2. Development of a Hydrodynamics-Water Quality Simulation Model

2.1 Objectives

The primary objective of developing a numerical simulation model in the present study was to investigate the spatial distribution of key water quality indices to enable optimum selection of water quality monitoring strategies. In addition, such a model would be utilized as a planning and management tool for water pollution mitigation and water quality conservation. Such a model could assist the reassessment of the ongoing monitoring scheme in response to any significant changes in pollutant load that might occur by industrialization in the catchment and coastal areas, or by implementation of load-reduction measures. It is also possible to utilize such a model for marine environmental impact assessments of proposed industrial developments involving significant changes in pollutant load or local hydrodynamics.

In order to meet the above objectives, it was essential that the simulation model developed for the present study provided insights into the water pollution mechanism, such as the relationship between pollutant load and water quality, and the linkage between the nutrient load and primary production. To this end, the study team proposed that the simulation model be composed of two distinctive components: a three-dimensional hydrodynamics model and a three-dimensional biochemical cycle model. These models are described in the following sections.

2.2 Practicality of the Simulation Model

In order for the counterpart to utilize the simulation model effectively and efficiently, the study team proposed to minimize the computational resources requirement and to streamline the application procedures by the following means:

1) Promoting participation of the counterpart personnel in the planning and construction processes of the model components for thorough understanding of the structure and the operational procedure of the model being developed;
2) Providing a plain and clear user's guide;
3) Simplifying the procedures of assigning and modifying input parameters by grouping and reducing the number of factors;
4) Optimizing the number of grid points both horizontally and vertically, just sufficient for the simulation objectives;
5) Drastically reducing the computational through-put time required for the overall simulation by storing and reusing typical flow patterns obtained from the hydrodynamics simulation beforehand;
6) Employing a color graphics output scheme for ready analyses of the simulation results.

The counterpart expressed its expectation that the model under consideration consist of a water quality model and a practical ecosystem model, in addition to a hydrodynamics model. However, the study team considers that biochemical processes and water quality are inseparable elements in an estuarine environment such as the Pearl River Estuary. The study team proposed, therefore, to develop a biochemical cycle model that included both the functions expected by the counterpart, along with a three-dimensional hydrodynamics model.

2.3 Basic Functions Required for the Simulation Model

2.3.1 Three-dimensional Modeling

The quantity of the riverwater discharged into the shallow Pearl River Estuary, averaging only 5 m in depth, is exceptionally large, at an average rate of more than 5,000 m^3/s annually. Moreover, the river discharge is concentrated during the rainy season, draining nearly 80 % of the annual load between May and September. As a result of this large inflow of fresh water, substantial density stratification may occur in the rainy season when the tidal mixing is minimal during neap tide. Density currents generated under such conditions would result in a current pattern in which the upper layer flows toward the mouth of the estuary while the lower layer moves in the opposite direction.

In order to simulate such density-induced currents, a three-dimensional hydrodynamics model, capable of resolving the vertical distributions of density and currents was required. The study team committed itself to the development of a three-dimensional baroclinic model that numerically solved the hydrodynamics and salinity advection-diffusion equations simultaneously.

2.3.2 Biochemical Cycle Modeling

The significant increase in pollutant load during the past decades is thought to have advanced pollution and eutrophication of the Pearl River Estuary to a threatening degree that occasional red-tide blooms and the depression of the fishery and aquaculture industry have become evident. In a water quality simulation model dealing with such a productive marine environment, it is necessary to incorporate biochemical dynamics representing the processes of nutrient cycles, primary production, degradation of organic matter, and settling of particulate organic matter, as well as elution of nutrients from the bottom sediments. The study team proposed to develop a three-dimensional biochemical model that specified these fundamental processes.

Figure 2.3.1 shows a conceptual model of the proposed three-dimensional biochemical cycle processes. In the figure, the processes enclosed by an ellipse require field and laboratory analyses to quantify the rates of kinetics. It is important to carry out these analyses, since the rate parameters involved in these processes are invariably site-specific.

