One of the primary reasons for this shortcoming is most likely attributable to the thickness of the uppermost layer that must envelop at least half the tidal range in the present configuration. Nonetheless, the overall features of the hydrodynamics of the Pearl River Estuary are reproduced sufficiently well in the model, including the strong stratification in the neap tide and the enhanced mixing in the spring tide.

2.5 Biochemical Cycle Model

2.5.1 Basic Concepts of the Biochemical Cycle Model

The water quality simulation model is a biochemical cycle model capable of emulating the elementary low-level ecosystem of estuarine waters. The conceptual model shown in Figure 2.3.1 has been discussed earlier.

The main driving force of elementary ecosystem dynamics (biochemical cycle) is the primary production of organic matter by phytoplankton. In this process, phytoplankton produce organic matter and O_2, and utilize CO_2, H_2O, inorganic-nutrients (primarily I-N and I-P), and solar radiation. The organic matter produced is positioned at the bottom of the food chain in the marine ecosystem, and supports all forms of aquatic biota. This is why this process is referred to as primary production. The activity or efficiency of primary production largely depends on environmental water temperature and light intensity when the supply of nutrients is adequate. Other biochemical processes take place following primary production.

The decomposition of organic matter occurs as a result of bacterial activity. The model constituents and governing equations under consideration are listed below.

2.5.2 Model Constituents

Model Constituents, Abbreviated Symbols, and Units

< constituent>	< symbol >	<unit>
Phytoplankton	*P*	*mgC/L*
Detrital nitrogen	*PN*	*mgN/L*
Detrital phosphorus	*PP*	*mgP/L*
Inorganic nitrogen	*IN*	*mgN/L*
Inorganic phosphorus	*IP*	*mgP/L*
Dissolved oxygen	*DO*	*mg/L*
Chemical oxygen demand	*COD*	*mg/L*

Total-nitrogen (*T-N*) and total-phosphorus (*T-P*) are expressed by

T-N = *O-N* (organic nitrogen) + *I-N*,
T-P = *O-P* (organic phosphorus) + *I-P*,
O-N = phytoplanktonic nitrogen + detrital nitrogen, and
O-P = phytoplanktonic phosphorus + detrital phosphorus.

COD may be represented by summing of the contributions as

COD = phytoplanktonic COD + detrital COD + $COD1$,

in which $COD1$ corresponds to COD load of land origin, and is treated as a conservative substance within the advection-diffusion equation.

Practical representations of $T\text{-}N$, $T\text{-}P$ and COD are

$T\text{-}N = P/\underline{rCNp} + PN + IN$,
$T\text{-}P = P/\underline{rCPp} + PP + IP$, and
$COD = P \cdot \underline{rCODCp} + PP \cdot \underline{rCODCpp} + COD1$

in which underlined variables are conversion constants.

2.5.3 Governing Equations and Biochemical Reaction Terms

The governing equation for the fate of each water quality constituent is the usual advection-diffusion equation plus the biochemical reaction terms. Details of the biochemical reaction terms, reaction processes, and methods of quantification are described in the supporting report.

2.5.4 Biochemical Cycle Modeling

A conceptual basis of the biochemical cycle model was established through detailed discussion with the counterpart personnel during the first and second study periods, as summarized in the Progress I, II, and Interim Reports. Taking into consideration the field survey results, both during the rainy and the dry seasons, a skeletal basis of a three-dimensional water quality model for the Pearl River Estuary was developed. During the course of development and calibration, the following unique features found during the field survey were taken into consideration:

- exceptionally high degrees of tidal flushing and mixing;
- very large quantity of freshwater inflow,
- very low salinity in the northern half of the bay,
- strong stratification in the southern half of the bay during the neap tide,
- moderate level of organic contents in the bay water;
- no significant *DO* deficit;
- abundance in nitrogen;
- low to moderate levels of inorganic phosphorous (except in Shenzhen Bay);
- high water temperature;
- exceptionally high turbidity;
- low chlorophyll-a levels during the spring tide, moderate levels during the neap tide;
- dominance of freshwater phytoplankton in the northern half of the bay;
- low organic content and a positive redox potential in the bottom sediments.

In view of the above findings, the Pearl River Estuary in the rainy season can be characterized by a strong tidal influence as well as a large quantity of river discharge. The biological productivity in the bay is low compared to typical estuarine bays. Its productivity appears to be primarily limited by the short retention time and light-limited by the high level of *SS*, and is probably salinity-limited.

During the dry (winter) season, when the *SS* level decreases lower and salinity increases, chlorophyll-a levels are higher than in the rainy season. Nitrogen is abundant and the water temperatures are within the optimal ranges for the primary production throughout a year. The PO_4-P levels are comparatively low, but much higher than the growth-limiting level for phytoplankton.

