# Modeling nitrogen and phosphorus cycles and dissolved oxygen in the Pearl River (Zhujiang) Estuary.

## II. Model results*

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**Abstract**—In the present study, the ecosystem based water quality model was applied to the Pearl River estuary. The model results successfully represent the distribution trend of nutrients and dissolved oxygen both in the horizontal and vertical planes during the flood season, and it shows that the model has considered the key part of the dynamical, chemical and biological processes existing in the Pearl River estuary. The further studies illustrate that nitrogen is in plenty while phosphorus and light limit the phytoplankton biomass in the Pearl River estuary during the flood season.

**Key words** Pearl River estuary, nutrient, chlorophyll, dissolved oxygen

### 1. Introduction

The average annual discharge of the Pearl River is $3.32\times10^{11}m^3$, which ranks the Pearl River just second to the Changjiang River in China. The discharge occurring during the flood season between April and September accounts for 80% of the yearly total. The Pearl River has a yearly sediment load of about $1\times10^8$ tons, which also concentrates in the flood season (Zhao, 1990; Chen et al., 1998), The Pearl River delta, which has 12 cities of different sizes and more than 40 towns with a population higher in excess of 10,000 people, is the most economically developed area in China. From numerous towns and harbors, industrial effluent, ship-borne oily discharge, domestic sewage and even sludge and rubbish are discharged directly or indirectly into river and sea. For example, the total amount of sewage entering the Pearl River delta in 1991 and 1995 reach $1.74\times10^9$ and $2.26\times10^9$ tons, respectively (Chen, 1997). In recent years, organic pollution and eutrophication in the Pearl River estuary, especially in the Lingdingyan region, has aroused more and more attention, with special attention being paid to the pollution by nitrogen and phosphorous. As a result of eutrophication, the frequency and extent of red tide have increased in the Pearl River estuary (Tang, et al., 1985, Liang, et al., 1999). Algal blooms and red tides can destroy the biological diversity and further harm health of human. A great amount of dead planktons following events may produce more organic pollution associated with endemic bottom hypoxia in estuaries (Zhang et al., 1988). In addition, a great deal of suspended cohesive sediments and organic matters reduce light penetration in water and thus affect photosynthesis and then reduce plankton biomasses (Di Toro,

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A ecosystem based water quality model has been developed to integrate a modeling system together with the hydrodynamics and sediment models in Part I of this paper (Guan, Wong and Xu, 200?). The modeling system was utilized to numerically study the Pearl River estuary. In this part, the model results for the flood season will be introduced with an emphasis on water quality elements including nutrients, chlorophyll, dissolved oxygen and so on.

## 2. Hydrodynamics and sediment

Boundary conditions for the hydrodynamics model include freshwater inputs at the upstream branches, tide and coastal currents at the offshore boundary, and wind stresses and heat fluxes at the sea surface. Discharges at upstream branches, the uniform wind stress and heat flux for the whole domain were estimated from the monthly mean values of historical data for many years, and these boundary conditions were set to only vary from day to day. The lateral boundary conditions in the open sea were given according to the nearby field data. In the simulation for the flood season, the specified start time of the hydrodynamics model run is 0 o'clock, May 1, 1999. After the hydrodynamics model have run alone for 60 days and the influences of initial conditions have been greatly eliminated, the sediment and water quality model start to run together with the hydrodynamics model. The hydrodynamics model was calibrated first and then verified against the field data obtained by the vessel, Haijian 74, during the summer of 1999 (Fig. 1). From comparisons of measured and computed data for surface elevation, current, temperature and salinity, it shows that the relative errors are all smaller than 20%, and it is concluded that the hydrodynamics model can be allowed to perform further numerical studies. The model results for the flood season exhibit that, a large amount of freshwater quickly discharge via the upper layers and the front between saline and fresh water is far from the river mouths. Driven by the southwest wind and northeastward coastal currents, the plume moves toward the east at surface. The stratification is very strong inside the estuary, and the halocline steadily occurs in the water column. The stratification restrains the turbulence and weakens the vertical mixing, and thus affects the diffusion and transport of the sediment and biochemical variables.