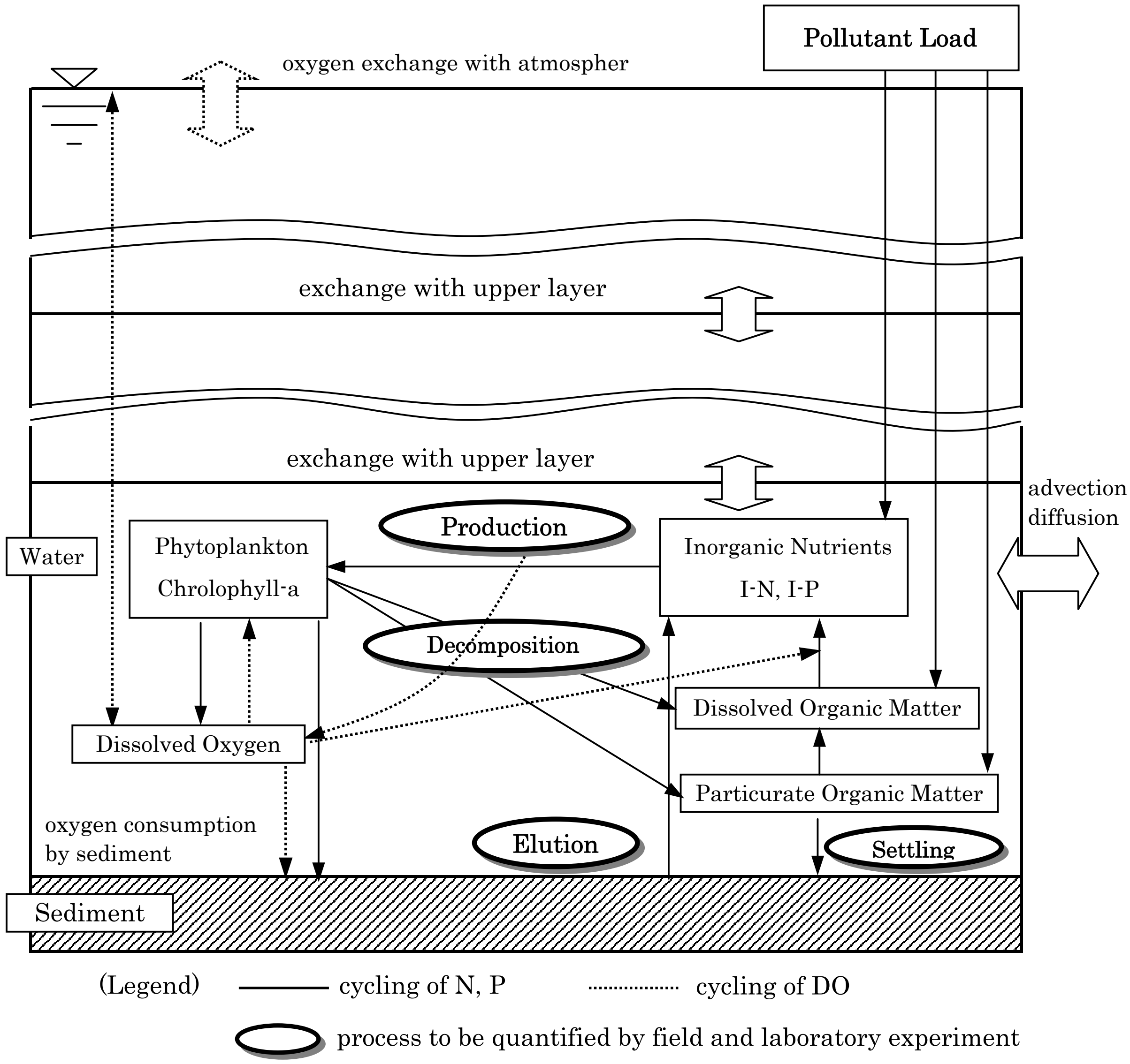


Figure 2.3.1 A Conceptual Model of Three-Dimensional Biochemical Cycle Processes

2.4 Hydrodynamics Model

2.4.1 Modeling Strategy

The hydrodynamics in a large estuarine bay, such as the Pearl River Estuary, is roughly composed of the components shown in Table 2.4.1. In the table, (2) to (4) are generally called 'mean currents' in which (2) is called 'residual', in the sense that it represents the semi-permanent current pattern extracted by averaging the tidal currents over several tidal cycles, thus eliminating the harmonic components. The 'mean currents' are known to be the major contributors to the dispersion processes of dissolved and suspended matter in tidally influenced water bodies. The main objective of hydrodynamics modeling in the present study is, therefore, to reproduce the 'mean currents' in the estuarine bay.

Table 2.4.1 Current Components in Tidal Estuary Bay

Driving Force	Classification
Tide	(1) Tidal Current
	(2) Residual Current
Fresh Water Inflow	(3) Density Current
Wind	(4) Wind-Driven Current

Accordingly, the most suitable hydrodynamics modeling strategy was to develop a multi-level baroclinic model designed to reproduce the 'mean currents' ((2) to (4)) as well as the 'tidal current' ((1)), driven by the river inflows, tide, and winds.

The system of governing equations pertinent to the aforementioned modeling strategy consists of the equations of continuity, momentum, and conservation of salinity. The vertical eddy viscosity and diffusivity (K_M and K_H), the key parameters in three-dimensional modeling governing the extent of vertical mixing, are functions of local balance between turbulence and gravitational stability. The concept of 'Level 2.0 turbulence closure model' (Mellor and Yamada, 1974, 1982) was adopted in the present study. Details are shown in the supporting report.

2.4.2 Revisions and Improvements Undertaken

Several areas for improving the hydrodynamics model development and test simulations were raised during the first and the second study periods in China. The major revisions and refinements undertaken are summarized below:

1) Treatment of River Outlets

It was possible to apply open-boundary conditions to the river outlets by prescribing a detailed time series of water levels somewhat upstream of each river mouth. The discharge rate for each outlet was adjusted by fine-tuning the frictional factors involved.

However, for complex reasons beyond the control of both the study team and the counterpart, the collection of dependable data for this purpose was not possible. In addition, accuracy in river discharge quantity is far more significant than is water level information for each river outlet for water quality modeling. Under the circumstances, therefore, the closed-boundary approach with prescribed discharge seemed to be the only option. Thus, the river discharges were assigned as steady seasonal-average flow rates, taken from the available literature.

2) Enhanced Stratification / Density Currents

During the first study period, the unanimous opinion of local scientists and researchers was that the degree of stratification and density currents should be much stronger in reality than what the early test simulation results indicated. The results of the rainy season field survey also revealed pronounced density stratification in the estuary, especially during the neap tide in the southern half of the estuary. To deal with this issue, the study team undertook several refinements including: the expansion of a computational domain further into the south; fine-tuning the vertical eddy viscosity/diffusivity; adapting the field survey results for the salinity boundary conditions; and increasing the number of vertical layers. These strategies combined brought about a marked improvement in the simulation results, as discussed in a later subsection.

3) Relocation of Tidal Open Boundary

From the simulation results of the rainy season during the first study period, it was found that the entire computational domain was dominated by freshwater discharged from the Pearl River outlets. It was also found that the location of the tidally-forced open boundary coincided with where the salinity fluctuation was most pronounced, which was inappropriate as the open boundary at which salinity must be prescribed during the flood tide. This issue was dealt with by extending the computational domain approximately 50 km southward into a zone where salinity variation is insensitive to river discharges.

4) Treatment of Hong Kong-Lantau Channel

In a meeting held at the end of the first study period, the steering committee pointed out that the exchange of water through the Hong Kong-Lantau Channel is significant despite its narrowness. As the initial test model developed in the first study period abbreviated the channel by a closed boundary, no water exchange was taken into consideration. The aforementioned expansion of the computational domain also resolved this issue.

2.4.3 Computational Conditions

1) Computational Domain and Bathymetry

Figure 2.4.1 shows the extended computational domain and its bathymetry. As already mentioned, the extension was needed to deal with the shortcomings found in the test simulation results during the first study period. The test simulation, in which the tidal open boundary coincided with the line connecting Macau and Lantau Island, resulted in an entire computational domain dominated by freshwater. In addition, it was found that the location of the open boundary was undesirable as the tidally-forced boundary, since salinity fluctuated widely near the boundary. A new open boundary was relocated approximately 50 km southward to avoid the zone of strong freshwater influence. The geometry and bathymetry data for the new computational domain were provided by the counterpart. The data, originally in a grid form with 0.5 minute step in both the longitudinal and the latitudinal directions, were converted to a uniform x-y mesh with a spacing of 1000 m.

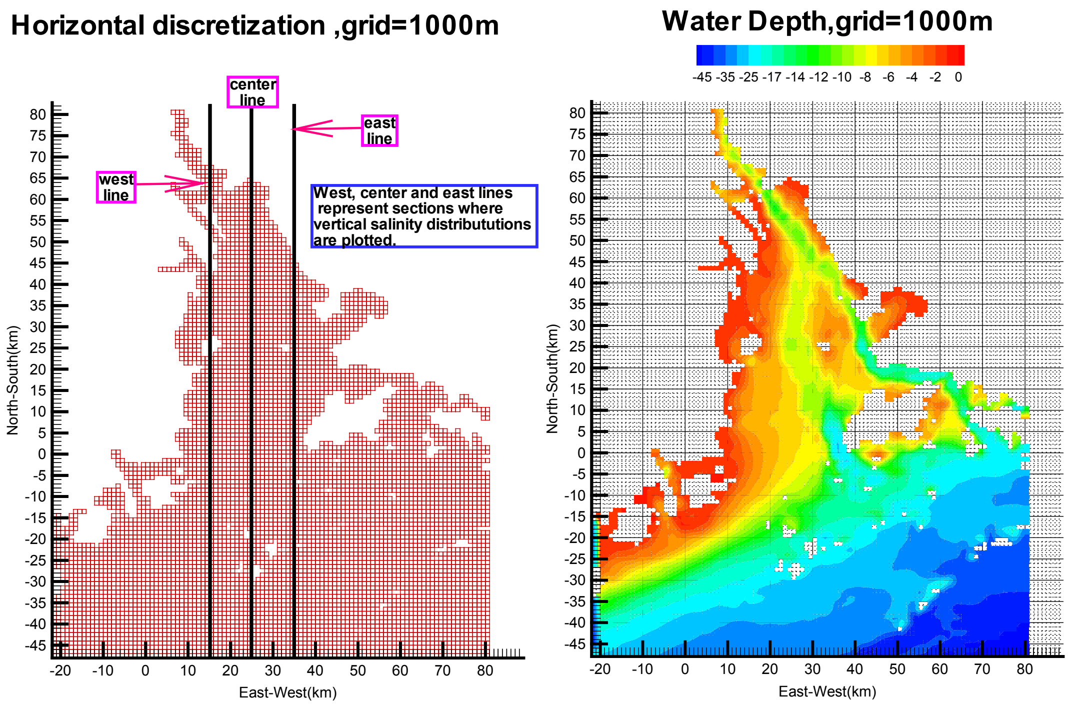


Figure 2.4.1 Extended Computational Domain and its Bathymetry.