The marked distribution patterns of phytoplankton species found by the field survey suggest that the very low salinity in the northern bay area is inhospitable to plankton species of marine origin and the higher salinity in the southern bay area is equally uninviting to the freshwater species.

In summary, the water quality of the estuary bay, except for Shenzhen Bay, appears to be governed primarily by transport phenomena, overwhelming the biochemical reactions. Although the basic structure and concept of the biochemical cycle model developed in the first and the second study periods may be retained, emphasis needs to be placed on the transport aspects.

2.5.5 Suspended Sediment (*SS*) Simulation

As discussed earlier, one of remarkable characters of the Pearl River Estuary is the exceptionally high concentration of suspended sediment (*SS*). Among the preliminary governing factors of photosynthesis, temperature, nutrients and solar radiation, both water temperature and nutrients are within the optimum levels for photosynthesis throughout the year. Thus, as a key limiting factor of primary production, *SS* simulation has a particular significance for the Pearl River Estuary.

Figures 2.5.1 to 2.5.2 are the results of *SS* simulation and tidal mean distributions in the spring tide and neap tides, respectively. In comparison to the rainy season field survey results for the spring tide, the simulation results are in general agreement, in the sense that the zones of high *SS* concentrations greater than 50 mg/L are restricted to the area north of Neilingding Island throughout the depths. The concentrations near the mouths of Humen and Hongquimen are also in agreement.

Discrepancies are also evident. In the field survey results, a zone of high concentrations, exceeding 200 mg/L, was seen in both the middle and the bottom layers in the area south of the Donguang coast. The simulation result, however, failed to reproduce this event. Considering that no significant external sources of *SS* exist in the area, and concentrations are higher toward the bottom layer, it is conceivable that the occurrence of high *SS* level in the area is attributable to the re-suspension of bottom sediments by the strong tidal currents. The present *SS* model does not consider a site-specific re-suspension process.

Furthermore, the field survey results showed that *SS* levels were significantly lower during the neap-tide period than those during the spring-tide period, while the simulation results for both the periods are similar. In the field survey, the *SS* levels near the river mouths are also lower during the neap-tide period, suggesting that the *SS* load becomes significantly lower during neap tide. The simulation results are based on the same *SS* loads for both tidal periods. The weaker tidal currents during the neap tide would also be a factor contributing to the reduced *SS* levels, by decreasing the bottom *SS* re-suspension.

