Chapter V.

Simulation Model Development

Chapter V. Simulation Model Development

1. Pollutant Load

1.1 Concept of Pollutant Load Analysis

1.1.1 Pollutant Load Sources - Definitions and Classification

The source of pollutant load to the Pearl River Estuary can be classified into (1) discharges of the Pearl River tributaries and (2) direct runoff discharges from the coastal area. The latter is divided into point sources and non-point (diffuse) sources.

Discharges of tributaries into the estuary run out from four outlets; Humen, Jiaomen, Hongquimen and Henmen. Pollutant loads from these tributaries should be estimated by the flow rate and the water quality, measured at four sites near the river mouths.

Point sources include sewage and industrial effluents of defined discharge points, generally subject to the effluent standard. Point sources always emerge as a result of human activities.

Discharges from non-point sources cannot be related to particular points but to a certain land surface. Loads from non-point sources are determined by the geographical features (natural factors) and the land use (anthropogenic factors).

Land use categories include residential (urban) land, forested land, cultivated land and so on. Non-point source load is brought to the river through the surface runoff of precipitation. Another important non-point pollutant source is atmospheric precipitation, which consists of the dry-fallout and rain.

The discharges from four outlets and point source loads can be estimated from regular effluent monitoring; data generally required by environmental and/or water resource management authorities. In the Pearl River Basin, these data should be obtainable from PRWRC, GEPB and others. Data from these authorities was not available for this study, however, because they are not disclosed officially.

Consequently, the Study Team tried to estimate the pollutant load using data from published research and statistical yearbooks.

Non-point source load must be presumed by the unit load method mentioned in the next section. Although there are few reference data available on non-point source load (mass of pollutant/area/time), even in the same land use category, the differences resulting from site-specific features can range as high as two orders of magnitude. Therefore, it is indispensable to acquire as much field data as possible in order to provide realistic load estimates for a particular water body.

1.1.2 Estimation Method Based on Unit Load

The estimation of the pollutant load is carried out based on the unit load concept. The rather simple idea, outlined in Figure 1.1.1, is widely used in load estimation in Japan and other countries. Based on this concept, the following load estimation is proposed.

The Pearl River Delta area will be divided into some sub-basins based on the boundary of cities and geographical features.

Effluent pollutant load (EPL) is calculated for each sub-basin as follows:

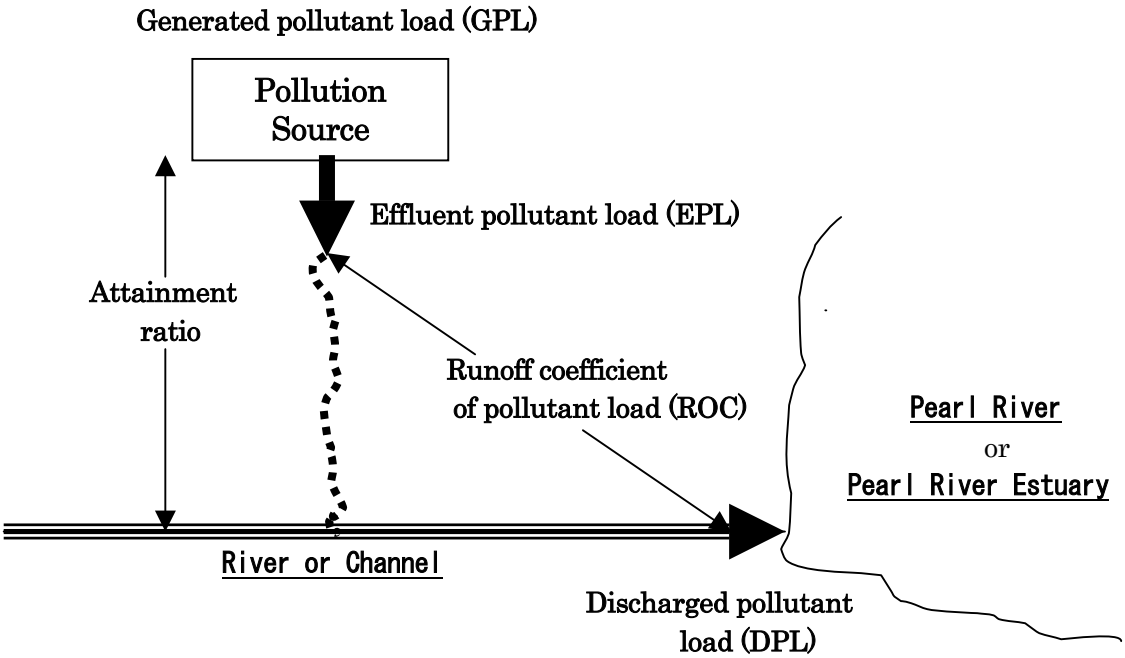
EPL = UPL x FPL
where,
UPL: Unit pollutant load
FPL: Frame for estimation of effluent pollutant load (size of source)

Discharge pollutant load (DPL) to the estuary is calculated as follows:

DPL = (amount of EPL) x ROC = C x Q
where,
ROC: Runoff coefficient of pollutant load
C: Concentration of pollutant at the discharging point of the river
Q: Flow rate of water discharged at the discharging point of the river

EPL will be multiplied by UPL and FPL, which can be obtained from existing literature and statistical values. If we obtain C and Q data at the river mouth (the end of the basin), DPL would be calculated, and an unknown DPL would be estimated by applying ROC to the basin.

A basin image of the Pearl River Estuary is shown in Figure 1.1.2.



EPL = GPL×RR or

EPL = amount of (UPL×FPL)

where,

EPL: Effluent pollutant load

GPL: Generated pollutant load

RR: Removal ratio by the water treatment or the decrease of run-out process

UPL: Unit pollutant load for effluents

FPL: Frame for estimation of effluent pollutant load (Size of source)

DPL = (amount of EPL)×ROC = C×Q

where,

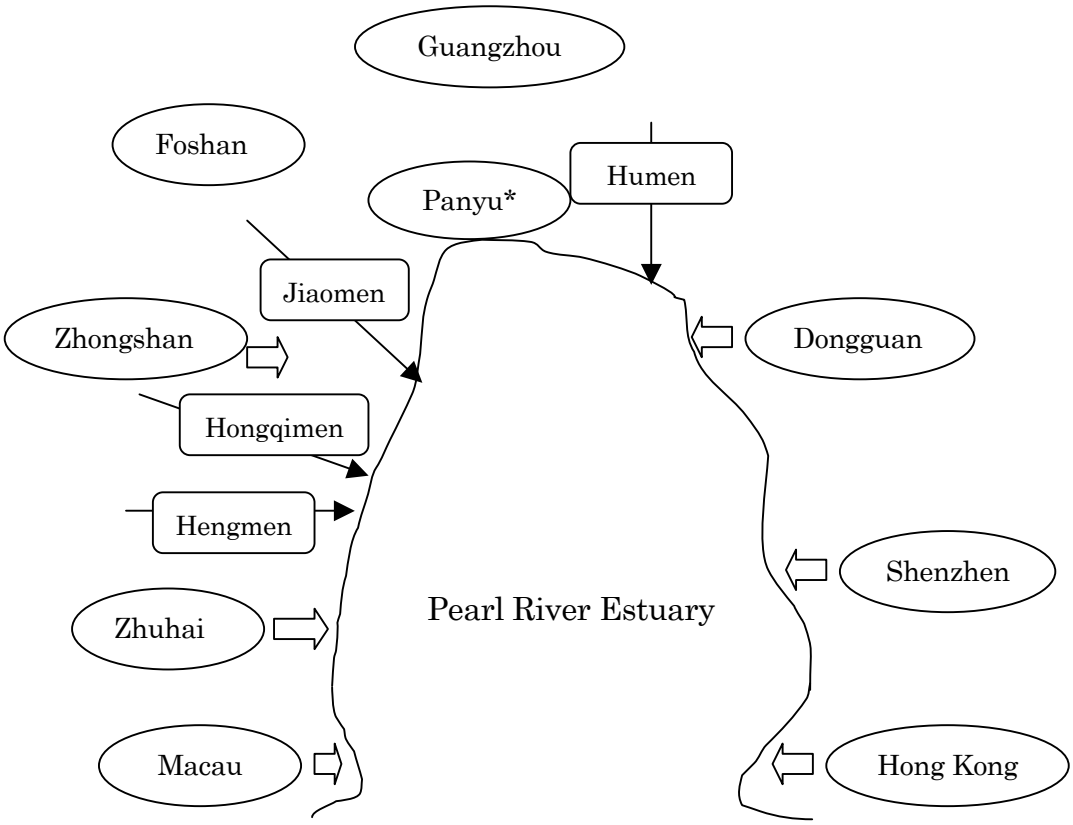
DPL: Discharged pollutant load

ROC: Runoff coefficient of pollutant load

C: Concentration of pollutant at the discharging point of the river

Q: Flow rate of water discharged at the discharging point of the river

Figure 1.1.1 Concept of Pollution Load Analysis



Note: Panyu is the county- level city inside Guangzhou.