2) River Discharge

River discharge data for the 8 outlets of the Pearl River system, in the form of monthly averages for 1997 to 1999, were acquired through the South China Sea Information Center. The rainy season discharge conditions were taken from the three-year averages for August.

3) Vertical Discretization

The test results of the hydrodynamics simulation during the first study period did not produce significant density stratification. The salinity profiles were nearly uniform in the vertical, with a distribution only in the horizontal. The rainy season field survey results, in agreement with the opinions of local scientists, showed that the degree of stratification and density currents are much stronger in reality, particularly during the neap tide when the tidal mixing process is weaker.

One of the measures taken to deal with this shortcoming, along with fine-tuning of the vertical eddy viscosity/diffusivity and the aforementioned relocation of the open boundary, was to improve the vertical model resolution. The number of model layers was increased from 10, in the test cases, to 15 in the current computational domain.

4) Tidal Forcing along the Open Boundary

One of the conspicuous features of the estuary found by the rainy season field survey was the marked difference in the degree of vertical mixing between the spring and the neap tides. A strong stratification forms during the neap tide period, while in the spring tide it weakens to almost nil. To capture these features, a hydrodynamics simulation was performed to envelop the cycles of the neap and spring tides continuously. The tidal data along the open boundary were provided by the SCSB staff.

5) Boundary Condition for Salinity

The salinity boundary conditions along the open boundary were prescribed according the results of the rainy season field survey.

2.4.4 Results of the Hydrodynamics Simulation

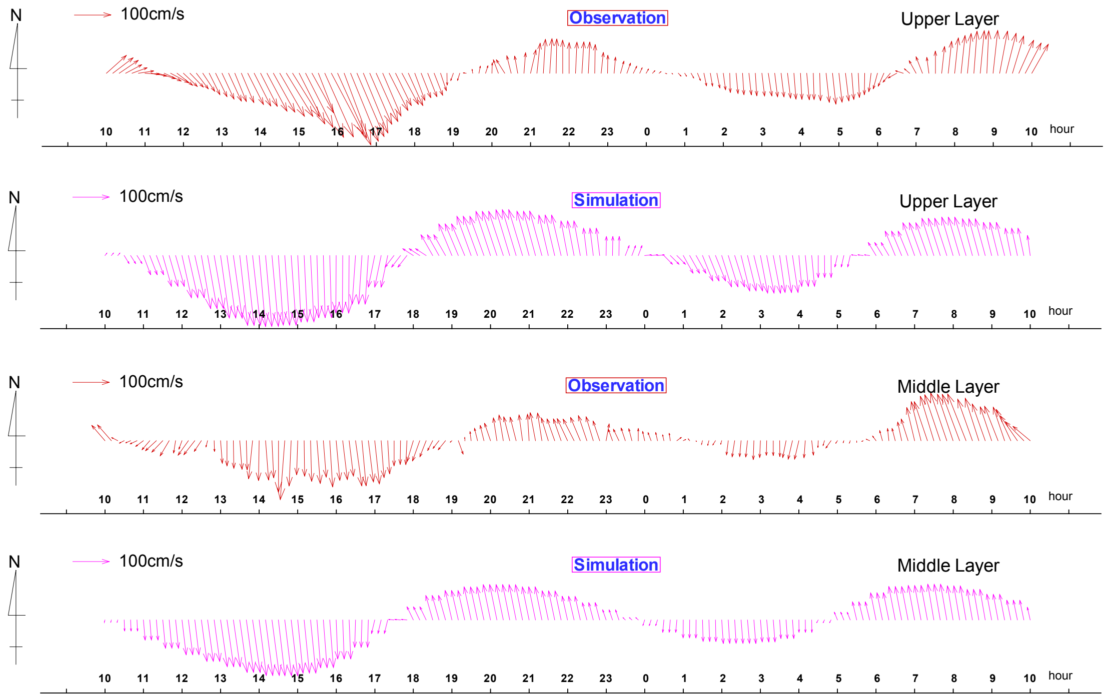
1) Comparison of Velocity Vectors

Figures 2.4.2 and 2.4.3 are comparisons of current vectors between the observation and the simulation at station P11 located in the center of the estuary. In the supporting report, comparisons at all stations are shown. At some locations, particularly in the bottom layer, the simulation results did not match the observation well, although at most of the other locations the simulation results were nearly identical to the observation.