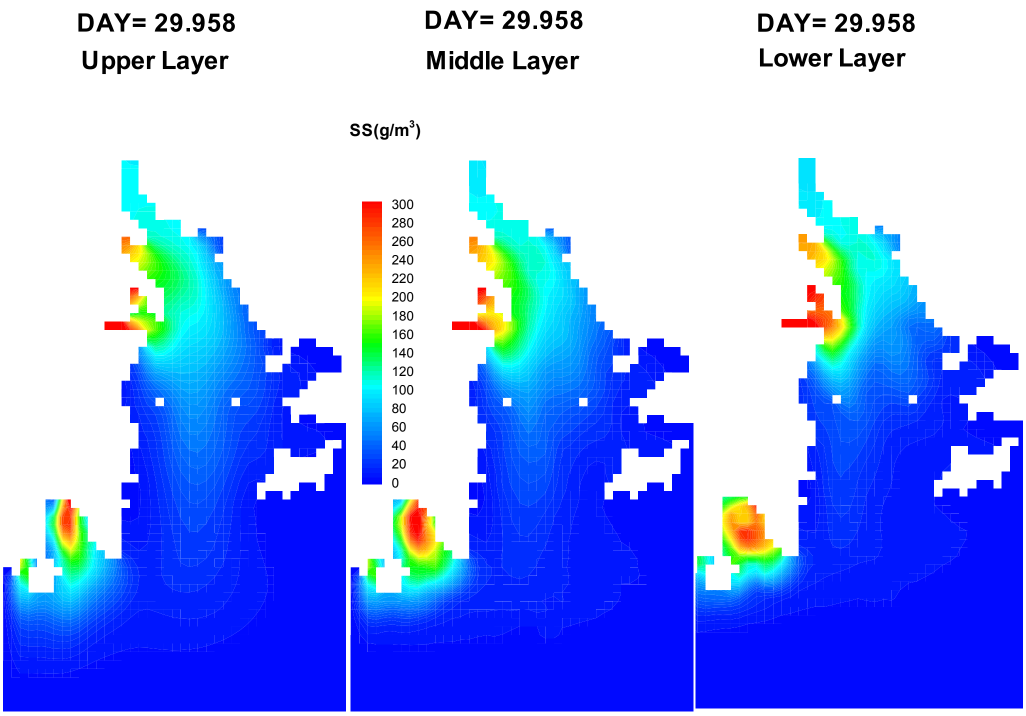


Figure 2.5.1 Results of the SS Simulation in Spring Tide

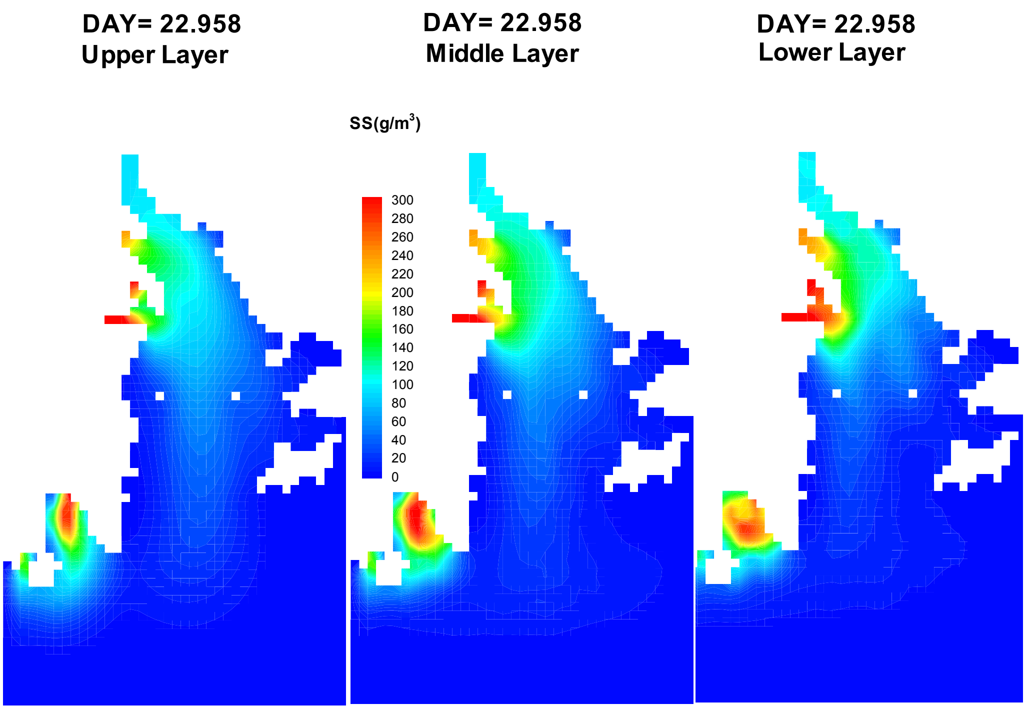


Figure 2.5.2 Results of the SS Simulation in Neap Tide

2.5.6 Biochemical Cycle Model Simulation

The optimum rate of primary production for the temperature range based on a laboratory experiment undertaken in the present study is 0.2 generations/day. This rate is considerably smaller than that found in the literature, which is usually greater than 1.0 generation/day. This is most likely attributed to the species of phytoplankton used in the experiment, *Skeletonema costatum*, a typical marine species. The experiment used the low-salinity field water taken from the estuary for this algal specie. Since the concept of 'primary production' in the present biochemical cycle model is targeted for the aggregate of multiple algal species, direct use of the experimental growth rate would be misleading. Thus, an optimum rate of 2.0 generations/day was applied in the present simulation.

Figures 2.5.3 to 2.5.8 are the results of the biochemical cycle simulation. Figures 2.5.3 to 2.5.5 are for the spring tide and 2.5.6 to 2.5.8 for the neap tide period.

In the upper layer, the chlorophyll-a concentration varies from less than 0.01 mg/L in the upper bay to about 0.02 mg/L in the offshore areas of Zhongshan and Zhuhai, and to more than 0.03 mg/L in Shenzhen Bay. In the lower layer, it is as low as 0.005 mg/L along the eastern coast of the bay, except in Shenzhen Bay where it is nearly as high as in the upper layer. Although the simulation does not precisely reproduce the chlorophyll-a concentration distribution observed during the field survey, the model is capable of highlighting some significant factors of eutrophication potential in Shenzhen Bay where water is stagnant and the *SS* level is low compared to elsewhere in the Pearl River Estuary.