【Discharges】 (m^3/sec)

	Humen	Jiaomen	Hongqimen	Hengmen	Total
Rainy Season	3.761	3,518	1,300	2,277	10.856
Intermediate Season	1,645	1,537	568	996	4,746
Dry Season	741	693	256	448	2,138
Annual Mean	2,049	1,916	708	1,241	5,914

Source: Table 1.1.1

【Statistics of cities】

	Area (km^2)	Population (10^4 persons)	Industrial Products (10^8 RMB)
Guangzhou	7,434	674.14	1,747.551
Shenzhen	2,020	114.60	1,636.252
Dongguan	2,465	148.77	456.578
Zhongshan	1,800	130.08	442.287
Zhuhai	1,630	69.48	512.210
Foshan	3,814	324.98	1,254.953
Total	19,163	1,462.06	6,049.830
Hong Kong	1,097	668.72	821.560(10^8HKD)
Macau	17.45	42.20	133.527(10^8MOP)

Source: Table 1.1.14, Table 1.1.15, and Table 1.1.16

Figure 1.1.2 Basin Image of the Pearl River Estuary

1.2 Pollutant Loads from Four Outlets of the Pearl River

1.2.1 Discharges from Four Outlets

Discharges and water qualities from eight outlets of the Pearl River have been monitored by PRWRC since 1984. Locations of these monitoring points are shown in Figure 1.2.1.

Discharges from the four outlets flowing into the Pearl River Estuary are shown in Tables 1.2.1 and 1.2.2.

The average annual discharge over the last three years from the four outlets is nearly 6,000 m^3/sec. In the rainy season, the discharge is up to about 11,000 m^3/sec.

One third of this discharge is from Humen, another third is from Jiaomen, and the other third is from Hengmen and Hongquimen.

There is a large seasonal change in discharge. In the rainy season (May to August), the flow rate of each outlet is five times larger than in the dry season (November to February).

1.2.2 Water Qualities in Four Outlets

Water quality data measured in recent years could not be obtained for some political reasons. Therefore, water quality at each river mouth of four outlets was estimated from the marine survey data of this study. Using the relationship between water quality and salinity on the data at the near point of the river mouth, the value of zero salinity was regarded as the water quality at the river mouth.

An example of this estimation is shown in Figure 1.2.2. Water qualities estimated by this method are shown in Table 1.2.3.

On the other hand, some representative water quality data from literature of past studies are shown in Table 1.2.4. The data are averages for the years 1984 - 1991. In the last ten years, the Pearl River Delta area has been developing rapidly, and so have discharges of industrial effluents and domestic sewage waters also increased, but the water treatment level needs to be developed. Comparing Tables 1.2.3 and 1.2.4, no significant change is recognized in each item of the water quality.

There is a tendency for values of COD (Mn) to be larger in the dry season than in the rainy season, but for values of total nitrogen (T-N) and inorganic nitrogen to be larger in the rainy season than in the dry season. This tendency of nitrogen indicates that nitrogen flows out to the river with the contribution of the non-point source, such as fertilizer, in the arable land.

1.2.3 Pollutant Loads from Four Outlets

The estimation of pollutant loads from the four outlets in Tables 1.1.1 and 1.2.3 are shown in Table 1.2.5. Pollutant loads throughout the four outlets are as follows:

- The COD (Mn) load is estimated as 1,800 ton/day in the rainy season and 500 ton/day in the dry season. The annual load of COD (Mn) is 400 thousand tonnes.
- The T-N load is estimated as 2,300 ton/day in the rainy season and 300 ton/day in the dry season. The annual load of T-N is 410 thousand tonnes.
- The T-P load is estimated as 53 ton/day in the rainy season and 11 ton/day in the dry season. The annual load of T-P is 11 thousand tonnes.

Referring to Table 1.2.6, which shows monitoring data at each river mouth collected by the South China Sea Information Center (SCSIC), the values mentioned above are estimated from actual loads in the present condition of the estuary. If newer and more accurate and abundant data can be obtained from monitoring, this estimation will be modified and made more precise.

Table 1.2.1 Discharges from four outlets in the Pearl River Estuary
(Average values in the terms of 1997-1999) (m^3 /sec)

Name of Outlet	Humen	Jiaomen	Hongqimen	Henmen	Total
January	595	557	206	361	1,719
February	683	638	236	413	1,970
March	1,064	997	369	646	3,076
April	1,744	1,634	604	1,058	5,040
May	2,427	2,273	840	1,470	7,010
June	3,783	3,540	1,308	2,290	10,921
July	5,540	5,180	1,913	3,353	15,986
August	3,293	3,080	1,140	1,993	9,506
September	2,317	2,163	801	1,401	6,682
October	1,453	1,354	498	880	4,185
November	1,011	946	349	611	2,917
December	675	632	234	409	1,950
Rainy Season	3.761	3,518	1,300	2,277	10,856
Intermediate	1,645	1,537	568	996	4,746
Dry Season	741	693	256	448	2,138
Annual Mean	2,049	1,916	708	1,241	5,914

Notes: Rainy Season; May, June, July and August
Intermediate Season; March, April, September and October
Dry Season; January, February, November and December
Source: Collected by the South Sea Information Center

Table 1.2.2 Discharges from Four Outlets in the Pearl River Estuary
(Average Values for 1959-1983) (m^3 /sec)

Name of Outlet	Humen	Jiaomen	Hongqimen	Henmen	Total
January	796	558	152	359	1,866
February	518	690	206	441	1,855
March	581	734	227	467	2,009
April	1,396	1,349	484	834	4,063
May	3,201	2,748	1,066	1,742	8,756
June	3,717	2,823	1,102	1,823	9,466
July	3,399	3,558	1,394	2,445	10,796
August	2,844	2,963	1,153	1,983	8,942
September	1,582	2,030	763	1,269	5,644
October	1,501	1,333	479	822	4,137
November	1,120	1,025	344	640	3,130
December	1,186	704	208	446	2,545
Annual Mean	1,830	1,717	635	1,111	5,292

Estimated by the following source; S.C.Kot and S.L.Hu, Water Flows and Sediment Transport in Pearl River Estuary and Waves in South China Sea near Hong Kong, Coastal Infrastructure Development in Hong Kong, Civil Engineering Office Hong Kong Government (1996)

Table 1.2.3 Water Qualities in Four Outlets Estimated by the Results of Marine Surveys in this study (2000)

		Humen	Jiaomen	Hongqimen	Henmen
COD_{Mn}	Rainy season	2.20	1.86	1.52	1.86
	Intermediate	2.63	2.22	1.82	2.22
(mg/L)	Dry season	3.06	2.59	2.11	2.59
T-N	Rainy season	2.41	2.41	2.41	2.41
	Intermediate	1.98	1.98	1.98	1.98
(mg/L)	Dry season	1.54	1.54	1.54	1.54
T-P	Rainy season	0.062	0.055	0.048	0.055
	Intermediate	0.064	0.056	0.049	0.056
(mg/L)	Dry season	0.065	0.058	0.050	0.058
Inorganic	Rainy season	1.53	1.52	1.50	1.52
Nitrogen	Intermediate	1.19	1.17	1.16	1.17
(mg/L)	Dry season	0.84	0.83	0.82	0.83
Inorganic	Rainy season	0.029	0.026	0.022	0.026
Phosphorus	Intermediate	0.040	0.035	0.030	0.035
(mg/L)	Dry season	0.051	0.045	0.039	0.045

Note:
1) Values of Rainy and Dry seasons in Humen and Rainy season in Hongquimen are estimated by results of this study. An example of the estimation is shown in Figure 1.1.4.
2) Value of Dry season in Hongquimen is calculated with one of Rainy season and the ratio of Rainy and Dry season's values in Humen.
3) Values of Intermediate season are average of Rainy season and Dry season in each outlet.
4) Values in Jiaomen and Henmen are average of Humen and Hongqumen in each season.

Table 1.2.4 Referenced Table: Water Qualities in Four Outlets
(Average values for 1984-1991)

Items		Humen	Jiaomen	Hongqimen	Henmen
COD_{Mn} (mg/L)	Rainy Season	2.0	1.7	2.2	2.1
	Intermediate	2.6	1.94	1.8	1.7
	Dry Season	2.4	2.3	2.3	2.0
Inorganic Nitrogen (mg/L)	Rainy Season	1.29	1.22	1.23	1.21
	Intermediate	1.26	1.04	1.09	1.10
	Dry Season	1.64	0.93	0.86	0.89
Inorganic Phosphorus (mg/L)	Rainy Season	0.025	0.031	0.025	0.024
	Intermediate	0.028	0.022	0.024	0.017
	Dry Season	0.023	0.013	0.018	0.016

Notes: 1) Values of COD and Inorganic N are the seasonal average for 1984-1991, based on Source 1.
2) Values of Inorganic P are the annual average for 1984-1991 based on Source 2, and the seasonal change ratio for 1990-1994 based on Source 1.