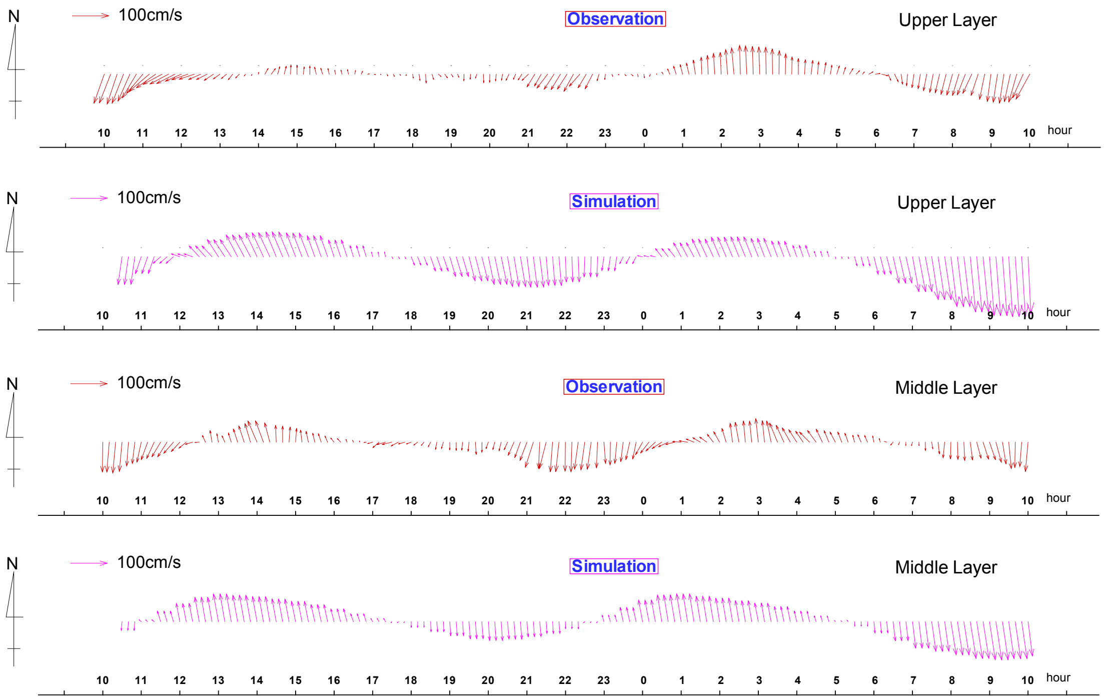
2) Comparison of Salinity Distribution

Figures 2.4.4 to 2.4.5 show comparisons of vertical salinity distributions between the observation and the simulation. The cross-sections of the vertical distributions were drawn as shown in Figures 2.4.1. The cross-sections for plotting the vertical salinity distributions for the simulation and the observation results are not identical. In addition, the observation results are a collection of measurements at various times during a neap or a spring-tide period and, therefore, are not synchronized. Conversely, the simulation results are plotted using values averaged over a tidal cycle. Therefore, caution is necessary because these comparisons are not strictly one-to-one.

These limitations notwithstanding, stronger stratification tends to be seen in the observation than in the simulation results. It is also seen that the lower layer salinity intrudes deeper into the bay in the observation than in the simulation results during neap tide. A thin freshwater layer on the surface stretched over a long horizontal expanse seen in the observation results for the neap tide is not clearly observed in the simulation result.



Figures 2.4.2 Comparison of Current Vectors between Observations and Simulation at the Center of the Pearl River Estuary (Spring Tide)



Figures 2.4.3 Comparison of Current Vectors between Observations and Simulation at the Center of the Pearl River Estuary (Neap Tide)

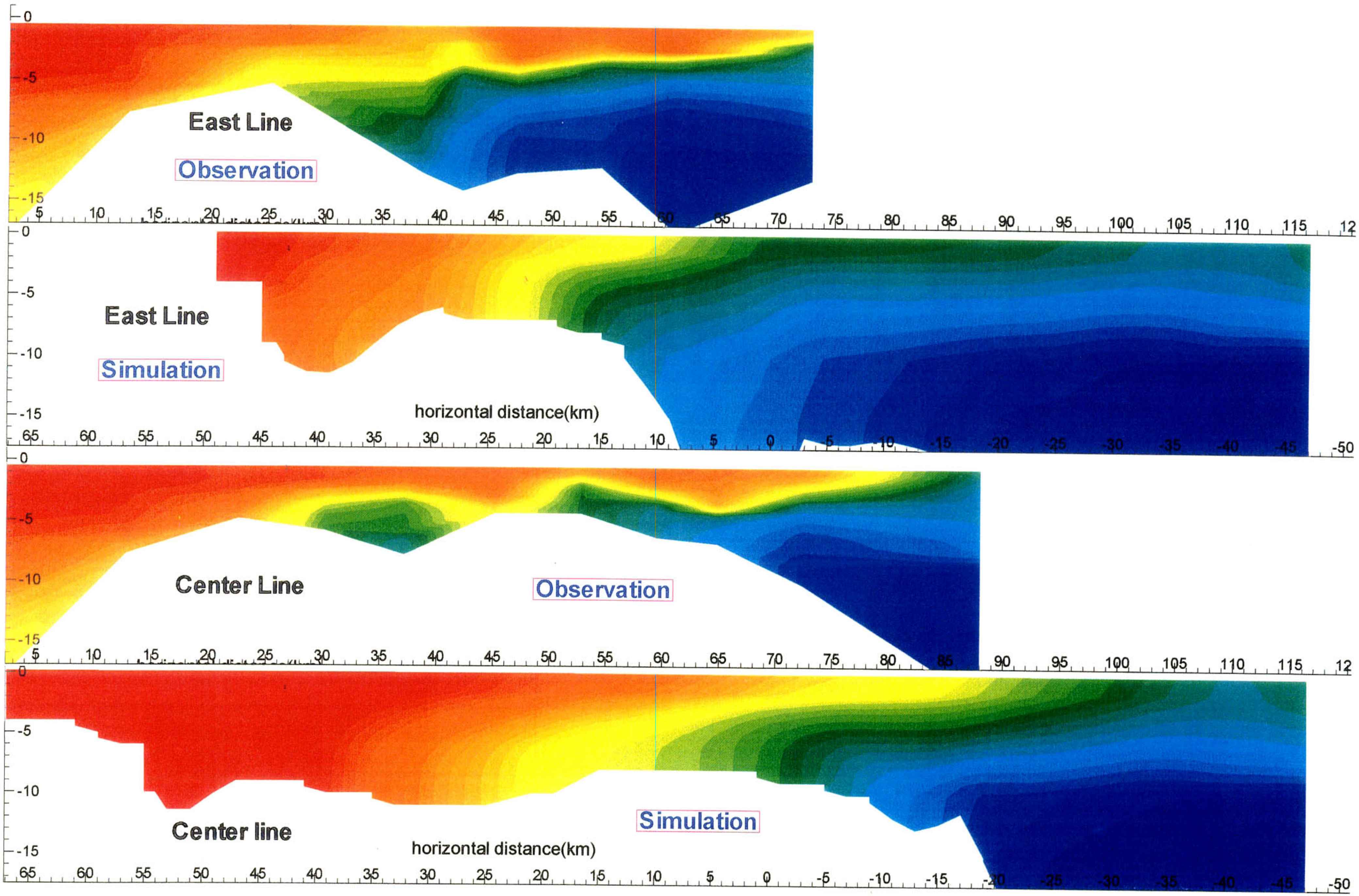


Figure 2.4.4 Comparison of Vertical Salinity Distribution in Neap Tide between Observation and Simulation