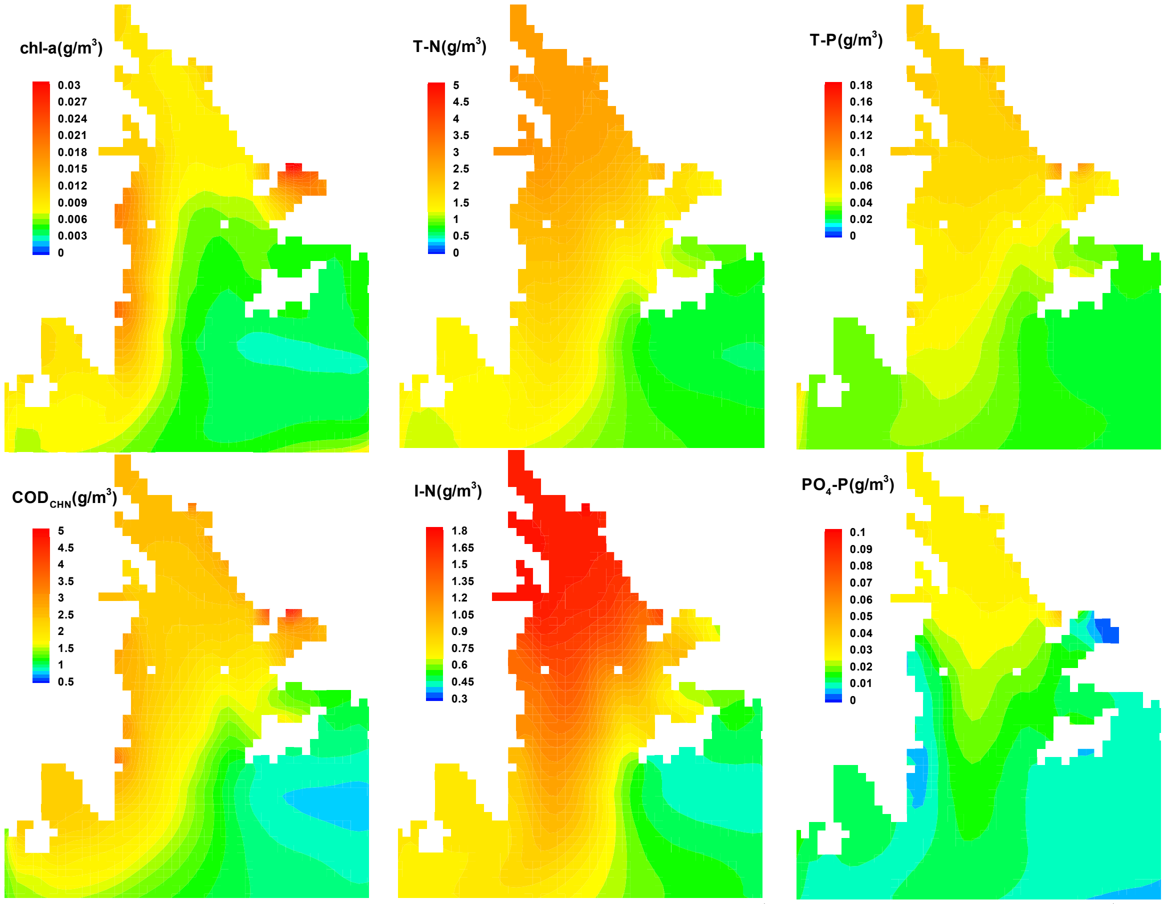
The simulation results for *COD* show 1.8 - 3 mg/L in the upper to the central zone of the estuary bay, and 1.2 - 2.5 mg/L near the bay mouth. In the Shenzhen Bay, it is considerably higher at 2 - 5 mg/L in the upper layer and 2 - 3.5 mg/L in the lower layer. These values are generally similar to the field survey results, but the distribution pattern is somewhat different.

The *T-N* simulation results also reproduce the field survey results well. In general, in both the simulation and the field results, the *T-N* concentration decreases southward from 3 mg/L in the upper bay to 1 - 2 mg/L near Lantau Island, without significant variations among the layers or between the neap and spring tidal cycles.

