

3.3 POLLUTION LOAD ANALYSIS

3.3.1 METHODOLOGY

The basic purpose of pollution load analysis is to estimate pollution load reaching the bay through each river basin and to estimate the contribution of pollution sources. Estimated pollution load has been used as input data for the water quality simulation model as well as base information for the estimation of pollution loads in the future. Estimates are made for the years 2000, 2010 and 2020 based on population estimates of the year in question. Further load estimates has been made assuming an increasing part of the population being served by at treatment plant. The load estimates has all been used for simulations of the water quality in the bay. *Figure 3.8* shows the schematic diagram of pollution load estimation.

(1) Category of Pollution Sources

Pollution sources are categorized into point and non-point sources. Point sources can be defined as known loads for which the location of discharge is known. WWTP discharge and large industry discharge are point sources. All other sources are categorized as non-point sources which include the areal pollution load originating from urban, agricultural and natural processes.

(2) Estimation of Pollution Load

Pollution loads are estimated for the following.

Point sources

- Generation of pollution load by population
- Pollution load discharge by WWTP and large industries
- Pollution load discharged by small-scale treatment units for shopping centers, hospitals, schools etc.

Non-Point sources

- Areal pollutant load reaching the river due to natural, agricultural and urban origin

(3) Pollution Load Reaching the Bay through Rivers

Based on the monitored river water quality and estimated river flow, monitored pollution load (L_{MON}) to the bay through each river basin is estimated to compare the pollution load generated and pollution load discharged to the bay utilizing water quality monitoring data and estimated basin discharge.

3.3.2 RIVER BASIN AND SEWER SYSTEM

Figure 3.9 shows boundaries of river basins and sewer systems. Sewer system boundary of CEDAE Sewer Master Plan is reviewed. Existing WWTP locations are also shown in the figure.

3.3.3 POLLUTION LOAD GENERATED BY HUMAN WASTE

Population connected to the WWTP (referred to as Sewage Treatment Population) is estimated based on the sewer service ratio and the incoming flow to WWTP. The below listed per capita pollution load generation for BOD, total N, total P and E. coli bacteria is used:

BOD: 54 g BOD/day, TN: 10 g N/day, TP: 2.5 g P/day E. coli: 10^9 /day

Pollution load generated ($L_{POP-without\ sewer}$) is calculated based on the unit per capita generation and population which is not connected to the sewerage for each river basin.

Table 3.4 shows the population by river basin based on the year 2000 census. *Table 3.5* shows estimate of BOD₅ load generation by total population classified into population connected to WWTP and population not connected to WWTP. Total BOD₅ load generated is 445 ton/day out of which (75 %) of the pollution load generated is not treated at WWTP.

3.3.4 POLLUTION LOAD AT WWTP

Pollution load discharged through WWTP ($L_{\text{WWTP-Dis}}$) is obtained considering efficiency of WWTP. As shown in *Table 3.6*, total BOD₅ load to WWTP is 110 ton/day out of which 73 ton/day is removed resulting in 37 ton/day discharged to “waterbody” of rivers or directly to the Bay. Six of the listed WWTP discharge to the Bay. These are: Icarai, San Goncalo, Penha, Alegria, I. Do Governado, I. Do Paqueta.

3.3.5 POLLUTION LOAD DISCHARGED BY INDUSTRIES

FEEMA is carrying out an action program to control the pollution load from industries and has established a database of industrial pollution load of major polluters and implementing a program to reduce pollution load of industries. Under these program, 455 industries are selected. Out of these, 55 industries are classified as Priority 1 industries, which discharge 80% of the pollution load. A database of pollution load discharged by the major polluting industries which consists of 155 industries including Priority 1 and Priority 2 industries was completed by FEEMA through self-reporting of industries and the data was obtained by the Study Team. Total BOD pollution load of these 155 industries in year 2000 is estimated to be 9.64 ton/day. Number of industries not covered under the above are small and medium scale industries but are large in number. Pollution load of these industries is approximately 12 ton/day.

Data on nutrient load from industries have not been available, therefore ratios for TN/BOD and TP/BOD of 0.44 g N/g BOD and 0.079 g P/g BOD has been used to estimate the industrial total N and total P load (Diego-Mclone *et al*, 2000)

3.3.6 OTHER POINT SOURCES (SMALL- SCALE TREATMENT UNITS)

Small-scale treatment units for developments such as condominium, hospitals, shopping centers, schools etc. has been registered with FEEMA under the “non-industry” category and data is obtained for 69 such units, on their location and pollution load.

Distribution of total industrial and non-industrial pollution load by river basin is shown in *Table 3.7*.

3.3.7 AREAL POLLUTION LOAD

Areal pollution load due to natural, agricultural or urban sources can be estimated for a known section of basin if monitoring data is available at the inlet and outlet of the river through the basin and the point source pollution load is known. Only one such location is available in the Macacu River at FEEMA Monitoring location MC-967 which coincides with SERLA river gauging station 18. At this location, which is the uppermost sub-basin where point sources are negligible, pollution load is due to natural origin for which a reasonable number of flow and water quality measurements are available for the year 1994, year 1999 and year 2000. Relationship between specific BOD load (L_{BOD}) and specific discharge (Q_s) is obtained through regression (*Figure 3.10*) as follows:

$$L_{\text{BOD}}=0.268Q_s^{0.824}$$

Where, L_{BOD} is in $\text{kg}/(\text{km}^2 \times \text{d})$ and Q_s is in $\text{L}/(\text{km}^2 \times \text{s})$.