Sources: 1) Tang Jinping et al., Water Environmental Impacts of Land-origin Pollutants in the Pearl River Estuary, Journal of Pearl River for the people, 1996. No.6. (in Chinese)
2) Wu Jianzhong et al., Analysis for the Tendency of the Organic Matter Consuming Dissolved Oxigen in the Pearl River Mouth Area, Technical Journal of Marine Environmental Monitaring, 1995, State Oceanic Administration

Table 1.2.5 Pollutant Loads from Four Outlets of the Pearl River Estuary
(ton/day)

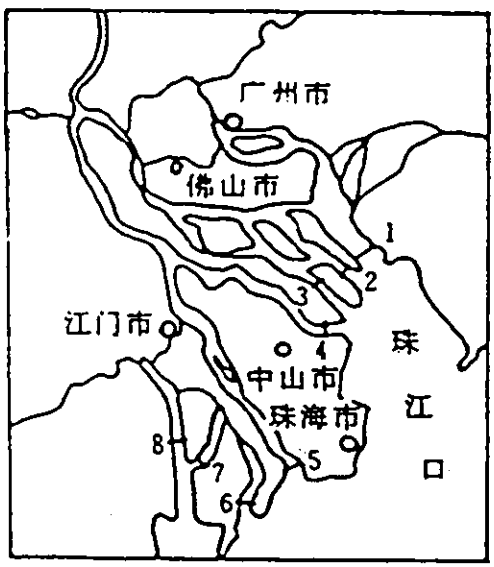
		Humen	Jiaomen	Hongqimen	Henmen	Total
COD_{Mn} Load	Rainy season	715	565	171	366	1,817
	Intermediate	374	295	89	191	950
	Dry season	196	155	47	100	498
T-N Load	Rainy season	783	733	271	474	2,260
	Intermediate	281	262	97	170	810
	Dry season	99	92	34	60	284
T-P Load	Rainy season	20	17	5	11	53
	Intermediate	9	7	2	5	24
	Dry season	4	3	1	2	11
Annual Total Load (ton/year)	COD_{Mn} Load	156,293	123,557	37,311	79,985	397,145
	T-N Load	141,429	132,253	48,871	85,616	408,169
	T-P Load	4,056	3,364	1,085	2,178	10,682

Table 1.2.6 Referenced Table: Pollutant Loads from Four Outlets (1996)
(ton/year)

	Humen	Jiaomen	Hongqimen	Henmen	Total
COD_{Cr} Load	729,600	415,300	150,000	116,800	1,411,700
COD_{Mn} Load	182,400	103,825	37,500	29,200	352,925
NH4-N Load	21,708	2,825	5,016	38,325	67,874
PO4-P Load	4,824	3,955	627	2,194	11,600

Notes: These values are calculated with the water quality and the discharge in each river mouth

Source: Collected by South China Sea Information Center



1:Humen, 2:Jiaomen, 3:Hongquimen, 4:Henmen, 5:Modaomen, 6:Jitimen, 7:Hutiaomen, 8:Yamen

Figure 1.2.1 Locations of Monitoring Points for Discharges and Water Qualities

Source: Dong Dehua et al., A Study on Laws of Sea-going Pollutant Flux in the Pearl River, Journal of Pearl River for the people, 1993. No.5

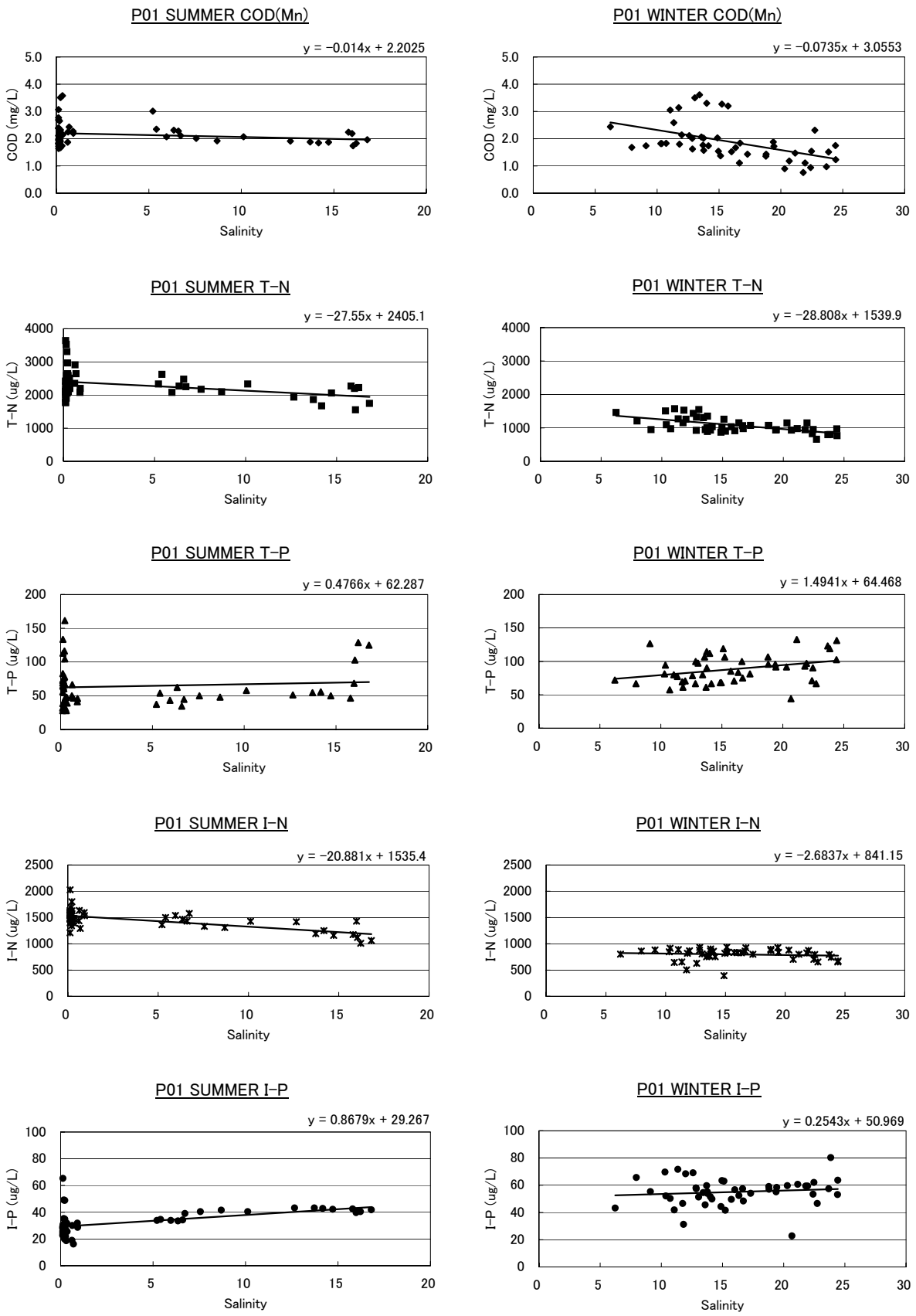


Figure 1.2.2 Water Quality at the point P01 (mouth of Humen)

1.3 Estimation of Pollutant Load from the Coastal Area

1.3.1 Setting Unit Pollutant Load

Values of unit pollutant load for the estimation of pollutant load were determined. A summary of unit pollutant load values is shown in Table 1.3.1. In this table, unit pollutant load values were considered and estimated for humans, livestock (cattle, buffalo, and hog), industrial effluent and non-point sources (land use: urban land, paddy fields, dry field, forested land, and others). Each consideration of setting of pollutant loads is as follows.

1) Humans and Livestock

The unit pollutant load for humans and livestock are considered as the foundation materials of a pollutant load analysis. The loads are shown in Table 1.3.2. Although most values in the table were based on common values in Japan, used for the planning of a sewer system, some of them were obtained by the studies in Shenzhen and Hong Kong (Xinyuan et al. 1997; Sin et al. 1996).

The values for humans in different studies are almost same value for BOD and T-N. COD is also the same, because the measuring value by COD (Cr) method used in China is generally 2 or 2.5 times of the value by the COD (Mn) method used in Japan.

2) Industrial Effluents

The unit pollutant loads for industrial activity is calculated as in Table 1.3.3, based on some statistical data in China. Unit pollutant load of COD is estimated as 40 kg/day/10^8 RMB as the average value of the three cities, Guangzhou, Shenzhen and Zhuhai.

In order to estimate the unit pollutant load of BOD, T-N, and T-P, it was estimated from the effluent water quality in Japanese factories as shown in Table 1.3.4. Representative values of some industrial categories were estimated as follows.

BOD: 400 mg/L, COD: 400 mg/L, T-N: 50 mg/L, T-P: 10 mg/L

These values are comparable to values in wastewater discharge in China, except for T-P concentration.