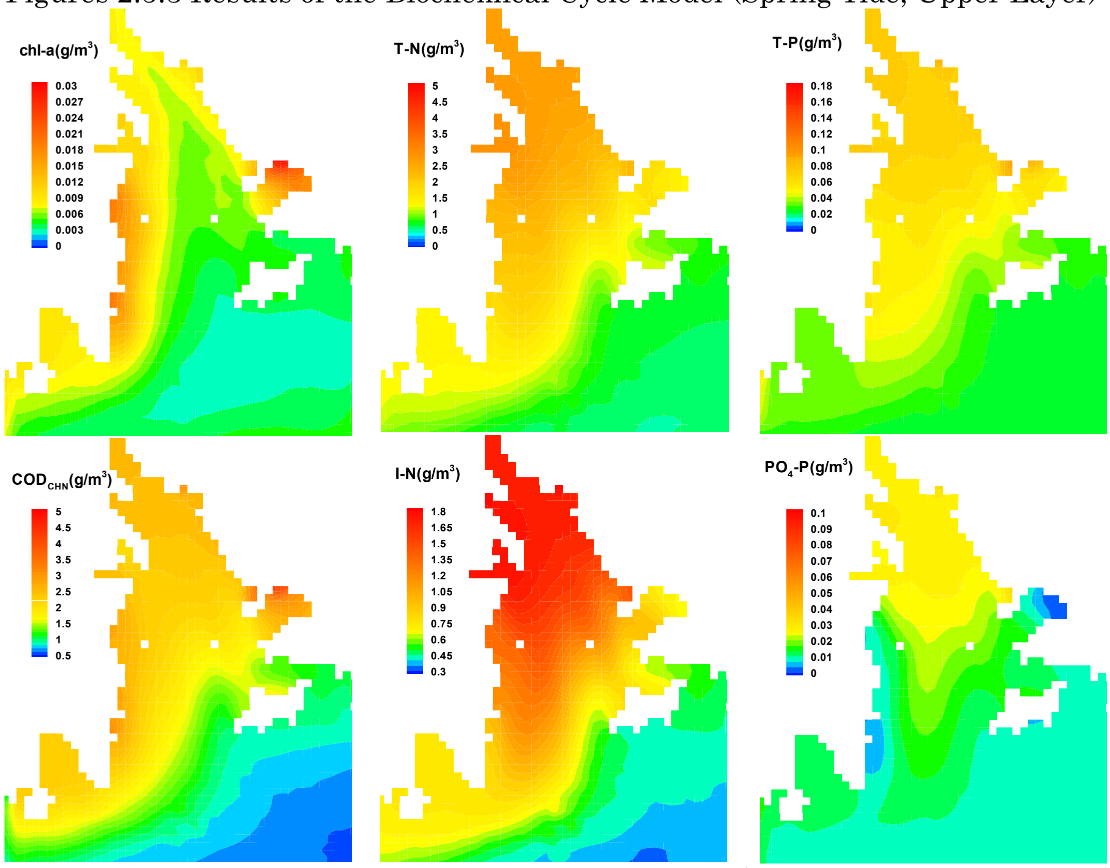
The *I-N* concentration also decreases southward from 2 mg/L to 0.7 - 1.3 mg/L in both the simulation and the field survey (NO_3-N) results. The field survey results show a more distinctive vertical distribution pattern, suggesting the presence of counter flow: the upper layer river water moving southward while the outer marine water intrudes northward in the lower layer.

The *T-P* concentration in the simulation also decreases southward from 0.8 mg/L to 0.03 - 0.06 mg/L, within the range found in the field survey results. The distribution pattern is more complex in the field survey results, particularly during the neap-tide period.

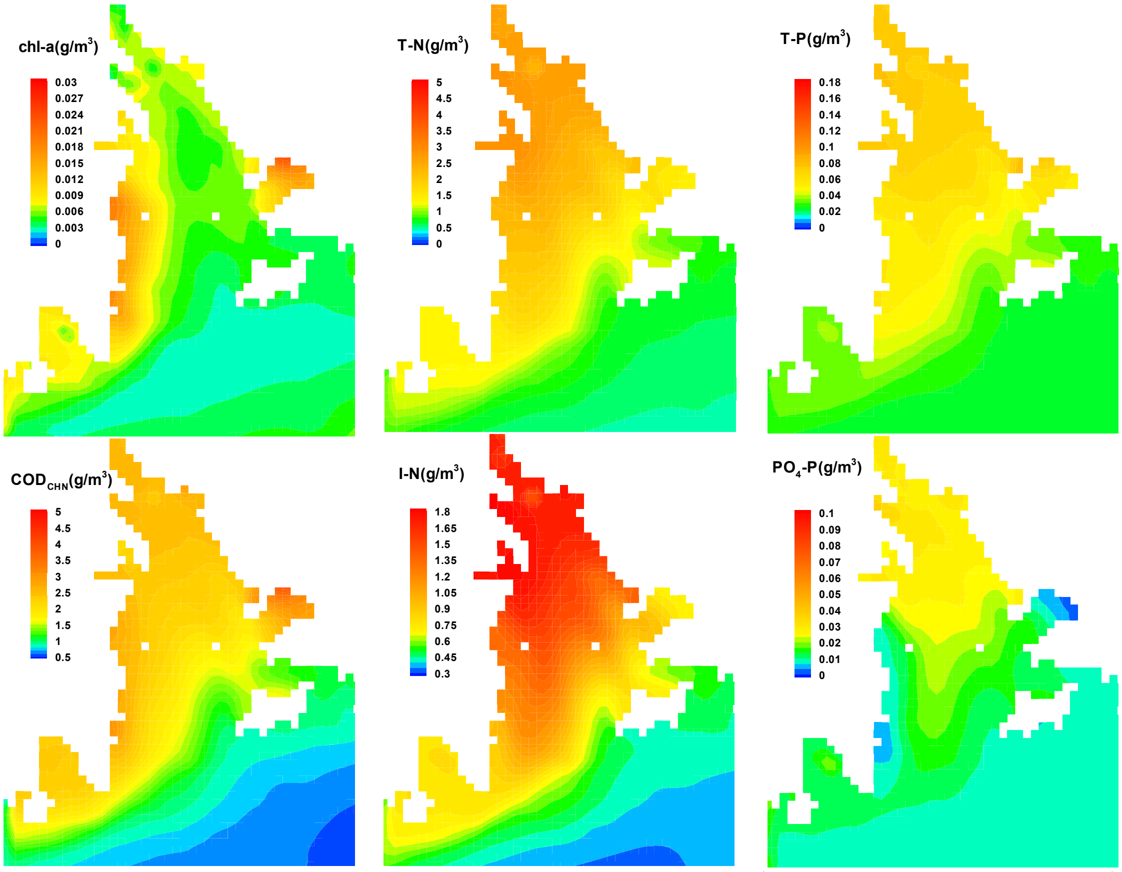
As for PO_4-P, the simulation results exhibit the tendency that the river water spreads over the estuary, gradually diluted by the dispersion process in a manner similar to the cases for *T-P* and *T-N*. Further south of the bay mouth, toward the South China Sea, however, PO_4-P concentration decreases rapidly by the uptake process of primary production. The field survey results, for both the spring- and neap-tide periods, indicate that in zones with high chlorophyll-a level the PO_4-P level is low and vice versa, i.e., there is an inverse relationship, possibly suggesting that PO_4-P is a limiting factor for primary production. While the simulation results do not precisely reproduce such distribution patterns, general concentration levels are in reasonable agreement.