In the setup of the sediment model, sediment concentrations at upstream branches and lateral boundaries were set according to historical and remote sensing data. The settling velocity, critical shear stresses for deposition and erosion and the erosion constant were calibrated by the help of field data,. The results of the sediment model also fit the distribution trend of suspended sediment during the flood season. The validated sediment model will supply the water quality model with grids of suspended sediment concentration.

Fig. 1 Sampling stations in the Pearl River estuary during the summer of 1999

## 3 . Water quality elements

In the water quality model, the boundary conditions for biochemical elements at all branches were specified by referring to the observed data nearby. For example, these boundary conditions of the five northern branches at Humen, Jiaomen, Hongqili, Hengmen and Modamen, respectively, are given the same value for every element as follows: dissolved inorganic nitrogen is set at a constant of 100 μmol N /L, dissolved inorganic phosphorus 0.75μmol P /L, detritic organic nitrogen 1.0 μmol N /L, detritic organic phosphorus 0.08 μmol P /L, phytoplanktonic nitrogen 1.2 μmol N /L, zooplanktonic nitrogen 0.4 μmol N /L, dissolved oxygen 4.2 mg/L. There are the same values for these elements at the other branches except that dissolved inorganic nitrogen is set at a constant of 60 μmol N /L, dissolved inorganic phosphorus 0.3μmol P /L, detritic organic nitrogen 0.6 μmol N /L, detritic organic phosphorus 0.03 μmol P /L. The boundary conditions at offshore are specified according to the nearby field data too. The model utilizes the five-day normals of cloud amount base on the field data observed at the Hong Kong Observatory between 1961 and 1990 to calculate the available light intensity.

The length of simulation of the water quality model together with the hydrodynamics and sediment models is one month or so, which covers the period of the field investigations implemented by the vessel, Haijian 74, during the summer of 1999 (Fig. 1). The water quality model runs under specified initial conditions. The initial conditions are replaced by the results at Day 30 and the model runs again. Repeating these processes for several times may obviously eliminate the influences of initial conditions. Snapshots of the distributions of nutrients, phytoplankton and dissolved oxygen at 6 o’clock, July 26,1999, are given sequentially in Figures 2, 3, 4 and 6. The field data, which are also plotted in these figures, are observed by only one vessel named by Haijian 74, i.e., they do not occur simultaneously and thus they just exhibits the approximate trend of distribution of biochemical variables.

In the model, the total distribution trend of the dissolved inorganic nitrogen and phosphorus is that the concentrations decrease from mouths to offshore. But the interactions among the river mouths and non-uniformities of the biomasses of plankton make the distributions of nutrients in the Pearl River estuary more complicated. In the field data, dissolved inorganic nitrogen is replaced with the summation of $NO_3$-N, $NO_2$-N and $NH_4$-N, and dissolved inorganic phosphorus is replaced with $PO_4$-P. The observed data show the same trends and become more complex because of the existence of pollutant sources which are not considered in the model.

Chlorophyll-*a* is a portion of phytoplankton, and it is often used to indicate the biomass of phytoplankton because its measurement is relatively easy. In this study, 1 μmol N /L phytoplanktonic nitrogen denotes the same quantity of phytoplankton as 1 μg /L chlorophyll-a. Near the river mouths inside the estuary, the phytoplanktonic biomass is totally lower owing to the influences of runoff and suspended sediment. However, there is a plenty of phytoplankton in the region where currents are weak because of the abundant nutrients and increased available light due to settling of suspended sediment. Owing to enough nutrients and appropriate light, there exists a zone with high biomass of phytoplankton along the coastline form southwest to northeast. There are not available images on chlorophyll obtained by remote sensing during simulation, but there is such a rather good image, which also shows a high biomass zone of chlorophyll, in the next month but during the same season (Fig. 5). Disturbances due to a great deal of suspended sediment existing in the Pear River estuary significantly affect the estimation of chlorophyll, so that only a few qualitative analyses can be performed on the chlorophyll data observed by satellites. Phytoplankton distributes in clusters in the actual estuary but continuously in the model. As a result, the model can not obtain such higher concentrations of 14.37 and 19.18 μg/L observed by the Haijian 74 to the south of the Hong Kong Island.