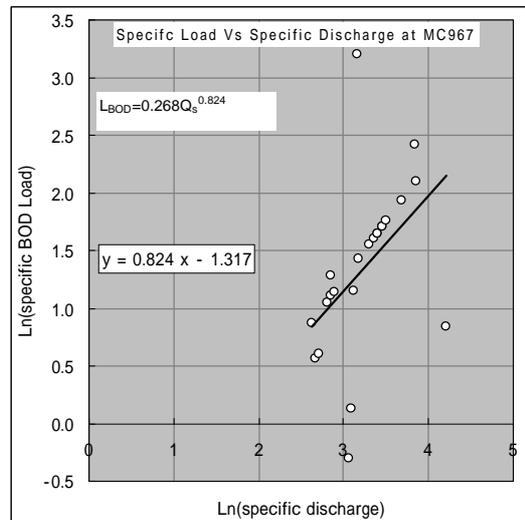


Figure 3.10 Relationship between Specific Load and Specific Discharge at MC967

Relationship between specific TN load (L_{TN}), TP load (L_{TP}), PO₄-P load (L_{PO_4}), DIN load (L_{DIN}) and specific discharge (Q_s) is obtained through regression as follows:

$$L_{\text{TN}}=0.072Q_s^{0.9142}$$

$$L_{\text{TP}}=0.0032Q_s^{1.3016}$$

$$L_{\text{PO}_4}=0.00286Q_s^{0.9905}$$

$$L_{\text{DIN}}=0.0821Q_s^{0.6201}$$

In the absence of monitored data, the above relationships have been utilized to estimate the real pollution load though they don't include the load during extreme rainfall events.

3.3.8 RUN OFF RATIO OF GENERATED POLLUTION LOAD

Monitored pollution load (L_{MON}) is calculated for river basins utilizing water quality monitoring data where available and estimated basin discharge. There were six measurements of water quality in year 2000 and monitoring of water quality is generally not during storms. To include the load due to rain, it is assumed that the water quality of the river remains constant throughout the year and is obtained from the average of monitored quality. For those stations without water quality monitoring station, approximate estimation is made based on either population density or area depending on the type of basin. Estimated discharge load to the bay for year 2000 is 252 ton/day.

For each of the river basin, run-off ratio is calculated. Run-off ratio is calculated as total pollution load (L_{RIVER}) discharged to the rivers (as shown in *Table 3.7*) which is the sum of pollution load discharged through WWTP ($L_{\text{WWTP-Dis}}$), pollution load generated by large industries (L_I), small-scale treatment units (L_{NI}), and areal pollution load (L_{AREAL}) to the monitored pollution load (L_{MON}).

$$L_{\text{RIVER}} = L_{\text{WWTP-Dis}} + L_{\text{POP-without sewer}} + L_{\text{I}} + L_{\text{NI}} + L_{\text{AREAL}}$$

$$\text{Run-off Ratio} = L_{\text{MON}} / L_{\text{RIVER}}$$

Preliminary estimate of the run-off ratio is 0.67 for the whole of the basin of Guanabara Bay assuming that all of the pollution load generated by the population not treated by the WWTP reaches the bay.

When comparing the monitored load with the generated load basin by basin a great variation in the Run-off ratio can be observed. In some cases the monitored load is higher than the generated load, a great deal of this variation can be related to lack of frequent and consistent measurements of both concentrations and discharge on the same location in the river.

It has therefore decided to estimate the run-off ratio for each major basin based on assumed degradation rates for of BOD, TN, TP and E. coli and an estimated the average retention for the water each basin. The mineralization of BOD, the death of E. Coli, denitrification and other immobilization of TN and immobilization of TP is described by the below equation exemplified by BOD:

$$L = \text{BOD} * e^{-K*t}$$

Where K is the daily mineralization rate (1/d) and t is the average time for pollutants in a specific basin to flow from the source to the Bay. The average retention time is estimated from the distance of the pollution centers in term of cities or industrial areas to the Bay and a velocity of the water in the river. The average velocity of the water is set to 0.05 m/sec. K values for different components are set to:

$$\text{BOD: } K=0.3 \text{ 1/d, } \text{TN: } K=0.2 \text{ 1/d, } \text{TP: } K=0.1 \text{ 1/d } \text{E. coli: } K=0.8 \text{ 1/d}$$

Please refer to *Supporting 5* on Pollution Load Analysis for run-off ratios by river basin .

3.3.9 POLLUTION LOAD DISCHARGED TO BAY

The total BOD load reaching the Bay through rivers after self-purification and directly from WWTP discharging to the Bay is presented in the *Table 3.8*. Please refer to *Supporting 5* on Pollution Load Analysis for total N, P and E. coli load reaching the bay after self-purification.