By applying the ratios of the above four water quality items, unit pollutant loads of BOD, T-N, and T-P were estimated as the following, and are summarized in Table 1.1.7.

- BOD : 40 g/day/10^8RMB
- COD : 40 g/day/10^8RMB
- T-N : 5 g/day/10^8RMB
- T-P : 1 g/day/10^8RMB

3) Non-point Sources

A unit pollutant load of non-point sources in the land use category was determined from data in the existing literature as shown in Table 1.3.6. Although most values of this table are based on common values in Japan, used for the planning of a sewer system, some of them were obtained from the study of Xinyuan et al. (1997) in Shenzhen.

1.3.2 Frame of Statistics for Estimation

Frame statistics for the human population and the livestock population were collected based on statistical yearbooks for the state, province, and each city.

Frame statistics of six cities and the direct runoff area (D.R.A.) around the Pearl River Estuary are shown in Table 1.3.7. Direct runoff area means the area around the estuary where effluents do not flow into the Pearl River and its tributaries, and the area that does not pass through the four outlets.

Estimated numbers of humans and animals in the D.R.A., including Hong Kong and Macau are as follows:

- Human population : 6,700 thousand
- Cattle population : 2.6 thousand
- Buffalo population : 3.6 thousand
- Hog population : 430 thousand

Frame statistics of six cities and their direct runoff area (D.R.A.) for the estimation of industrial effluent loads are shown in Table 1.3.8.

Industrial products in the D.R.A. are estimated about 290 billion RMB per year.

Frame statistics of six cities and direct runoff area (D.R.A.), for the estimation of non-point source loads, are shown in Table 1.3.9. In this table, land use areas of D.R.A. are calculated by satellite image analysis.

The total area of the D.R.A. is estimated about 2,200 km^2. The area of each land use category is as follows.

- Urban land and bare land : 820 km^2
- Forested land : 520 km^2
- Paddy fields : 140 km^2
- Dry fields : 220 km^2
- Other land : 500 km^2

1.3.3 Effluent Pollutant Load

By multiplication of the unit pollutant load and the frame, effluent pollutant loads in D.R.A. were calculated. Results of the estimation of effluent pollutant loads are shown in Table 1.3.10 to 1.3.13. Total loads from the direct runoff area of the Pearl River Estuary were estimated as follows.

- BOD load : 348 ton/day
- COD load : 307 ton/day
- T-N load : 64 ton/day

- T-P load : 8.6 ton/day

1.3.4 Setting of Runoff Coefficient of Pollutant Load

The setting of a runoff coefficient is necessary in order to estimate the discharged pollutant load. Although the available data in China is scarce, only data found in case of a study for Shenzhen was adopted, with a runoff coefficient of 0.8 (Xinyuan et al., 1997).

By comparison, according to some studies in Japan, annual mean runoff coefficients ranged from 0.6 to 1.0 (Kunimatsu et al., 1994).

Since the geographical features of the Pearl River Basin are more than those of basins in Japan, the runoff coefficient in the basin studied here could be smaller than the above values. As there was no data adopted in this area, a runoff coefficient of 0.6, as a minimum of the above values is adopted in this study.

Table 1.3.1 Unit Pollutant Load Adopted for this Study

	Unit	BOD	COD	T-N	T-P
Human life	g/day/capita	21	17.5	4.25	0.65
Cattle and Buffalo	g/day/head	64	53	29	5
Hog	g/day/head	49	26	24	1
Industrial Effluent	kg/day/10^8RMB	40	40	5	1
Urban Land	ton/km^2/year	25	17.5	0.5	0.28
Paddy Field	ton/km^2/year	13.7	13.7	1.9	0.204
Dry Field	ton/km^2/year	1	1	7.6	0.069
Afforested Land	ton/km^2/year	2.1	2.1	0.36	0.029
Other Land	ton/km^2/year	3.3	10	0.84	0.1

Note: Value of Human life is for effluents treated by septic tanks.

Sources: Referring to Table 1.1.8, Table 1.1.9, Table 1.1.10 and Table 1.1.11.

Table 1.3.2 Unit Pollutant Load from Human Life and Livestock

(g/capita/day)

	BOD	COD	T-N	T-P	Source
Human life	-	70*	-	-	1)
	42	90*	8.5	-	2)
	58	27**	11	1.3	3)
Cattle	64	53**	29	5	3)
Hog	49	26**	24	1	3)

Source:

1) Liu Xinyuan, Fan Liping and Luo Chengping, Water Resources Utilization and Coastal Water Environment in Shenzhen City, Symposium on Coastal Ocean Resources and Environment'97 (1997) (in Chinese)
2) W.S.Sin, P.K.Chan and K.M.Chau, Sewage and Stormwater Disposal, Coastal Infrastructure Development in Hong Kong, Civil Engineering Office Hong Kong Government (1996)
3) Japan Sewagewater Works Association, Manual of Planning for Sewage System in River Basins (1999) (in Japanese)

Notes:

1) Value of Cattle is for field breeding.
2) Value of Hog is for breeding in facilities without flash cleaning.
3) Value marked(*) is for COD (Cr) method, and value marked (**) is for COD (Mn) method. Generally, COD (Cr) value is 2.0-2.5 times of COD (Mn).

Table 1.3.3 Unit Pollutant Load from Industrial Effluents of Major Cities in the Pearl River Estuary

		Guangzhou	Shenzhen	Zhuhai	Average of 3 cities	Guangdong
Discharge	Ton/day/10^8RMB	382	42	189	214	307
COD	Kg/day/10^8RMB	71.2	2.5	54.7	40.2	94.4
Suspended Solid(SS)	Kg/day/10^8RMB	34.3	0.9	15.6	17.8	57.6
Mercury(Hg)	g/day/10^8RMB	0.063	0.000	0.000	0.028	0.056
Cadmium(Cd)	g/day/10^8RMB	0.392	0.000	0.000	0.176	1.012
Chromium(Cr)	g/day/10^8RMB	1.599	0.553	0.160	0.970	6.220
Lead(Pb)	g/day/10^8RMB	9.140	0.201	0.695	4.276	36.234
Arsenic(As)	g/day/10^8RMB	4.202	0.000	0.000	1.885	13.060
Phenol	g/day/10^8RMB	14.235	0.000	0.000	6.385	18.561
Cyanide(CN)	g/day/10^8RMB	5.064	0.352	0.053	2.426	10.731
Oil	kg/day/10^8RMB	1.215	0.003	0.054	0.553	0.529
Sulfur(S)	kg/day/10^8RMB	0.051	0.001	0.083	0.034	0.139

Estimated based on 'China Environment Yearbook (1998)'

Table 1.3.4 Range of Industrial Effluents Water Quality in Japanese Factories

(mg/L)

Category of Industry	BOD	COD	T-N	T-P
Food: Meat products	300-600	200-300	50-80	10-15
Food: Dairy products	50-350	50-200	30-40	5-8
Wood: Wood products	20-240	120-300	0.5-2.0	1-7
Paper: Pulp and Paper products	300-2000	500-3000	70-100	2-3
Chemicals: Oil and Fat products from Animals and Plants	100-2000	100-1500	20-30	40-80
Chemicals: Inorganic products	20	40	60-100	2-50
Chemicals: Organic products	100-1000	1000-1500	250-350	220-350
Petroleum: Oil refinement	20-200	100	20-30	5
Representative value of above all	400	400	50	10

Estimated based on 'Japan Sewagewater Works Association, Manual of Planning for Sewage System in River Basins (1999) (in Japanese)'

Table 1.3.5 Integrated Wastewater Discharge Standard (GB8978-1996)

items	Kind of industry	Built before 1997.12.31			Built after 1998.1.1		
		Class of Receiving water body			Class of Receiving water body		
		1st Class	2nd Class	3rd Class	1st Class	2nd Class	3rd Class
BOD_5 (mg/L)	Sugar refining by sugar cane Tanning Fiberboard by wet method	30	100	600	20	60	600
	Sugar refining by beat Alcohol Synthetic seasoning Leather Synthetic fiber	30	150	600	20	100	600
	Sewage treatment plant	20	30	-	20	30	-
	Other industrial factories	30	60	300	20	30	300
COD_{Cr} (mg/L)	Sugar refining by beat Coking Synthetic fatty acid Fiberboard by wet method Dying Wool washing Organ phosphorus chemicals	100	200	1000	100	200	1000
	Synthetic seasoning Alcohol Medicine materials Biological medicine materials Tanning Leather Synthetic fiber	100	300	1000	60	300	1000
	Oil chemicals	100	150	500	60	120	500
	Sewage treatment plants	60	120	-	60	120	-
	Other industrial factories	100	150	500	100	150	500
NH_3-N (mg/L)	Medicine materials Dying Oil chemicals	15	50	-	15	50	-
	Other industrial factories	15	25	-	15	25	-
PO_4-P (mg/L)	All industrial factories	0.5	1.0	-	0.5	1.0	-

Source: State Standards for Environmental Qualities and Pollutant Discharges (2nd edition), 1998, China Standard Publishing company

Table 1.3.6 Unit Pollutant Load from Non-Point Sources

(ton/km²/year)

	BOD	COD	T-N	T-P	Source
Urban Area	25	35*	0.5	0.28	1)
	12.8	14.1*	1.97	0.36	2)
Cultivated Land	2.5	13.5*	1	0.068	1)
(Paddy Field)	13.7	13.7*	1.90	0.204	2)
(Dry Field)	1.0	1.0**	7.6	0.069	2)
Fruit Land	6.5	15*	13	0.55	1)
Afforested Land	2.1	2.1**	0.36	0.029	2)
Other Land	3.3	20*	0.84	0.10	1)
	2.1	2.1**	0.36	0.03	2)

Sources:

1) Liu Xinyuan, Fan Liping and Luo Chengping, Water Resources Utilization and Coastal Water Environment in Shenzhen City, Symposium on Coastal Ocean Resources and Environment '97 (1997) (in Chinese)

2) Japan Sewagewater Works Association, Manual of Planning for Sewage System in River Basins (1999) (in Japanese)

Notes:

Value marked (*) is for COD (Cr) method, and value marked (**) is for COD (Mn) method. Generally, COD (Cr) value is 2.0-2.5 times of COD (Mn).