The content of dissolved oxygen in water is affected by many factors such as the state of sea surface, hydrodynamic and biochemical processes, and thus its distribution is very complicated. At surface, the regions with high content of dissolved oxygen are corresponding to those with high concentration of phytoplankton, and dissolved oxygen exceeds the saturation point somewhere. The outer water containing less dissolved oxygen enters the estuary along the deep channels. In addition, the dissolved oxygen content becomes lower owing to the oxygen consumption by benthic demand.

Fig. 2 Horizontal distributions of model dissolved inorganic nitrogen concentrations (μmol N /L) at 6 o'clock, July 26, 1999 (left panel), and measured values (right panel) at surface

Fig. 3 Horizontal distributions of model dissolved inorganic phosphorus concentrations (μmol P /L) at 6 o'clock, July 26, 1999 (left panel), and measured values (right panel) at surface

Fig 4. Horizontal distributions of model phytoplanktonic nitrogen concentrations (μmol N /L) at 6 o'clock, July 26, 1999 (left panel), and measured values of Chlorophyll-*a* concentrations (μg /L) (right panel) at surface. Phytoplanktonic nitrogen in μmol N /L may be converted to μg Chlorophyll-*a* /L assuming a constant ratio of 1 in this study.

Fig. 5 Horizontal distributions of surface chlorophyll-a concentrations (μg /L) retrieved by satellite on Aug. 17, 1999

Fig. 6 Horizontal distributions of model dissolved oxygen concentrations (mg /L) at 6 o'clock, July 26, 1999 (left panel), and measured values (right panel) at surface

Besides the above reasonability verification on distribution trends of biochemical elements, error analyses are also carried out on the profile data acquired by Haijian 74. The total number of observation samples is about 94 at all layers. Comparing these data with the simulated data at the same layer of the same location and at the same time, statistics include root-mean-square (RMS) of error are given in table 5, where the relative error is considered as a quotient of the RMS of error by the mean. The relative errors of dissolved inorganic nitrogen, dissolved inorganic phosphorus and dissolved oxygen all are less than 50%, but the relative of phytoplankton reaches 121.4%. For the higher error of phytoplankton, there are many causes such as the simplification of biochemical processes considered in the model, discontinuity of distribution of phytoplankton and larger observation error.

Comparison between the observed and modeled data at stations 1, 10, 20 and 31 from inside to outside along the longitudinal transect are drawn in Fig. 7. From these comparisons, the variation trends and values of biochemical elements in the model are close to those in observation, that is to say, the model successfully reproduces the observed results at least along the longitudinal transect of the Pearl River estuary.

Table 5. Comparisons of observation and calculation (where dissolved inorganic nitrogen concentrations is in μmol N /L, dissolved inorganic phosphorus concentrations in μmol P /L, and Dissolved oxygen in mg /L)

| | Mean | RMS of error | Relative error |
|---|---|---|---|
| Dissolved inorganic phosphorus | 53.21 | 16.94 | 31.8% |
| Dissolved inorganic phosphorus | 0.52 | 0.26 | 49.7% |
| Phytoplankton | 2.27 | 2.75 | 121.4% |
| Dissolved oxygen | 5.44 | 1.59 | 29.2% |

Fig. 7 Comparisons of the observed (blue solid) and modeled data (red dashed) at stations (a) 1, (b) 10, (c) 20 and (d) 31 from inside to outside along the longitudinal transect. Where dissolved inorganic nitrogen concentrations is in μmol N /L, dissolved inorganic phosphorus concentrations in μmol P /L, chlorophyll-*a* concentrations in μg /L, and Dissolved oxygen concentrations in mg /L