In year 2000, the load to the bay is estimated to be 275 ton BOD/day, 72 ton TN/day, 18.4 ton TP/day and 3.07×10^{15} E. coli bacteria per day.

3.3.10 POPULATION IN YEAR 2010 AND 2020

To be able to predict the load to the Bay in the future, the population size has to be predicted for the future. In the present study, year 2010 and year 2020 has been chosen as future reference years. The average annual growth ratio (AAGR) until year 2020 for the whole basin has been estimated to be 0.67 %. The annual growth ratios however vary over time and with administrative areas and thereby also with basins.

Total population in the Bay catchment was 8,290,300 in year 2000. The projections of the population size for 2010 and 2020 by river basin are presented in *Table 3.4*. The population size is expected to increases to 9,013,026 in year 2010 and 9,619,561 in year 2020.

3.3.11 FUTURE LOAD AND LOAD SCENARIOS

The load of BOD and nutrients has been estimated to be able to predict the future water quality in the Bay with the eutrophication model.

A series of simulations has been conducted with the purpose of estimating the load at which standards of 10 mg BOD/l and 5 mg BOD/l are achieved in the Bay. The series include simulations of year 2000, year 2010 and year 2020 populations and industrial development. In *Table 3.9*, the scenarios are presented under title “Water Quality in Bay Relative to Load”. The table includes columns with data for generated load, load to Bay, population and population with sewage treatment. Three set of reduced domestic and industrial loads are included in this series: one with 80 % BOD, 30 % TN and 50 % TP reduction of domestic and industrial load after existing treatment but before self purification in rivers; one with 90 % BOD, 35 % TN and 80 % TP reduction; and one with 90% BOD, 80% TN and 80% TP load reduction. The small natural background load is the same for all scenarios.

A second series of simulations (under title “PDBG1” in *Table 3.9*) has been conducted predicting the water quality in the Bay implementing treatment according to the PDBG1 plan for populations and industrial load of year 2000, year 2010 and year 2020. The population with sewage treatment is assumed to increase with the increase in population within existing areas connected to a treatment plant.

A third series of simulations (under title “Feasibility Study” in *Table 3.9*) has been conducted estimating the water quality in year 2010 using a Feasibility Plan with about 55 % of the population connected to a treatment plant. One scenario is labeled “Year 2010 Feasibility Study” assuming secondary treatment removing 90 % BOD, 25 % TN and 20 % TP for all plants except for 3 plants (Icarai, Sarapuí & Puvuna) which all have primary treatment with chemical precipitation giving a reduction of 55% BOD, 35 % TN and 80 % TP. And the other scenario is where all treatment plants have secondary treatment with chemical precipitation reducing the load with 90 % for BOD, 30 % for TN and 50 % for TP.

And fourth series of load scenarios (under title “Strategy Plan” in *Table 3.9*) has been prepared according to the Strategy Plan for year 2020 and for year 2035 using population size of year 2020. Scenario for year 2020 assumes all treatment plants have secondary treatment except Icarai, Sarapuí and Puvuna, which has primary treatment with precipitation. Scenario for year 2035 assumes all treatment plants having secondary treatment but the population size is from year 2020. The last scenario for year 2035 assumes all treatment plants having 90% BOD, 30% TN and 50% TP removal.

References for section 3.3

Maria Louredes San Diego-Mclone, Stephen V. Smith, Vivian F. Nicolas. Stoichiometric Interpretations of C:N:P ratios in organic waste materials. *Marine Pollution Bulletin* Vol. No. 4 pp 325-330, 2000.