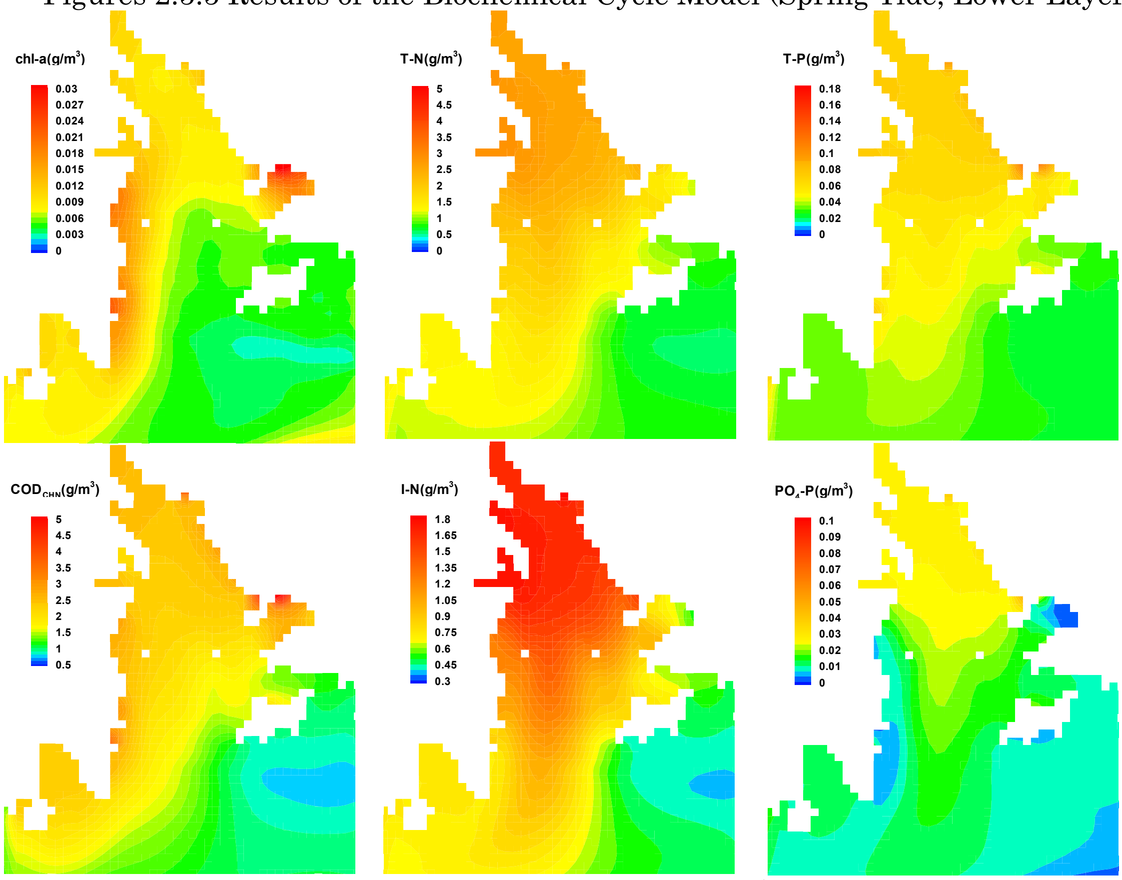
Figures 2.5.3 Results of the Biochemical Cycle Model (Spring Tide, Upper Layer)