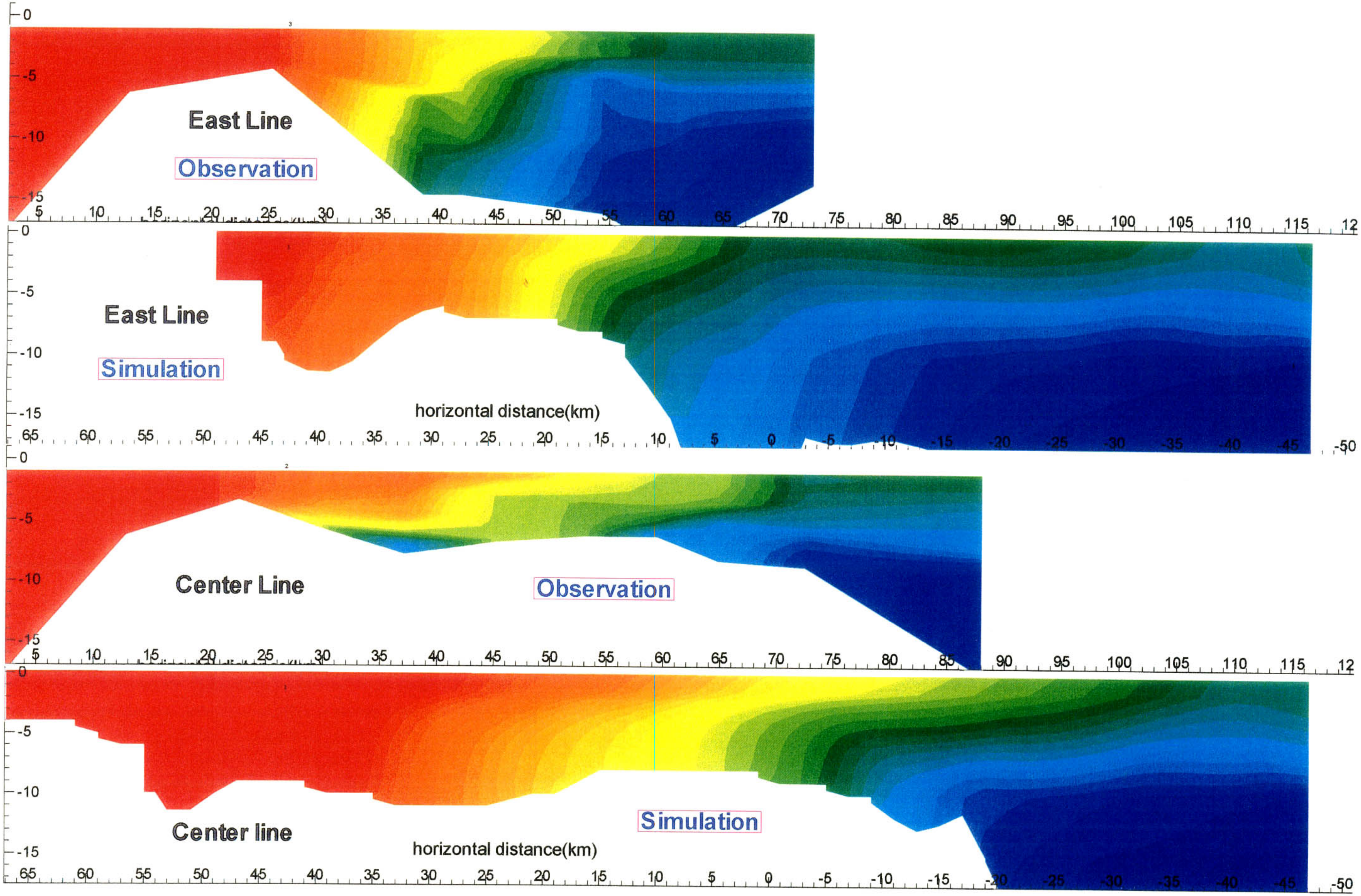


Figure 2.4.5 Comparison of Vertical Salinity Distribution in Spring Tide between Observation and Simulation

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-N, T-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 one of the limiting factors 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.

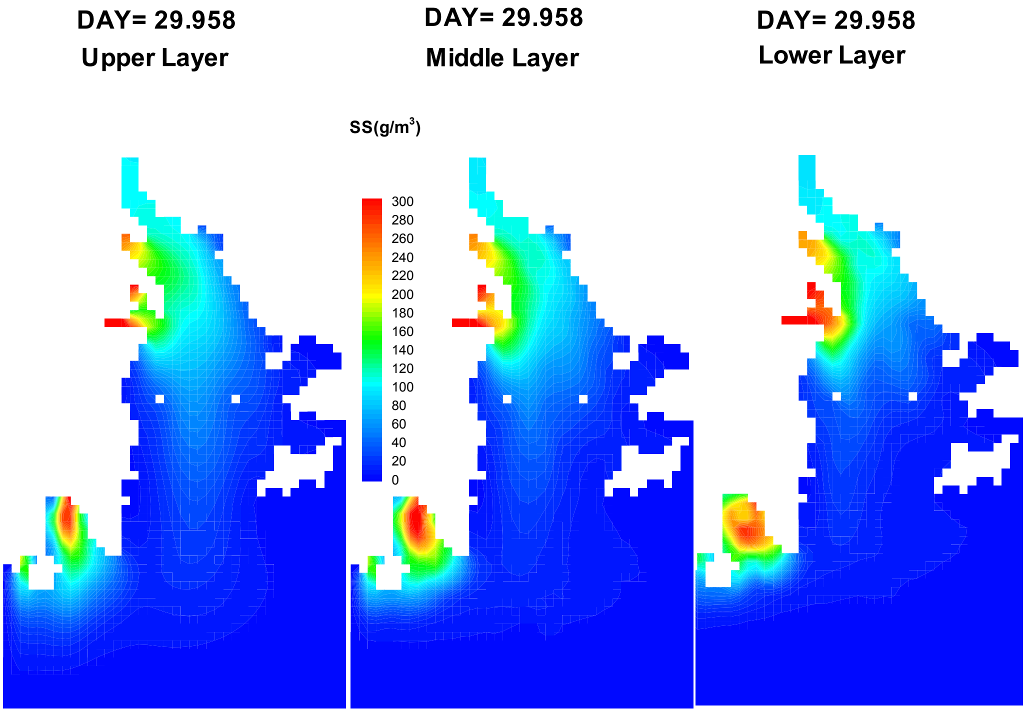


Figure 2.5.1 Results of the SS Simulation in Spring Tide

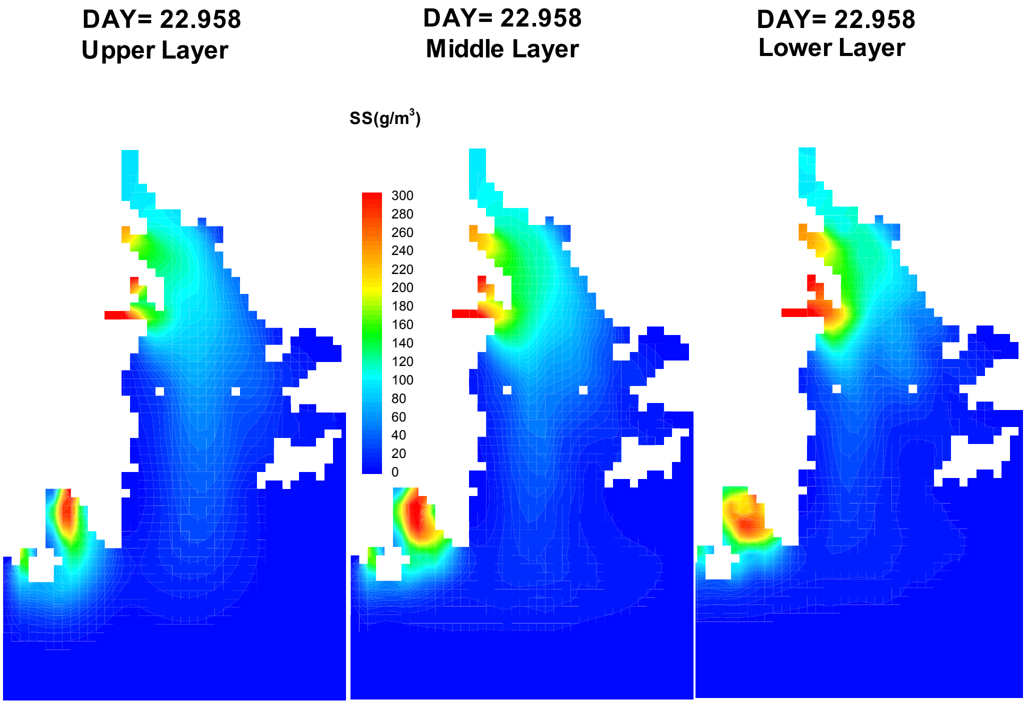


Figure 2.5.2 Results of the SS Simulation in Neap Tide

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.