Table 1.3.7 Frame Statistics for the Estimation of Human Life and Livestock Pollutant Loads

(10^4 person/heads)

	Humans	Cattle	Buffalo	Hog
Whole City Area				
Guangzhou	674.14	3.47	6.66	87.11
Shenzhen	394.96	0.08	0.02	30.09
Dongguan	148.77	0.65	0.40	77.69
Zhongshan	130.08	0.03	0.11	18.21
Zhuhai	69.48	0.05	0.19	15.01
Foshan	324.98	0.20	2.88	65.92
Hong Kong	668.72	-	-	-
Macau	42.20	-	-	-
Direct Runoff Area (D.R.A.)				
Guangzhou D.R.A.	89.55	0.08	0.17	11.00
Shenzhen D.R.A.	305.89	0.04	0.01	15.00
Dongguan D.R.A.	12.81	0.06	0.04	7.77
Zhongshan D.R.A.	13.00	0.00	0.01	1.82
Zhuhai D.R.A.	40.07	0.08	0.13	7.73
Hong Kong D.R.A.	165.00	0.00	0.00	0.00
Macau D.R.A.	42.20	0.00	0.00	0.00
Total of D.R.A.	668.52	0.26	0.36	43.32

Source: China Statistical Yearbook (1999), Guangdong Statistical Yearbook (1999), Guangzhou Statistical Yearbook (1999), Shenzhen Statistics and Information Yearbook (1999), Zhuhai Statistical Yearbook (1998), Dongguan Statistical Yearbook (1999), Hong Kong 1999

Table 1.3.8 Frame Statistics for the Estimation of Industrial Effluents (Industrial Products)

	Manufacturing	Mining & Quarrying	Electricity, Gas and Water	Total	Unit
Whole City Area					
Guangzhou	1,747.551	58.068	30.329	1,835.948	10^8RMB
Shenzhen	1,636.252	0.483	23.932	1,660.667	10^8RMB
Dongguan	456.578	0.269	24.411	481.259	10^8RMB
Zhongshan	442.287	0.000	3.882	446.169	10^8RMB
Zhuhai	512.210	0.319	2.324	514.852	10^8RMB
Foshan	1,254.953	1.376	16.323	1,272.652	10^8RMB
Hong Kong	821.560	2.730	292.200	1,116.490	10^8HKD
Macau	133.527	0.174	18.230	151.932	10^8MOP
Direct Runoff Area (D.R.A.)					
Guangzhou D.R.A.	489.224				10^8RMB
Shenzhen D.R.A.	1,491.503				10^8RMB
Dongguan D.R.A.	38.084				10^8RMB
Zhongshan D.R.A.	44.201				10^8RMB
Zhuhai D.R.A.	479.095				10^8RMB
Hong Kong D.R.A.	202.712				10^8HKD
Macau D.R.A.	133.527				10^8MOP
Total of D.R.A.	2,894.515				10^8RMB

Notes: 1 HKD = 1.06 RMB, 1 MOP = 1.03 RMB

Source: China Statistical Yearbook (1999), Guangdong Statistical Yearbook (1999), Guangzhou Statistical Yearbook (1999), Shenzhen Statistics and Information Yearbook (1999), Zhuhai Statistical Yearbook (1998), Dongguan Statistical Yearbook (1999), Hong Kong 1999

Table 1.3.9 Frame Statistics for the Estimation of Non-Point Pollutant Loads

(km²)

	Total Land	Urban Land & Bare Land	Forested Land	Cultivated Land			Other Land
				Total	Paddy	Dry	
Whole City Area							
Guangzhou	7,434	1,740	3,086	1,254	1,118	137	1,353
Shenzhen	2,020	607	897	41	31	10	475
Dongguan	2,465	718	613	442	352	90	692
Zhongshan	1,800	534	339	427	232	195	500
Zhuhai	1,630	475	510	254	197	57	391
Foshan	3,814	1,131	736	864	550	314	1,083
Hong Kong	1,097	497	220	61	-	-	319
Macau	27	11	7	4	2	2	5
Direct Runoff Area (D.R.A.)							
Guangzhou DRA	188	30	40	46	26	20	72
Shenzhen DRA	861	398	164	145	52	93	154
Dongguan DRA	210	79	45	47	22	25	39
Zhongshan DRA	287	59	89	53	19	34	86
Zhuhai DRA	251	96	70	34	9	25	51
Hong Kong DRA	397	147	108	35	10	25	107
Macau DRA	27	11	7	4	2	2	5
Total of D.R.A.	2,221	820	523	364	140	224	514

Source: 1) Values of each city are based on following statistics.

China Statistical Yearbook (1999), Guangdong Statistical Yearbook (1999), Guangzhou Statistical Yearbook (1999), Shenzhen Statistics and Information Yearbook (1999), Zhuhai Statistical Yearbook (1998), Dongguan Statistical Yearbook (1999), Hong Kong 1999

2) Values of D.R.A. are estimated by the satellite analysis of this study.

Table 1.3.10 BOD Loads from Direct Runoff Area around the Pearl River Estuary

(kg/day)

	Human	Livestock	Industry	Non-point	Total
Guangzhou DRA	18,806	5,550	19,569	3,967	47,891
Shenzhen DRA	64,237	7,382	59,660	31,803	163,082
Dongguan DRA	2,690	3,871	1,523	6,917	15,001
Zhongshan DRA	2,730	898	1,768	6,137	11,533
Zhuhai DRA	8,415	3,922	19,164	7,845	39,346
Hong Kong DRA	34,650	0	8,595	12,101	55,346
Macau DRA	8,862	0	5,501	919	15,283
Total	140,389	21,624	115,821	69,689	347,522

Table 1.3.11 COD Loads from Direct Runoff Area around the Pearl River Estuary

(kg/day)

	Human	Livestock	Industry	Non-point	Total
Guangzhou DRA	15,671	2,993	19,569	4,672	42,904
Shenzhen DRA	53,531	3,927	59,660	26,452	143,569
Dongguan DRA	2,242	2,073	1,523	6,009	11,848
Zhongshan DRA	2,275	479	1,768	6,503	11,025
Zhuhai DRA	7,012	2,121	19,164	6,809	35,106
Hong Kong DRA	28,875	0	8,595	11,045	48,515
Macau DRA	7,385	0	5,501	785	13,672
Total	116,991	11,592	115,821	62,275	306,678

Table 1.3.12 T-N Loads from Direct Runoff Area around the Pearl River Estuary

(kg/day)

	Human	Livestock	Industry	Non-point	Total
Guangzhou DRA	3,806	3,263	2,446	798	10,313
Shenzhen DRA	13,000	4,365	7,458	3,268	28,091
Dongguan DRA	544	2,282	190	877	3,895
Zhongshan DRA	553	531	221	1,173	2,478
Zhuhai DRA	1,703	2,303	2,395	885	7,286
Hong Kong DRA	7,013	0	1,074	1,127	9,214
Macau DRA	1,794	0	688	86	2,567
Total	28,412	12,743	14,478	8,215	63,847

Table 1.3.13 T-P Loads from Direct Runoff Area around the Pearl River Estuary

(kg/day)

	Human	Livestock	Industry	Non-point	Total
Guangzhou DRA	582	123	489	64	1,258
Shenzhen DRA	1,988	153	1,492	407	4,039
Dongguan DRA	83	83	38	92	296
Zhongshan DRA	85	19	44	93	240
Zhuhai DRA	260	88	479	103	930
Hong Kong DRA	1,073	0	215	161	1,448
Macau DRA	274	0	138	12	424
Total	4,345	464	2,896	932	8,637

1.4 Atmospheric Deposition

The load of atmospheric deposition that falls directly into the Pearl River Estuary cannot be ignored. Atmospheric deposition includes dry fall-out and rain. There, available data concerning atmospheric deposition on the open sea from the estuary is scarce because the measurement is difficult due to location, and the length of time required to get meaningful averages.