## 4 . Discussion and conclusions

An integrated model system including the hydrodynamics, sediment and water quality models has been developed to simulate nutrient cycles and dissolved oxygen in the Pearl River estuary. The model domain almost covers the whole region of the Pearl River estuary, and the model owns higher horizontal and vertical resolution. The model system has successfully reproduced the distribution trends of nutrients and dissolved oxygen both in the horizontal and vertical planes during the flood season, and it shows that the model has considered the key part of the dynamical, chemical and biological processes existing in the Pearl River estuary. In the flood season, there exists a zone with high biomass of phytoplankton along the coastline form southwest to northeast owing to enough nutrients and appropriate light. At surface, the regions with high content of dissolved oxygen are corresponding to those with high concentration of phytoplankton.

In the meantime, some numerical experiments were utilized to survey responses of the model on various changes and some conclusions are achieved. For instance, if the impact of suspended sediment on available light is omitted, the area of higher phytoplankton concentration will move towards the Lingdingyang region of the Pearl River estuary (Fig. 8a), and therefore this experiment demonstrates that the suspended sediment greatly restrains phytoplankton growth. If only the loads of dissolved inorganic nitrogen at all river mouths are halved, the differences between this experiment and the standard mentioned above run are too tiny to be distinguished (Fig. 8b). However, if only the loads of dissolved inorganic phosphorus at all river mouths are halved, the results will distinguishably vary from the standard run (Fig. 8c). In conclusion, these experiments illuminate that nitrogen is abundant while phosphorus and light limit phytoplankton growth in the Pearl River estuary in the flood season.

Fig. 8 Horizontal distributions of model phytoplanktonic nitrogen concentrations (μmol N /L) at surface at 6 o'clock, July 26, 1999 when (a) the impact of suspended sediment on available light is omitted, (b) only the loads of dissolved inorganic nitrogen at all river mouths are halved, and (c) only the loads of dissolved inorganic phosphorus at all river mouths are halved.

Neglecting horizontal advection-diffusion effects, The 3-D water quality model can become a series of vertical 1-D models. The 3-D hydrodynamics model only supplies these 1-D water quality models with vertical eddy diffusion coefficients and bottom shear stresses which are used to calculate the fluxes of sedimentation and resuspension at the sediment-water interface, while the 3-D sediment model provides suspended sediment concentrations to them for calculation of light extinction coefficient. If the 3-D hydrodynamics and sediment models previously store time-series of vertical eddy diffusion coefficients and bottom shear stresses and suspended sediment concentrations for the selected grid points, the 1-D water quality models at these grid points can run alone. The 1-D model can be used to not only calibrate biochemical parameters, but also perform sensitivity experiments and other numerical studies. For instance, selecting the 1-D water quality model at Station 27, the initial values of dissolved inorganic phosphorus are set 1.0 μmol P /L for the whole vertical line, those of phytoplanktonic nitrogen are set 1.0 μmol N /L, and the initial values of other variables and biochemical parameters are same as those used in the 3-D water quality model. The results of that 1-D model show that, the dissolved inorganic phosphorus at surface is exhausted at the 12th day, but the concentration of phytoplankton at sub-surface reaches a peak of 12.0 μmol N /L. Thenceforth, the maximum value of phytoplankton reduces and lowers its position in the vertical.

From the above studies, it is shown that the 3-D water quality model described in this paper owns higher resolution both in space and in time, and it can reflect biochemical processes and their relationship with hydrodynamics more accurately. Therefore, the model can be used everywhere, especially at these regions with serious stratifications. The model can also simulate long-term phenomena, but it needs corresponding variable boundary conditions. In fact, the model can be further improved. For example, the model may consider some benthic processes and divides the water quality bed into same layers as the sediment bed, moreover, the model may take into account the absorption and desorption of fine sediment on particulate matters. In conclusion, this paper gave an example to explain how to develop a water quality model for the applications of environment problems. For the specified problem, the processes considered in the model can certainly be modified, adjusted and added.

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