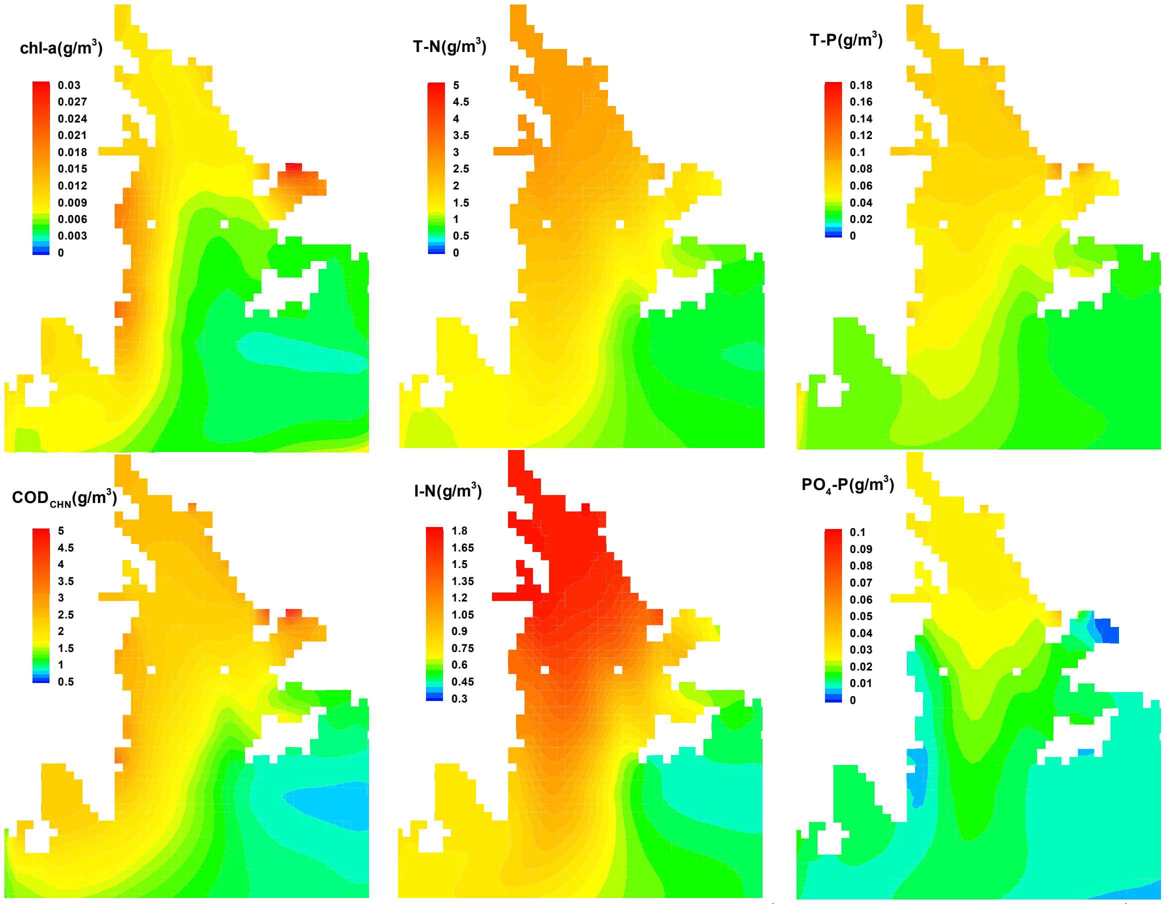
The simulation results for COD show 1.8 - 3 mg/L in the upper to the central zone of the estuary bay, and 1.2 - 2.5 mg/L near the bay mouth. In the Shenzhen Bay, it is considerably higher at 2 - 5 mg/L in the upper layer and 2 - 3.5 mg/L in the lower layer. These values are generally similar to the field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

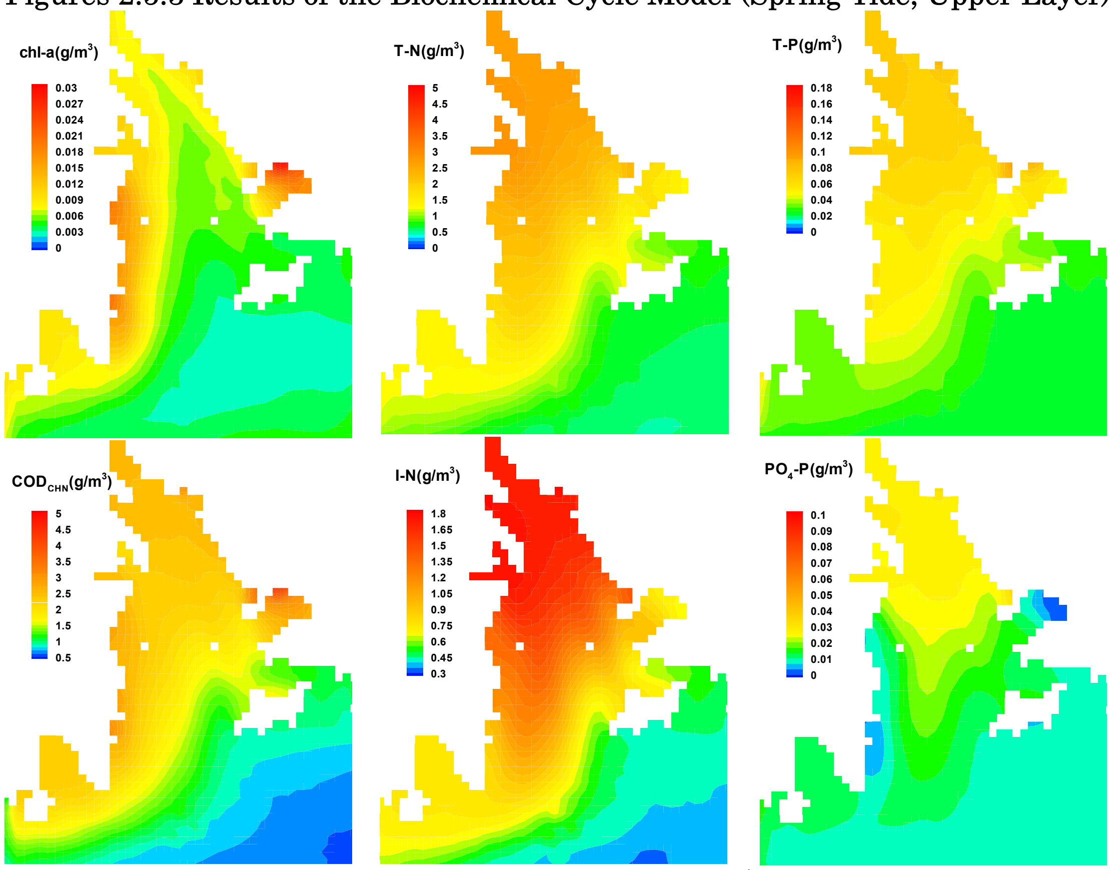
The I-N concentration also decreases southward from 2 mg/L to 0.7 - 1.3 mg/L in both the simulation and the field survey (NO_3-N) results. The field survey results show a more distinctive vertical distribution pattern, suggesting the presence of counter flow: the upper layer river water moving southward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