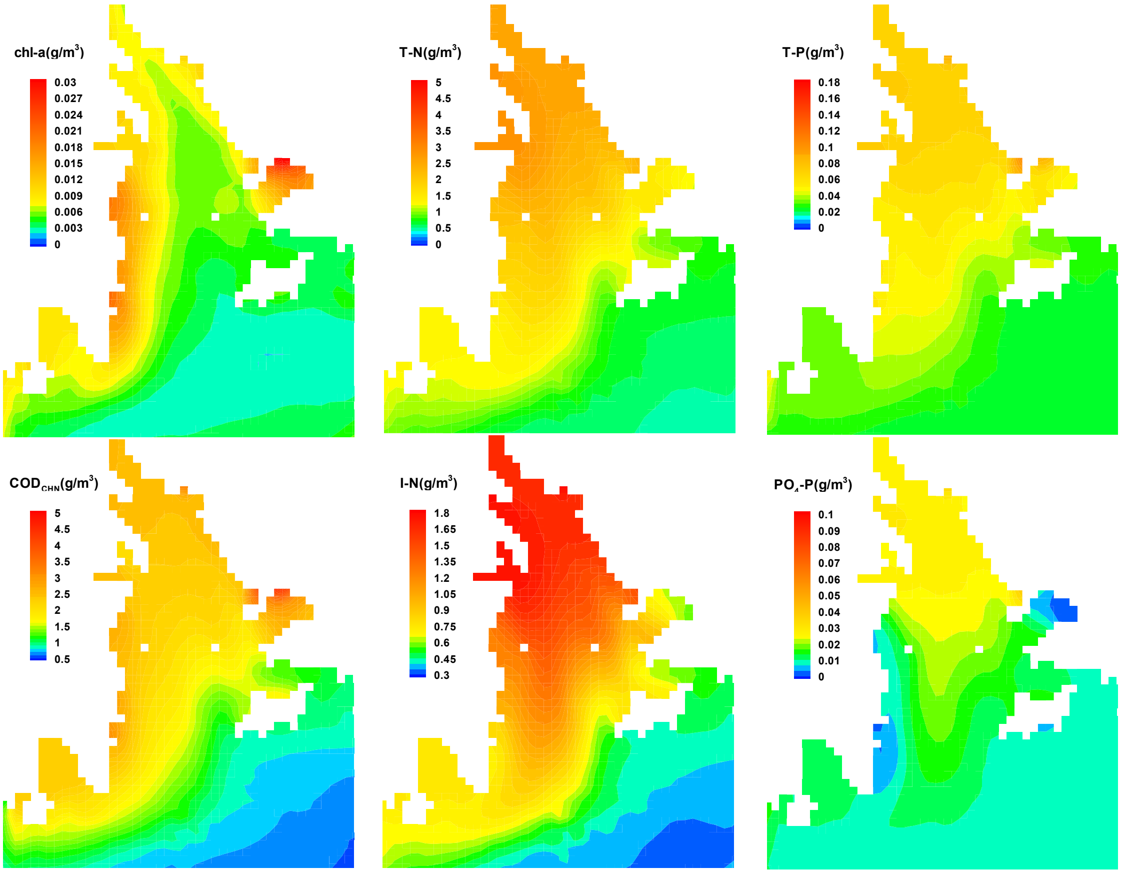
Figures 2.5.4 Results of the Biochemical Cycle Model (Spring Tide, Middle Layer)