Table 3.4 Population in the Basin for Year 2000, 2010 and 2020

Region	No.	Basin Name	Basin Area (km ²)	Population (year 2000)	Population (year 2010)	Population (year 2020)	Sewage Treatment Population (year 2000)	Population without Sewage Treatment (year 2000)
E	B0100	B. Charitas	9.46	30,559	31,989	33,686	13,752	16,807
E	B0200	Canal Canto do Rio	6.21	90,467	94,702	99,725	40,710	49,757
E	B0300	B. Catedrar	7.57	91,390	95,668	100,742	41,126	50,264
E	B0400	B. Norte Centro	9.26	71,373	74,704	78,666	32,118	39,255
E	B0500	Rio Bomba	26.78	241,500	269,240	294,737	54,491	187,009
E	B0600	Rio Imboassu	29.43	157,098	178,840	198,168	19,987	137,111
NE	B0700	B. Itaoca	8.54	2,578	2,935	3,252	328	2,250
NE	B0800	Rio Alcântara	173.07	593,400	676,100	748,144	-	593,400
NE	B0900	Rio Cacerebú	811.34	256,254	311,969	353,046	-	256,254
NE	B1000	Rio Guapimirim	1,262.03	87,059	104,593	122,045	-	87,059
NE	B1100	Canal de Magé	17.08	33,734	43,009	49,309	-	33,734
NE	B1200	Rio Roncador	115.19	30,316	38,641	44,271	-	30,316
NE	B1300	Rio Iriri	19.63	4,659	5,938	6,800	-	4,659
NE	B1400	Rio Surui	84.44	22,169	28,253	32,354	-	22,169
NW	B1500	B. Maua	17.92	13,450	17,141	19,629	-	13,450
NW	B1600	Rio Estrela	348.88	385,215	451,791	508,699	-	385,215
NW	B1700	Rio Iguaçu	716.72	1,024,170	2,452,033	2,647,683	-	1,024,170
W	B1707	Rio Sarapuí		1,172,773			476,450	696,323
W	B1800	B. Cabo do Brito	19.72	54,430	62,559	70,699	21,772	32,658
W	B1900	Rio S. J. Meriti	154.26	1,397,082	1,453,394	1,506,410	415,833	981,249
W	B2000	Rio Irajá	50.95	682,128	706,115	728,215	544,770	137,358
W	B2100	Canal do Cunha	70.23	899,762	931,393	960,535	147,500	752,262
W	B2200	B. São Cristóvão	6.41	30,459	31,530	32,516	5,269	25,190
W	B2300	Canal do Mangue	37.95	440,731	456,225	470,500	73,454	367,277
W	B2400	B. Botafogo	21.68	262,642	271,875	280,382	8,970	253,672
I	B2500	I. do Governador	36.28	209,426	216,788	223,571	159,164	50,262
I	B2600	I. do Fundão	5.35	1,826	1,890	1,949		1,826
I	B2700	I. de Paquetá	2.21	3,586	3,712	3,828	3,227	359
I	B2800	I. do Engenho	0.98	-	0	0		-
I	B2900	I. de S. Cruz	1.10	-	0	0		-
Total			4,070.7	8,290,200	9,013,026	9,619,561	2,058,900	6,231,300

Source: This Study

Table 3.5 BOD Load Generation in the Basin for Year 2000

Region	No.	Basin Name	Basin Area (km ²)	Total BOD5 Load Generated (ton/d)	BOD5 Load to WWTP within Sewer System Area (ton/d)	BOD5 Load Generated by Population without Sewage Treatment
E	B0100	B. Charitas	9.46	1.7	0.7	0.9
E	B0200	Canal Canto do Rio	6.21	4.9	2.2	2.7
E	B0300	B. Catedrar	7.57	4.9	2.2	2.7
E	B0400	B. Norte Centro	9.26	3.9	1.7	2.1
E	B0500	Rio Bomba	26.78	13.0	2.9	10.1
E	B0600	Rio Imboassu	29.43	8.5	1.1	7.4
NE	B0700	B. Itaoca	8.54	0.1	0.0	0.1
NE	B0800	Rio Alcântara	173.07	32.0	-	32.0
NE	B0900	Rio Cacerebú	811.34	13.8	-	13.8
NE	B1000	Rio Guapimirim	1,262.03	4.7	-	4.7
NE	B1100	Canal de Magé	17.08	1.8	-	1.8
NE	B1200	Rio Roncador	115.19	1.6	-	1.6
NE	B1300	Rio Iriri	19.63	0.3	-	0.3
NE	B1400	Rio Surui	84.44	1.2	-	1.2
NW	B1500	B. Maua	17.92	0.7	-	0.7
NW	B1600	Rio Estrela	348.88	20.8	-	20.8
NW	B1700	Rio Iguaçu	716.72	55.3	-	55.3
W	B1707	Rio Sarapuí		63.3	25.7	37.6
W	B1800	B. Cabo do Brito	19.72	2.9	1.2	1.8
W	B1900	Rio S. J. Meriti	154.26	75.4	22.5	53.0
W	B2000	Rio Irajá	50.95	36.8	29.4	7.4
W	B2100	Canal do Cunha	70.23	48.6	8.0	40.6
W	B2200	B. São Cristóvão	6.41	1.6	0.3	1.4
W	B2300	Canal do Mangue	37.95	23.8	4.0	19.8
W	B2400	B. Botafogo	21.68	14.2	0.5	13.7
I	B2500	I. do Governador	36.28	11.3	8.6	2.7
I	B2600	I. do Fundão	5.35	0.1	-	0.1
I	B2700	I. de Paquetá	2.21	0.2	0.2	0.0
I	B2800	I. do Engenho	0.98	-	-	-
I	B2900	I. de S. Cruz	1.10	-	-	-
Total			4,070.7	447.7	111.2	336.5
Per capita BOD generation			54 g/(capita×d)			