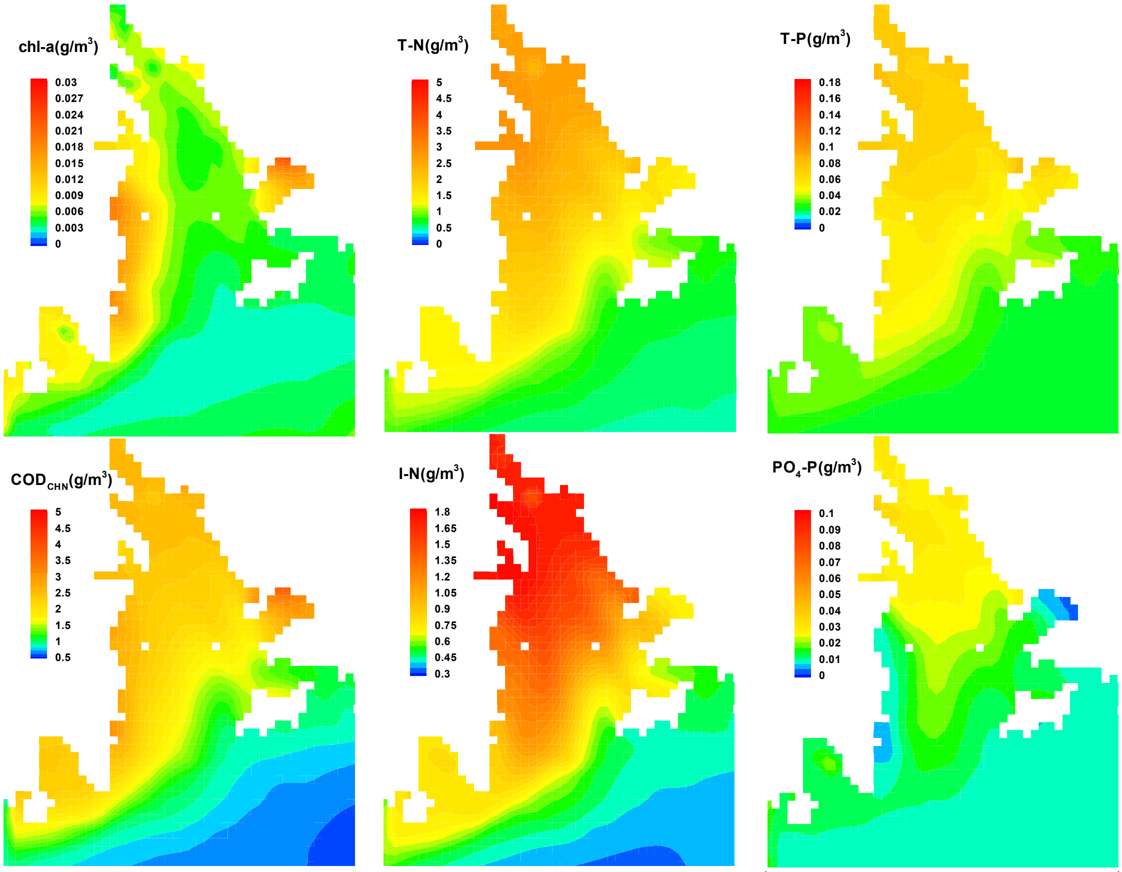
As for PO_4-P, the simulation results exhibit the tendency that the river water spreads over the estuary, gradually diluted by the dispersion process in a manner similar to the cases for T-P and T-N. Further south of the bay mouth, toward the South China Sea, however, PO_4-P concentration decreases rapidly 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.



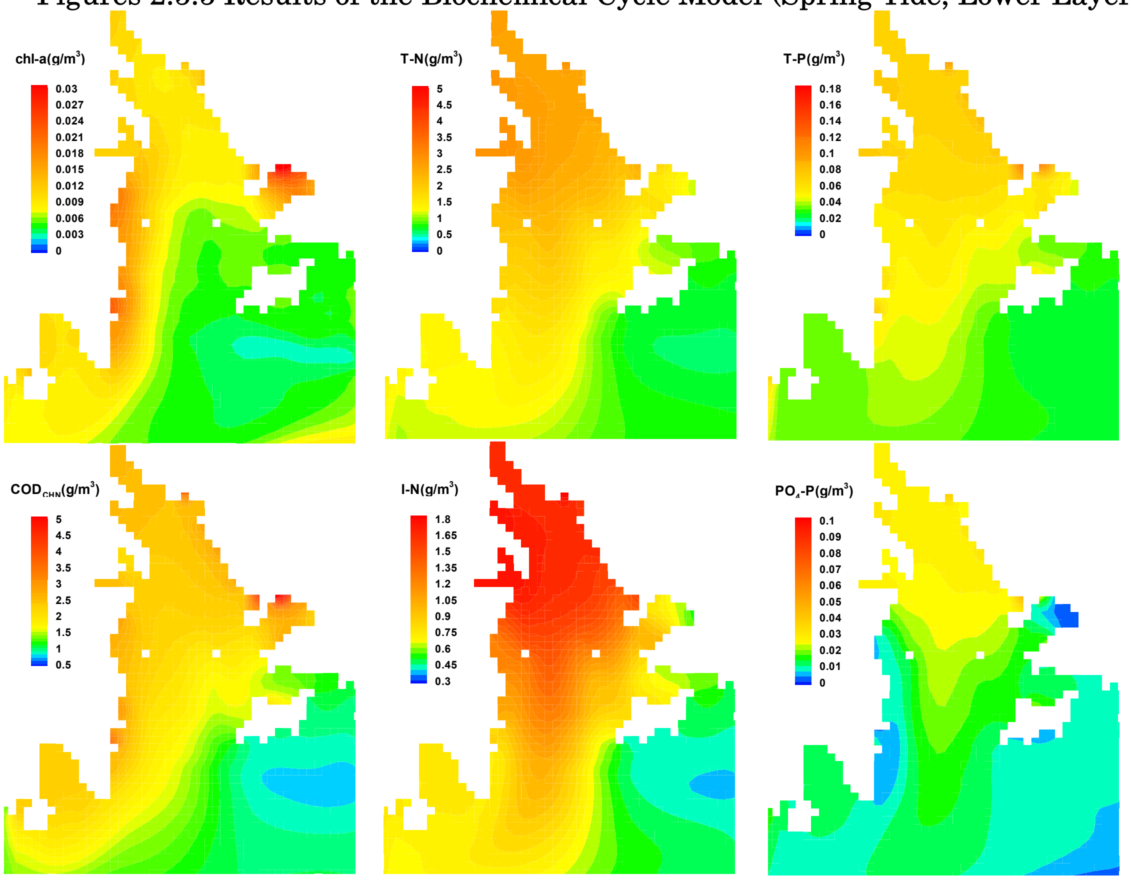
Figures 2.5.3 Results of the Biochemical Cycle Model (Spring Tide, Upper Layer)



