) indicates that the DIN concentration due to

Figure 8. Comparison of predicted and measured dissolved inorganic nitrogen (DIN) and chemical oxygen demand (COD) concentrations. Error bars are used to denote the variation range due to the tidal fluctuations

Figure 9. Sensitivity analysis of decay coefficients

atmospheric deposition is higher in the southern PRE than in the northern region and outer sea. In the northern region, the DIN level is relatively low because material from atmospheric deposition has been diluted by a large amount of freshwater, while in the outer sea the water depth is greater and thus the concentration is lower. In the southern part of the PRE the maximum concentration is about 0.030 mg/l. Compared with the real DIN concentration in the PRE, which is about 1.2 mg/l, as shown in Figure 7(d), the contribution due to atmospheric deposition is very small (i.e. less than 1/40). Figures 10(b) to 10(e) show that the concentrations due to DIN fluxes passing through the major entrances to the inner PRE, namely Hu-men, Jiao-men, Hongqi-men and Heng-men, are about 0.5, 0.3, 0.1 and 0.2 mg/l respectively. These high contributions are thought to be related to the high DIN loads shown in Figure 3. However, for Medao-men (Figure 10(f)), the SSR concentration in the PRE is lower than 0.1 mg/l, even though its DIN load is relatively large (see Figure 3). This is because this entrance is located near the outer sea. With the lower DIN loads being located near the outer sea, the contributions from Jiti-men, Hutiao-men and Ya-men to the DIN contribution in the PRE are smaller than that of Medao-men.

5.3 Prediction for pollution reduction

One of the main purposes of this study was to provide information to the local environmental protection agency to aid the development of effective water management measures. DIN was chosen as a main indicator owing to its high concentration in the PRE. Figures 11(a) and 11(d) show the present water quality distribution, from which it can be seen that the water quality in the whole of the PRE and some adjacent areas belongs to WQL 5 (i.e. the worst polluted; see Table 2).

The SSR distributions of all pollution loads (Section 5.2) were

Figure 10. Contributions of atmospheric deposition (a) and riverine inputs ((b)–(f)) to dissolved inorganic nitrogen concentration (mg/l) in the Pearl River estuary

used to determine the environmental capacity and optimal special layout of DIN flux with an optimisation method in which the present socio-economic status was taken into account. With this optimal layout, the total DIN load needs to be reduced by 66% in order to enable all areas of the PRE, with various functions specified by government, to reach present water quality standards. The model predictions for this ideal scenario with the allowable load are shown in Figures 11(b) and 11(e), in which most areas, except the local area in the northern PRE, would reach WQL 1 or WQL 2. However, even assuming that all existing planned reduction measures for DIN were implemented in the relevant catchments for the next 18 years (until 2030), the maximum DIN load reduction is only about 35% – about half the required reduction. In this scenario with the planned DIN load, most areas in the PRE would still remain in the worst condition of WQL 5 (see Figures

11(c) and 11(f)) even though the polluted area would decrease significantly in comparison with the present status (Figures 11(a) and (d)). Further DIN reduction measures are thus needed.

6. Conclusion

Based on data from field surveys, a numerical water quality model has been used to investigate the distributions and seasonal variations of DIN and COD concentrations in the PRE and adjacent coastal areas. The model predictions generally agree well with the field data obtained from the present and previous studies.

Sensitivity analysis showed that the decay coefficient of COD is found to be in the region of 0.05–0.10/day. For DIN, the decay coefficient is sufficiently small that it can be regarded as a conservative matter in this hydrodynamic environment – it is

Figure 11. Model-predicted water quality distribution due to dissolved inorganic nitrogen in scenarios with the present load ((a) and (d)), allowable load ((b) and (e)) and planned load ((c) and (f)). WQL, water quality level

	WQL 1	WQL 2	WQL 3	WQL 4	WQL 5
DIN: mg/l	<0.2	>0.2, <0.3	>0.3, <0.4	>0.4, <0.5	>0.5

Table 2. Water quality level (WQL) according to DIN concentration

likely to be flushed out by the discharge before it decays substantially.

The contribution of each major source was predicted using the water quality model. It was shown that the high DIN concentration in the PRE (about 1.2 mg/l) is mainly caused by DIN loads passing through four major entrances to the inner PRE: the concentrations attributed to Hu-men, Jiao-men, Hongqi-men and Heng-men are about 0.5, 0.3, 0.1 and 0.2 mg/l respectively. The other four major entrances located in the outer sea area contribute less to the high DIN concentration in the PRE, even though the DIN load from Medao-men is large. The contribution from atmospheric deposition is also at a very low level, with the maximum value being about 0.030 mg/l.

According to the Chinese seawater quality standard, the present status of the whole of the PRE and some adjacent areas is WQL 5 – the worst polluted water. Model predictions show that a

66% DIN load reduction is required in order to enable all functional areas in the PRE to reach the required water quality standards. Taking all of the planned DIN load reduction measures into account in the catchment until 2030 would result in a 35% DIN load reduction ratio, and water quality in most areas in the PRE would still be WQL 5. Further plans for reduction are therefore required.

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