Source: This Study

Table 3.6 BOD Load at WWTP for Year 2000

Region	No.	Basin Name	Basin Area (km ²)	Name of WWTP	Load to WWTP (ton/d)	Load Removed at WWTP (ton/d)	WWTP Load Discharged to Water Body (ton/d)
E	B0100	B. Charitas	9.46				
E	B0200	Canal Canto do Rio	6.21	Icarai	8.913	4.902	4.011
E	B0300	B. Catedrar	7.57				
E	B0400	B. Norte Centro	9.26				
E	B0500	Rio Bomba	26.78	San Goncalo	2.018	1.816	0.202
E	B0600	Rio Imboassu	29.43				
NE	B0700	B. Itaoca	8.54				
NE	B0800	Rio Alcântara	173.07				
NE	B0900	Rio Cacerebú	811.34				
NE	B1000	Rio Guapimirim	1,262.03				
NE	B1100	Canal de Magé	17.08				
NE	B1200	Rio Roncador	115.19				
NE	B1300	Rio Iriri	19.63				
NE	B1400	Rio Surui	84.44				
NW	B1500	B. Maua	17.92				
NW	B1600	Rio Estrela	348.88				
NW	B1700	Rio Iguaçu	716.72	Sarapuí Gramacho	25.728	14.311	11.427
NW	B1800	B. Cabo do Brito	19.72				
W	B1900	Rio S. J. Meriti	154.26	Pavuna Acarai	22.455	13.806	8.649
W	B2000	Rio Irajá	50.95	Penha	29.418	26.476	2.942
W	B2100	Canal do Cunha	70.23	Alegria	12.700	3.810	8.890
W	B2200	B. São Cristóvão	6.41				
W	B2300	Canal do Mangue	37.95				
W	B2400	B. Botafogo	21.68				
I	B2500	I. do Governador	36.28	I. do Governador	8.595	7.735	0.859
I	B2600	I. do Fundão	5.35				
I	B2700	I. de Paquetá	2.21	I. de Paquetá	0.174	0.141	0.017
I	B2800	I. do Engenho	0.98				
I	B2900	I. de S. Cruz	1.10				
Total			4,070.7		110.10	73.01	36.99

Source: This Study

Table 3.7 Summary of Total BOD Load for Year 2000

Region	No.	Basin Name	Basin Area (km ²)	WWTP Load (ton/d)	Untreated Domestic Load (ton/d)	Industrial/Non-industrial Load (ton/d)	Surface Pollution Load (ton/d)
E	B0100	B. Charitas	9.46	-	0.91	0.735	0.011
E	B0200	Canal Canto do Rio	6.21	4.01	2.69	0.033	0.007
E	B0300	B. Catedrar	7.57	-	2.71	-	0.009
E	B0400	B. Norte Centro	9.26	-	2.12	-	0.010
E	B0500	Rio Bomba	26.78	0.20	10.1	4.108	0.032
E	B0600	Rio Imboassu	29.43	-	7.40	-	0.033
NE	B0700	B. Itaoca	8.54	-	0.12	-	0.010
NE	B0800	Rio Alcântara	173.07	-	32.04	0.997	0.180
NE	B0900	Rio Cacerebú	811.34	-	13.84	0.183	0.722
NE	B1000	Rio Guapimirim	1,262.03	-	4.70	1.308	0.003
NE	B1100	Canal de Magé	17.08	-	1.82	0.000	0.022
NE	B1200	Rio Roncador	115.19	-	1.64	0.054	0.240
NE	B1300	Rio Iriri	19.63	-	0.25	-	0.022
NE	B1400	Rio Surui	84.44	-	1.20	0.051	0.118
NW	B1500	B. Maua	17.92	-	0.73	-	0.020
NW	B1600	Rio Estrela	348.88	-	20.80	2.398	0.674
NW	B1700	Rio Iguaçu	716.72	11.42	55.31	2.666	1.003
W	B1707	Rio Sarapuí			37.60	3.051	
W	B1800	B. Cabo do Brito	19.72	-	1.76	0.218	0.029
W	B1900	Rio S. J. Meriti	154.26	8.65	52.99	1.826	0.217
W	B2000	Rio Irajá	50.95	2.94	7.42	0.900	0.075
W	B2100	Canal do Cunha	70.23	8.89	40.62	3.049	0.108
W	B2200	B. São Cristóvão	6.41	-	1.26	0.245	0.010
W	B2300	Canal do Manguê	37.95	-	19.83	0.425	0.054
W	B2400	B. Botafogo	21.68	-	13.7	0.898	0.027
I	B2500	I. do Governador	36.28	0.86	2.71	0.097	0.052
I	B2600	I. do Fundão	5.35	-	0.1	-	0.008
I	B2700	I. de Paquetá	2.21	0.02	0.02	-	
I	B2800	I. do Engenho	0.98	-	-	-	
I	B2900	I. de S. Cruz	1.10	-	-	-	
Total			4,070.7	36.99	336.5	23.2	3.8

Source: This Study

Table 3.8 Total Load of BOD in ton/day Reaching Guanabara Bay After Self-purification in the Basins, Year 2000