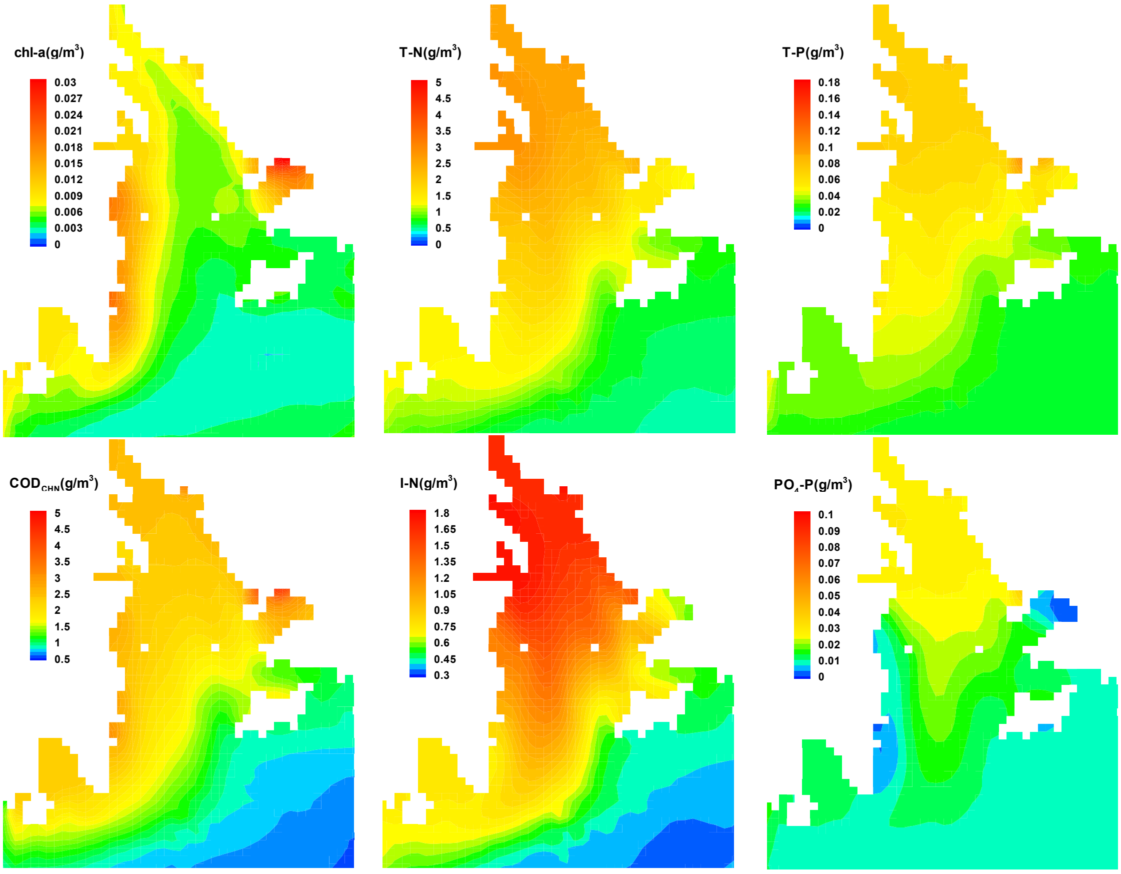
Figures 2.5.4 Results of the Biochemical Cycle Model (Spring Tide, Middle Layer)



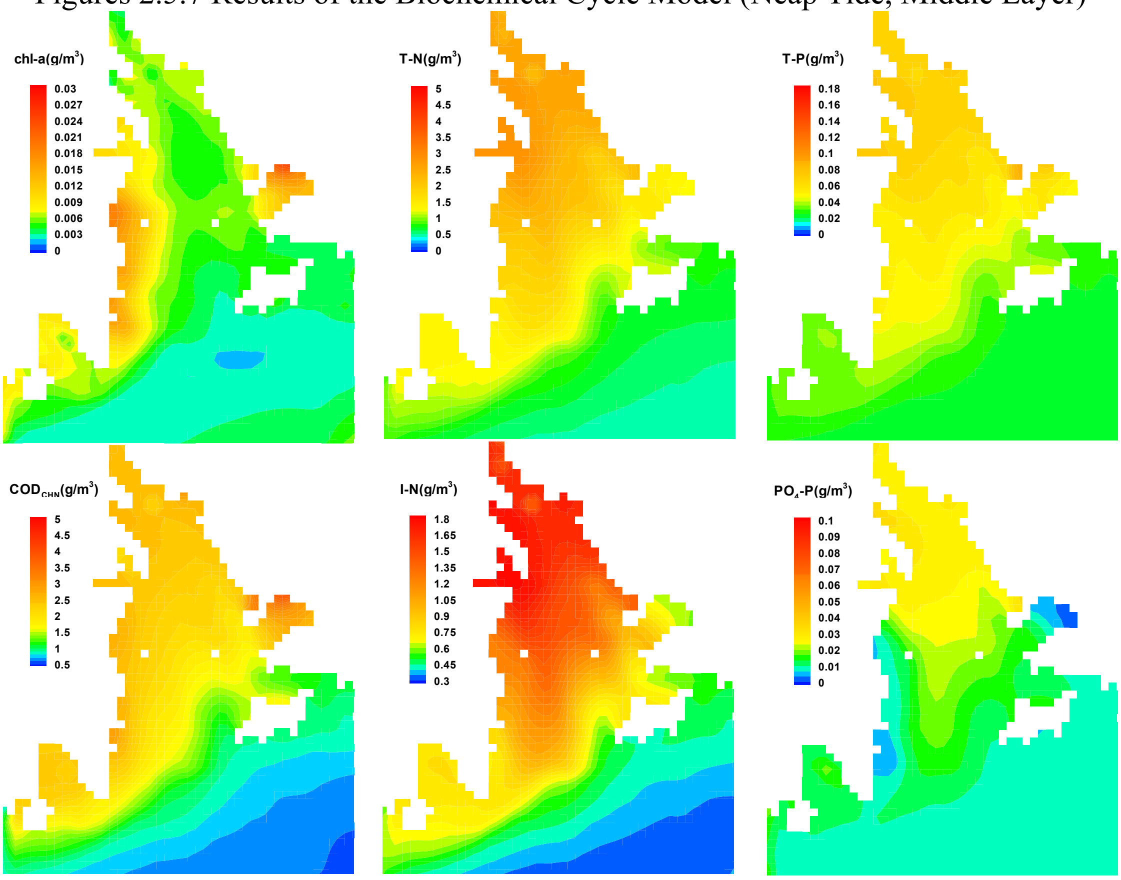
Figures 2.5.5 Results of the Biochemical Cycle Model (Spring Tide, Lower Layer)



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 also 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, development of a specialized eutrophication model for the bay is an urgent subject of future study.

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