Therefore, the unit load was determined from a survey on the land in Japan was adopted. The data are shown in Table 1.4.1. By applying average values from this table to the Pearl River Estuary, the effluent pollutant loads were calculated as follows.

- Area of the Pearl River Estuary (marine area): 4,000km^2
- COD unit pollutant load : 4.22 ton/km^2/year
- T-N unit pollutant load : 1.33 ton/km^2/year
- T-P unit pollutant load : 0.053 ton/km^2/year

- COD load : 46.2 ton/day (15.1 % of the effluent load from land area)
- T-N load : 12.4 ton/day (19.4 % of the effluent load from land area)
- T-P load : 0.58 ton/day (6.7 % of the effluent load from land area)

Note: Load from land area is shown in Tables 1.1.17 to 1.1.19 in the above section.

1.5 Pollutant Load to the Pearl River Estuary

Pollutant loads to the Pearl River Estuary included four outlets, coastal area and atmospheric deposition are summarized in Table 1.5.1.

Total pollutant loads were calculated as follows.

- COD load : 526,000 ton/year
- T-N load : 436,000 ton/year
- T-P load : 14,000 ton/year

The polluted load of the present condition to be used for the water quality simulation model is summarized in Figure 1.5.1.

Table 1.4.1 Pollutant Load from Atmospheric Deposition in Japan

(ton/km²/year)

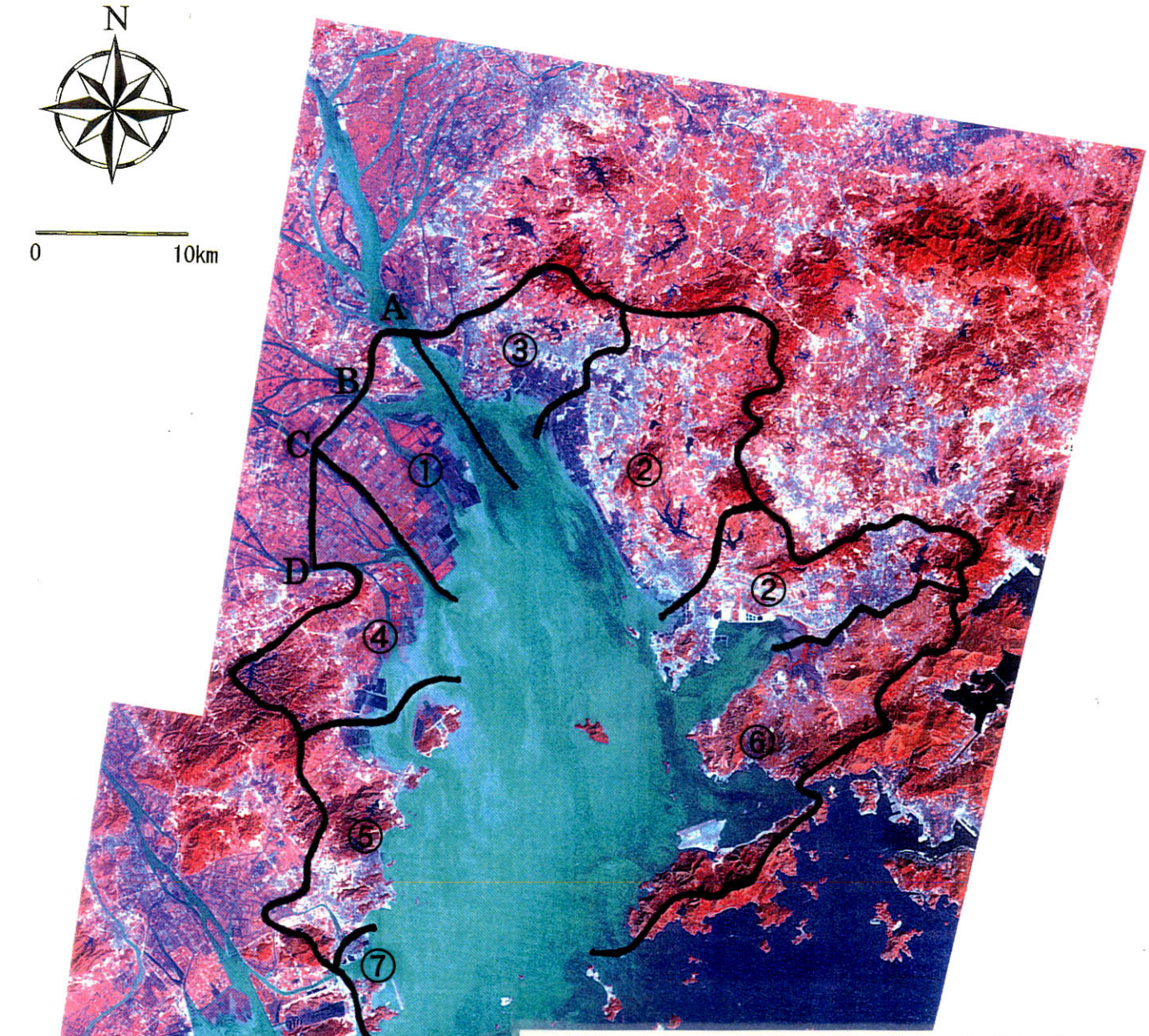
	COD	T-N	T-P
Minimum	1.72	0.45	0.009
Maximum	8.64	3.06	0.262
Average	4.22	1.13	0.053

Source: Japan Sewagewater Works Association, Manual of Planning for Sewage System in River Basins (1999) (in Japanese)

Table 1.5.1 Pollutant Load to the Pearl River Estuary

(ton/year)

	COD	T-N	T-P
Four outlets	397,145	408,169	10,682
Coastal area	67,163	13,983	1,892
Atmospheric deposition	16,880	4,520	212
Total load	525,948	435,991	14,046



Pollutant Load to the Pearl River Estuary in Rainy Season

Soueces			Discharge m3/sec	COD ton/day	T-N ton/day	T-P ton/day
River Load	A	Humen	3,761	714.9	783.1	20.1
	B	Jiaomen	3,518	565.4	732.5	16.7
	C	Hongqimen	1,300	170.7	270.7	5.4
	D	Henmen	2,277	365.9	474.1	10.8
	River-Total		10,856	1,816.9	2,260.5	53.1
Nonpoint Source Load from Coastal Area	①	Guangzhou		42.9	10.3	1.3
	②	Shenzhen		143.6	28.1	4.0
	③	Dongguan		11.8	3.9	0.3
	④	Zhongshan		11.0	2.5	0.2
	⑤	Zhuhai		35.1	7.3	0.9
	⑥	Hong Kong		48.5	9.2	1.4
	⑦	Macau		13.7	2.6	0.4
	Coastal-Total			306.6	63.8	8.6
Atmospheric deposition				23.1	6.2	0.3
Total of Pollutant Load			10,856	2,146.7	2,330.5	62.0

Figure 1.5.1 Pollutant Load for the Water Quality Simulation

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.