No.	Basin Name	BOD Produced	BOD to bay	WWTP direct	Back ground	Total
100	B. Charitas	1.6	1.5		0.011	1.5
200	Canal Canto do Rio	2.7	2.5	4.01	0.007	6.5
300	B. Catedrar	2.7	2.5		0.009	2.6
400	B. Norte Centro	2.1	1.7		0.010	1.8
500	Rio Bomba	14.2	12.4	0.20	0.032	12.7
600	Rio Imboassu	7.4	5.8		0.033	5.9
700	B. Itaoca	0.1	0.1		0.010	0.2
800	Rio Alcântara	33.0	16.5		0.180	17.2
900	Rio Cacerebú	14.0	4.9		0.722	5.8
1000	Rio Guapimirim	6.0	0.7		0.003	7.0
1100	Canal de Magé	1.8	1.5		0.022	1.6
1200	Rio Roncador	1.7	1.0		0.240	1.5
1300	Rio Iriri	0.3	0.2		0.022	0.3
1400	Rio Surui	1.2	0.9		0.118	1.3
1500	B. Maua	0.7	0.7		0.020	0.8
1600	Rio Estrela	23.2	16.4		0.674	18.6
1700	Rio Iguaquí	58.0	35.7		1.003	35.8
1707	Rio Sarapuí	52.1	32.0			32.0
1800	B. Cabo do Brito	2.0	1.8		0.029	2.0
1900	Rio S. J. Meriti	57.8	40.8		0.217	42.3
2000	Rio Irajá	8.3	5.9	2.94	0.075	9.2
2100	Canal do Cunha	43.7	35.5	8.89	0.108	44.8
2200	B. São Cristóvão	1.6	1.5		0.010	1.5
2300	Canal do Mangue	20.3	17.6		0.054	17.9
2400	B. Botafogo	14.6	13.6		0.027	13.8
2500	I. do Governador	2.8	2.8	0.86	0.052	3.7
2600	I. do Fundão	0.1	0.1		0.008	0.1
2700	I. de Paquetá	0.0	0.0	0.02		0.0
2800	I. do Engenho	0.0	0.0			0.0
2900	I. de S. Cruz	0.0	0.0			0.0
	Total	374.1	256.7	16.9	3.8	275.2

Note: The "BOD produced" is the sum treated and untreated load from population and industry discharged to rivers in the basin.

Source: This Study

Table 3.9 Load Scenarios Used for Simulation of Present and Future Water Quality

Scenario	BOD generated Ton/day	TN generated Ton/day	TP generated Ton/day	BOD to Bay Ton/day	TN to Bay Ton/day	TP to Bay ton/day	Population No.	Population No. with sewage treatment
Water Quality in Bay Relative to Load								
Year 2000	474.7	93.9	22.9	275.3	72.0	18.4	8290200	2058900
Year 2000 80% BOD, 30 % TN, 50 % TP	474.7	93.9	22.9	64.9	53.8	9.8	8290200	-
Year 2000 90% BOD, 35 % TN, 80 % TP	474.7	93.9	22.9	36.7	50.2	4.2	8290200	-
Year 2000 90% BOD, 80 % TN, 80 % TP	474.7	93.9	22.9	36.7	16.8	4.2	8290200	-
Year 2010	520.3	103.9	25.2	300.6	78.7	20.2	9013000	2165300
Year 2010 80% BOD, 30 % TN, 50 % TP	520.3	103.9	25.2	70.0	58.5	10.7	9013000	-
Year 2010 90% BOD, 35 % TN, 80 % TP	520.3	103.9	25.2	52.5	67.6	5.0	9013000	-
Year 2020	557.8	112.0	27.1	321.1	84.0	21.6	9619500	2262100
Year 2020 90% BOD, 35 % TN, 80 % TP	557.8	112.0	27.1	41.4	58.0	4.8	9619500	-
PDBG1								
Year 2000 PDBG1	474.7	93.9	22.9	214.3	69.9	17.8	8290200	3488600
Year 2010 PDBG1	520.3	103.9	25.2	238.3	76.3	19.5	9013000	3627700
Year 2020 PDBG1	557.8	112.0	27.1	257.8	81.4	20.9	9619500	3752400
Feasibility Study								
Year 2010 Feasibility Study	520.3	103.9	25.2	194.2	73.8	18.3	9013000	5003900
Year 2010 Feasibility Study, 90% BOD, 30% TN, 50% TP	520.3	103.9	25.2	181.3	72.9	17.2	9013000	5003900
Strategy Plan								
Year 2020 Strategy Plan	557.8	112.0	27.1	182.7	76.9	20.3	9619500	6700200
Year 2035 Strategy Plan, population year 2020	557.9	112.0	27.1	125.3	79.2	20.7	9619500	7914000
Year 2035 Strategy Plan, 90% BOD, 30% TN, 80% TP	557.9	112.0	27.1	125.3	76.0	10.8	9619500	7914000