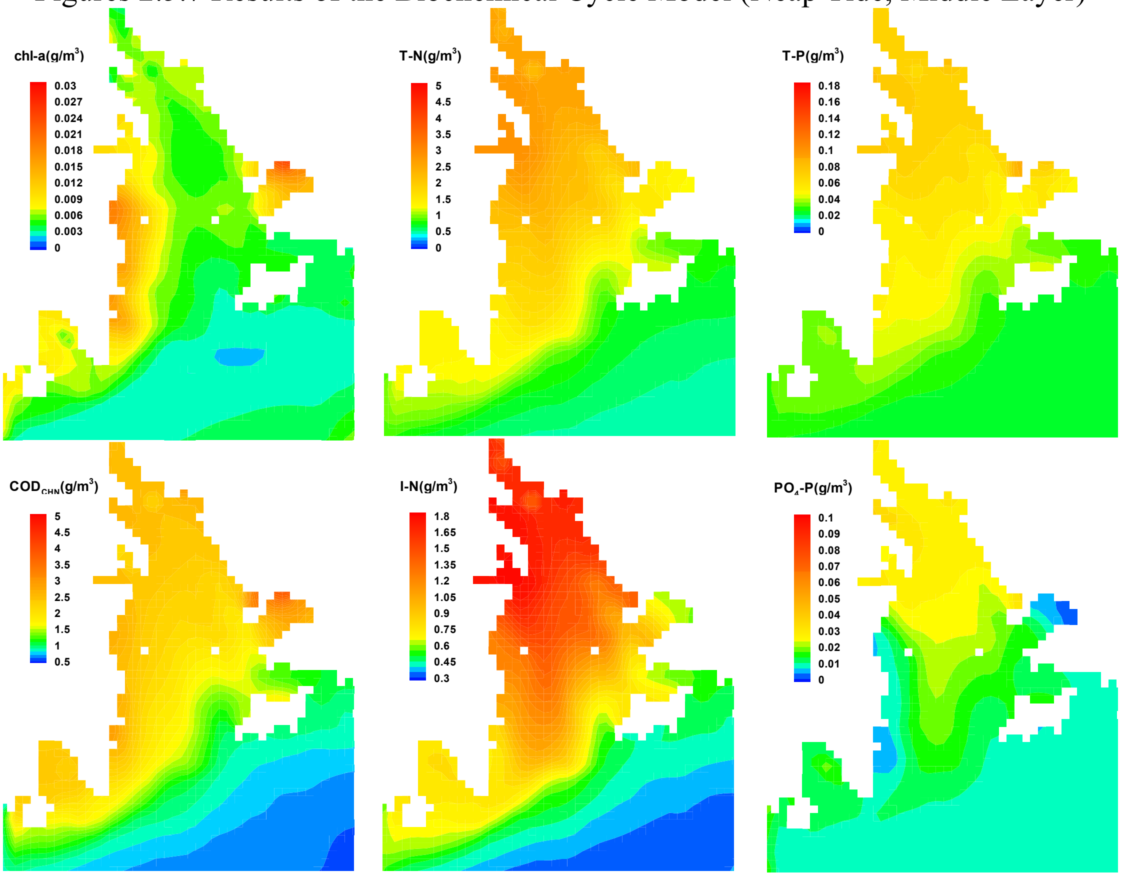
Figures 2.5.5 Results of the Biochemical Cycle Model (Spring Tide, Lower Layer)



Figures 2.5.6 Results of the Biochemical Cycle Model (Neap Tide, Upper Layer)



Figures 2.5.7 Results of the Biochemical Cycle Model (Neap Tide, Middle Layer)



Figures 2.5.8 Results of the Biochemical Cycle Model (Neap Tide, Lower Layer)

2.6 Summary and Subjects of Future Study

2.6.1 Hydrodynamics Model

- A 15-vertical level three-dimensional hydrodynamics simulation model has been developed to investigate the complex hydrodynamics of the Pearl River Estuary, frequently dominated by density stratification. By extending the computational domain further into the South China Sea and applying the 'level-2.0 turbulence closure sub-model', the model is capable of reproducing the hydrodynamics of the estuary satisfactorily, including the transition of density stratification throughout the low- to high-tide cycle.

2.6.2 Biochemical Cycle Model

- A standard form of low-level ecosystem model applicable to coastal areas describing a typical biochemical cycle process has been proposed.

- By analyzing the field survey results as well as the published literature, the following factors were found to govern the biochemical material cycle process in the Pearl River estuary, with the exception of Shenzhen Bay:

  1) An exceptionally large quantity of freshwater through-flow combined with shallowness of the basin and strong tidal flushing result in a very short retention time for the estuarine water.
  2) The northern half of the estuary is dominated by near-freshwater, forming a very strong salinity gradient toward the bay mouth.
  3) Despite the abundance of nutrients and optimum water temperature, primary production in the estuary is light-limited by unusually high levels of turbidity.
  4) The organic content of the bottom sediments is low, and the redox potential (*EH*) is high, indicating that no significant oxygen depletion exists in the estuary.

- As a governing light-limiting factor for primary production, the distribution of *SS* concentration was simulated. The results are less than satisfactory in reproducing the variability between the spring- to neap-tide cycles, as well as the occurrence of localized high-concentration areas. Inclusion of time-dependence in *SS* load from the river outlets, and refinements in the SS re-suspension model, are among subjects for further study.

- In the biochemical cycle model, reproduction of overall concentration levels was satisfactory for all the water quality constituents included in the model, but was insufficient in replicating the patterns of fluctuation and distribution for chlorophyll-a and related constituents, *COD* and PO_4-P. In addition to the complexity of water quality formation in the estuary that has not been grasped with sufficient detail, the aforementioned inadequacy in *SS* simulation is a significant contributing factor. Moreover, it was found through the field survey that both freshwater and marine phytoplankton coexist in the estuary according to the salinity distribution, complicating further the primary production processes. As the subject of future modeling study, it is desirable to consider at least two representative phytoplankton species of marine and freshwater origin, including their variability in salinity dependence and rate parameters.

- Shenzhen Bay is an anomaly within the Pearl River Estuary in the sense that its water is stagnant without significant river through-flow. Tidal flushing is also impeded by its narrow opening to the estuary. Consequently, Shenzhen Bay behaves more like a typical eutrophic water body, as indicated by both the field survey and simulation results. As the deterioration of Shenzhen Bay water quality appears to be accelerating, the development of a specialized eutrophication model for the bay is an urgent subject of future study.

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