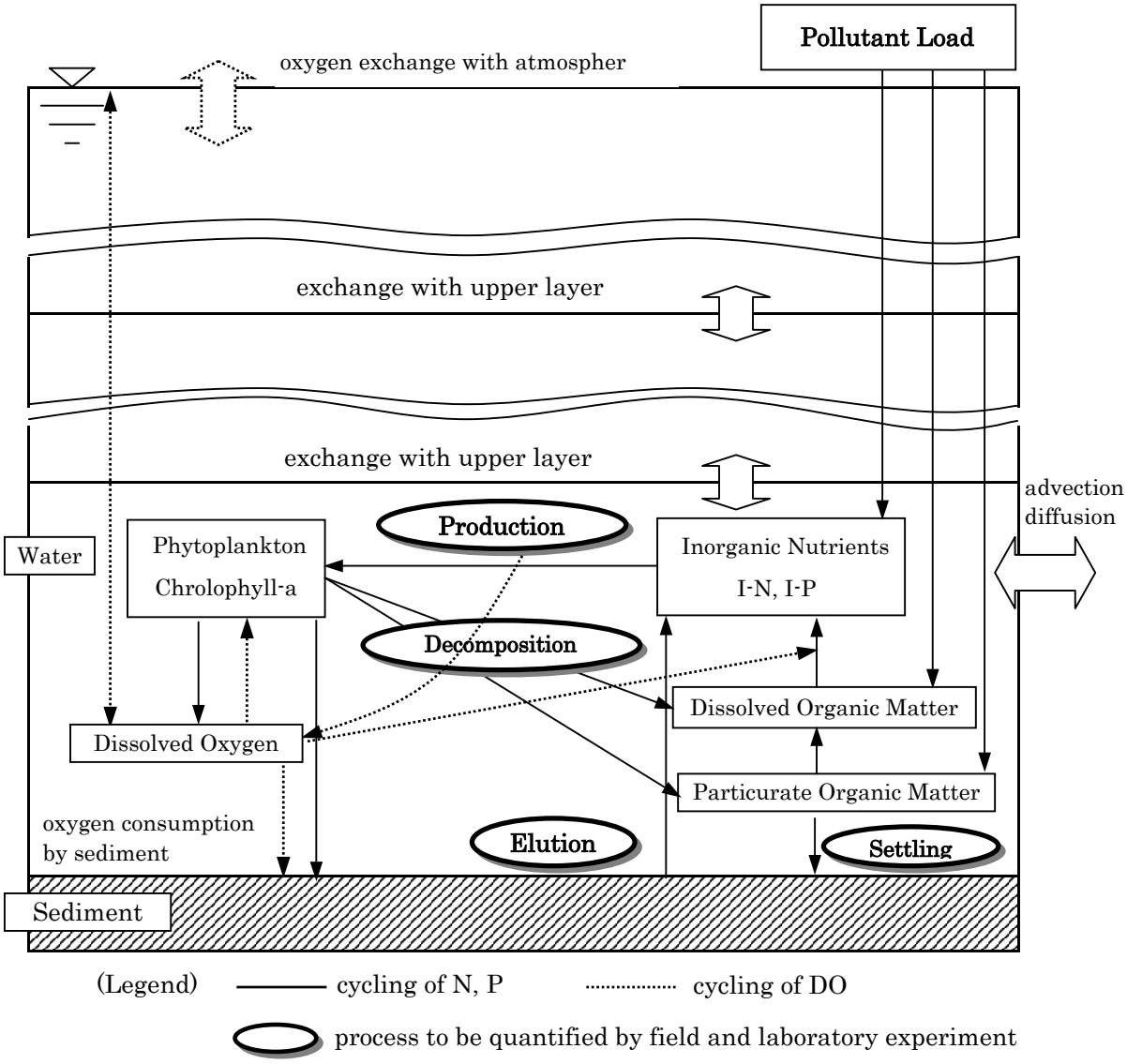


Figure 2.3.1 A Conceptual Model of Three-Dimensional Biochemical Cycle Processes

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.

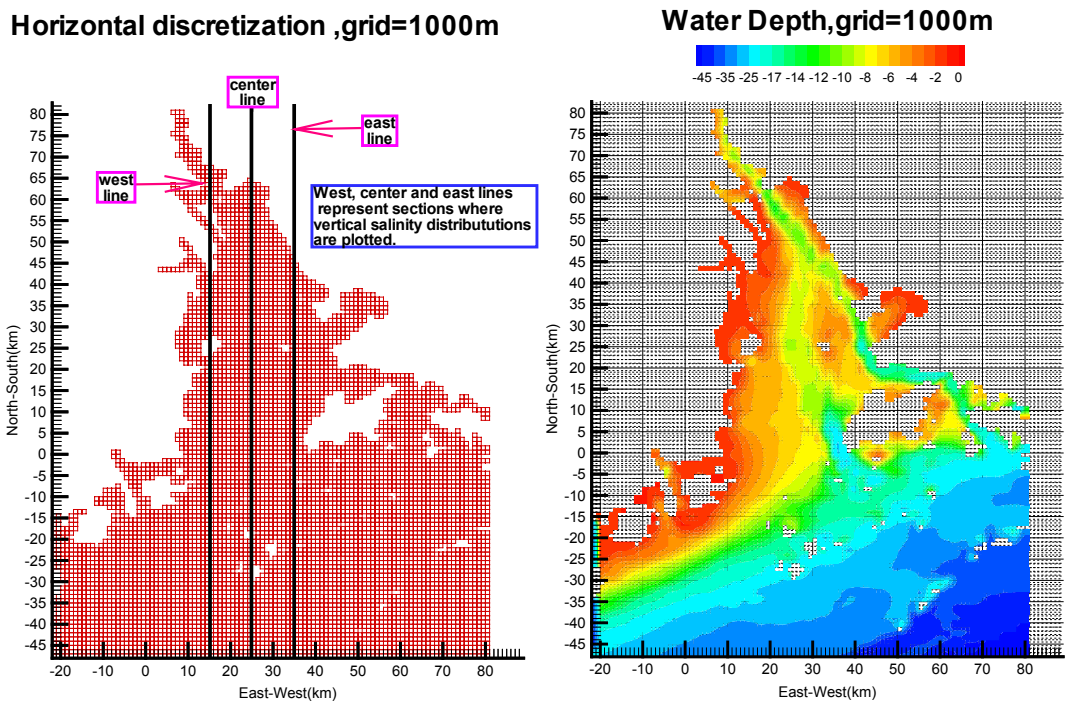


Figure 2.4.1 Extended Computational Domain and its Bathymetry.

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

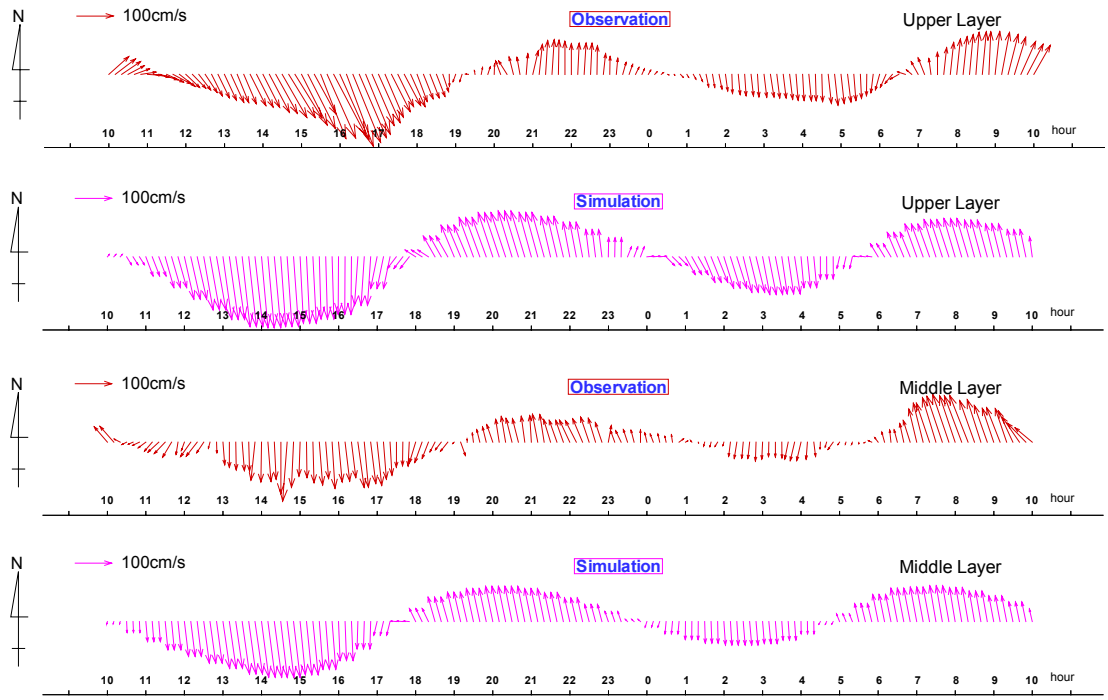
1) Comparison of Velocity Vectors

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.

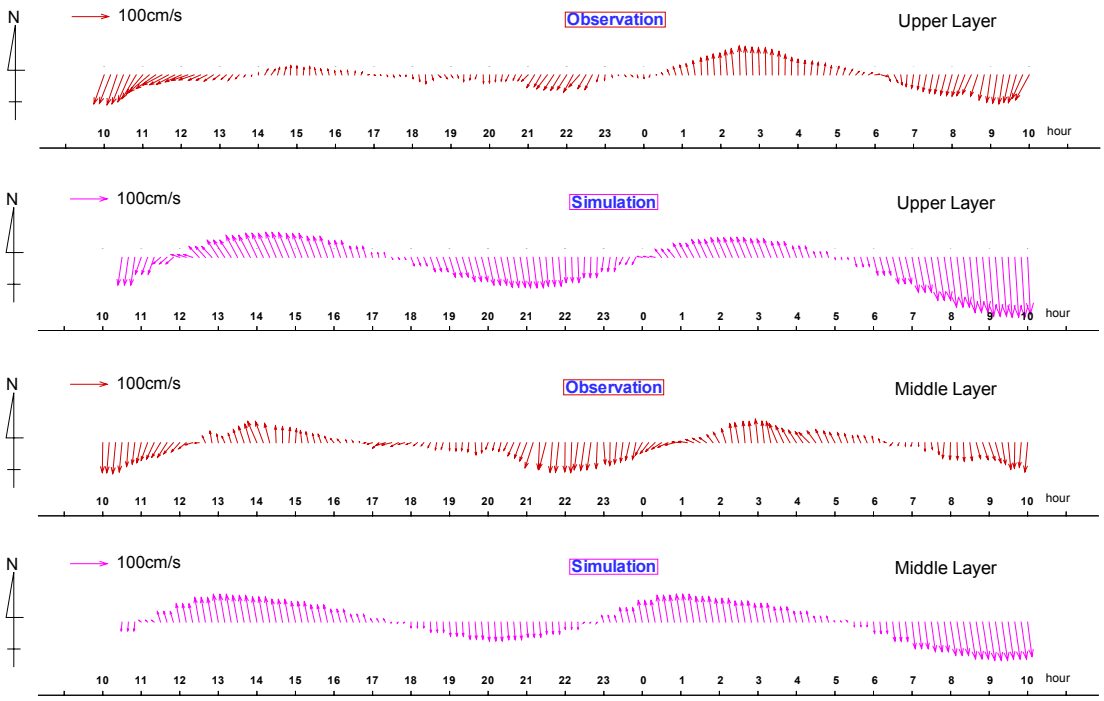
2) Comparison of Salinity

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)