Source: This Study

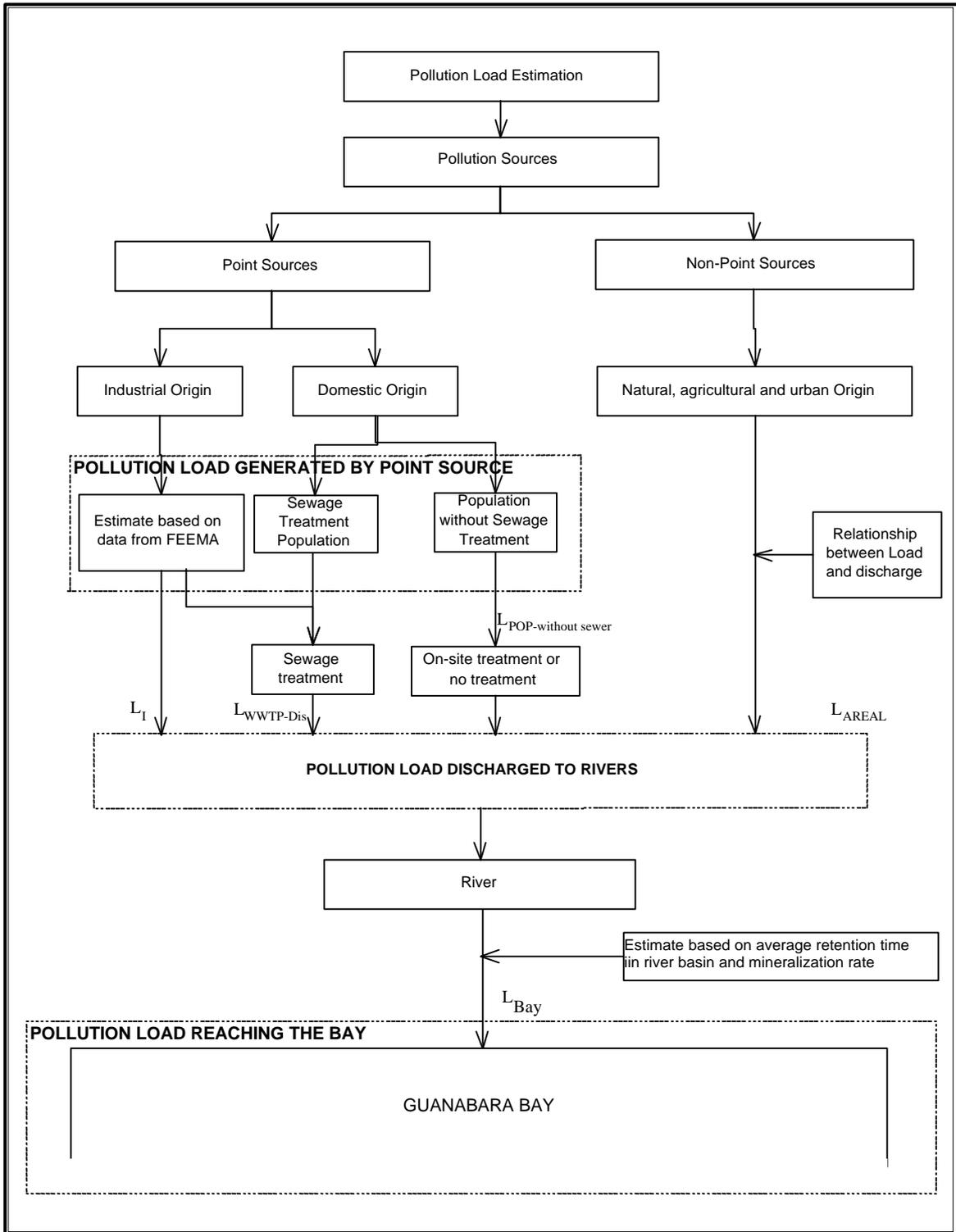


Figure 3.8 Pollution Load Estimation

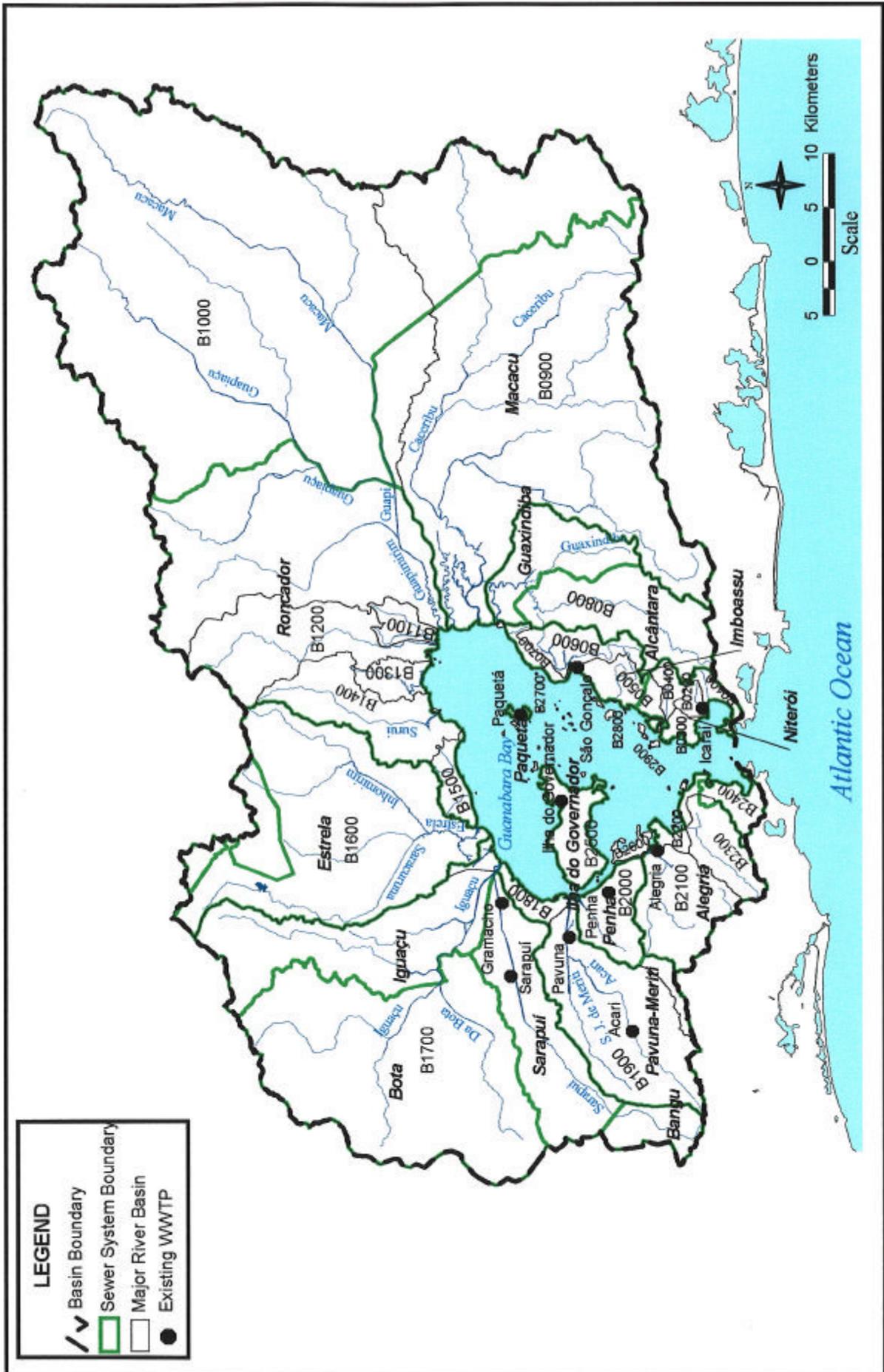


Figure 3.9 River Basin and Sewer System

3.4 WATER QUALITY SIMULATION MODEL

3.4.1 INTRODUCTION

A mathematical model has been set up for Guanabara Bay aquatic system. The model covers the bay proper, the bay entrance and a limited part of the Atlantic coast adjacent to the bay. The model is used to assess the present state of Guanabara Bay with respect to water quality and to assess the impact of selected priority sewerage projects within the Guanabara Bay Basin.

3.4.2 MODELING APPROACH

The adopted modeling approach combines a hydrodynamic model and an advection-dispersion model with process models describing the biological-chemical processes affecting the water quality parameters. Furthermore, a depth-integrated approach has been selected corresponding to mainly two-dimensional flow where stratification can be neglected. This approach is justified by the weak density stratification and by the tidally dominated flow of Guanabara Bay.

For this purpose, the MIKE 21 modeling system, which is a general modeling system for two-dimensional free-surface flows, is applied. This modeling system is structured in a modular manner with a basic hydrodynamic module simulating the water flow and a large number of add-on modules simulating related processes. For the present purpose, the hydrodynamic (HD) module, the advection-dispersion (AD) module, the water quality (WQ) module and the eutrophication (EU) module are applied. The latter has however proved out to be the best model to describe the water quality in the Bay.

Figure 3.11 depicts the inter-dependency of the applied modules of the MIKE 21 modeling system. The hydrodynamic module simulates the water flow (levels and fluxes) in response to forcing functions such as tide, local wind and freshwater inflow. The advection-dispersion module simulates concentration changes of dissolved or suspended water quality parameters in response to the water flow and pollution loads. Finally, the process modules (WQ/EU) simulate the concentration changes due to the biological-chemical and other processes.