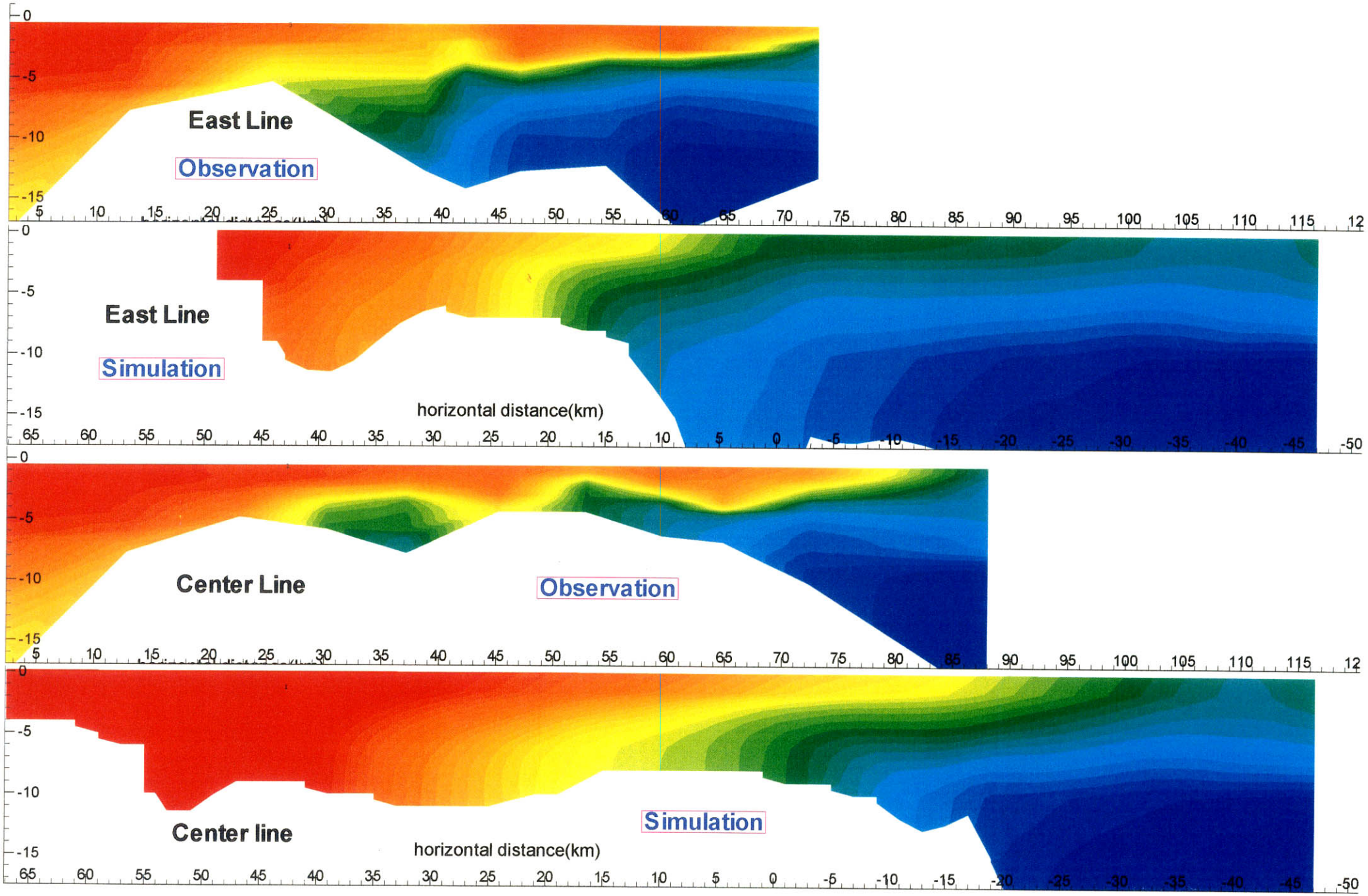


Figure 2.4.4 Comparison of Vertical Salinity Distribution in Neap Tide between Observation and Simulation

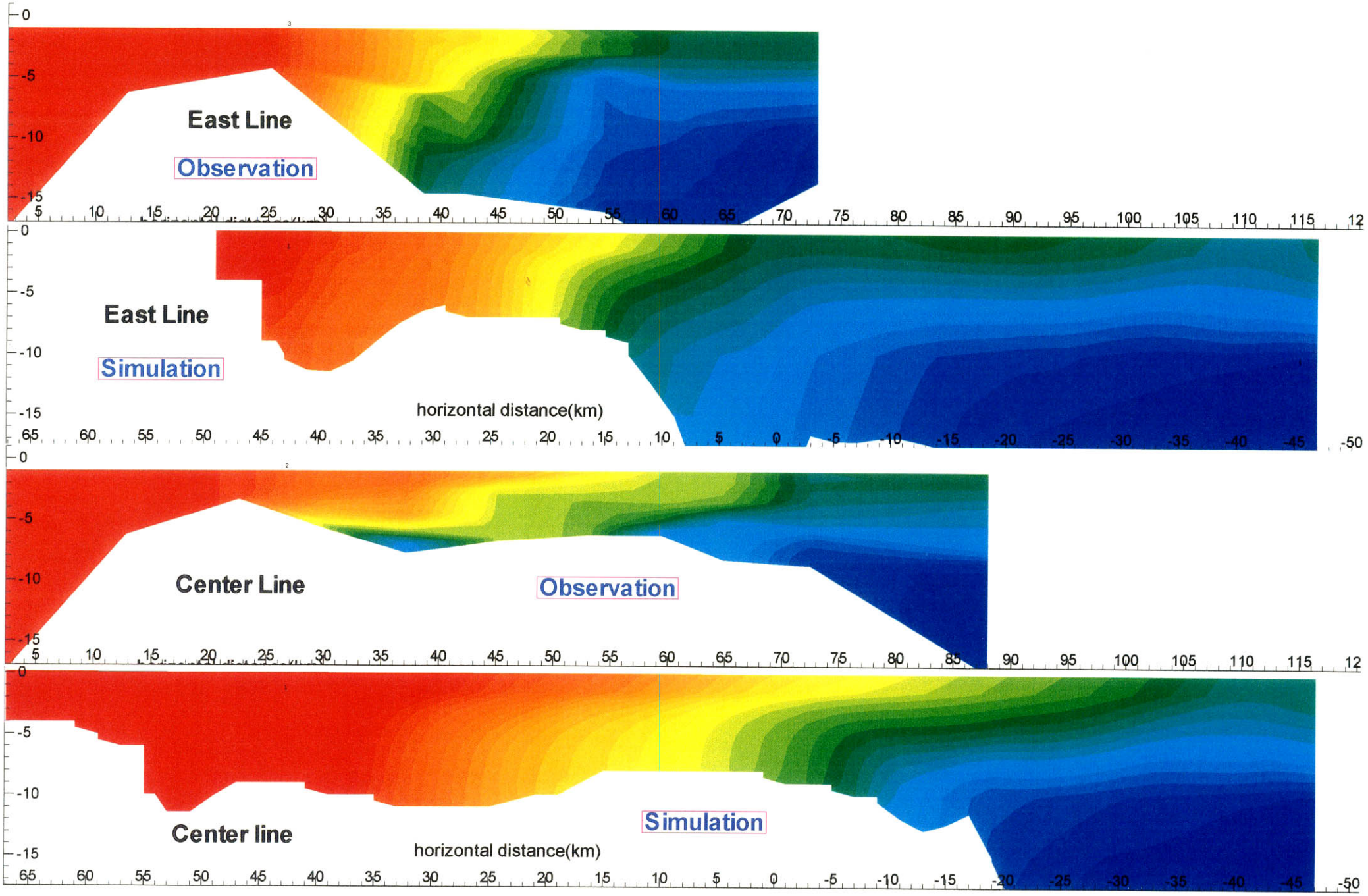


Figure 2.4.5 Comparison of Vertical Salinity Distribution in Spring Tide between Observation and Simulation