The applied version of MIKE 21 resolves the model state variables on a rectangular grid. The same computational grid is used by both the hydrodynamic module and by the add-on modules. The hydrodynamic and advection-dispersion modules apply finite difference solution techniques whereas the water quality and eutrophication modules apply the 4th order Runge-Kutta integration method.

3.4.3 MODEL DOMAIN AND DISCRETIZATION

The basis of the model is the so-called model bathymetry. The model bathymetry defines the model grid, i.e. the spatial discretization and the geographical setting of the model area, and contains information on the water depths and land-water boundaries within the model area. Since, the model is based on a rectangular grid, the spatial discretization is defined by the grid spacing and by the number of grid points in the two horizontal directions. The grid spacing is selected as a compromise between resolving the model area as well as possible and maintaining the simulation (or CPU) time within practical limits. For the present study, a grid spacing of 330 m is selected. However, model set-ups for grid spacing of 165 m and 660 m has been set up as well. The grid 660-m set up has been used for initial calibration of the water quality models whereas the fine grid 165-m set up is used when a fine spatial resolution is needed.

The prescription of the water depths and land-water boundaries of the model bathymetry includes the following tasks:

- 1) Digitization of appropriate hydrographic charts
- 2) Interpolation of the digitized data to the model grid
- 3) Manual correction and smoothing to remedy any data gaps
- 4) Reduction of the vertical datum from mean low water springs to mean sea level (MSL) using the chart datum defined at the Ilha Fiscal tidal station (0.69 m below MSL).

For the present purpose, two already vectorised Guanabara Bay sea charts from C-Map Norway (Chart codes 20-03880 and 20-00770, compilation date: 20020109) and the Brasil - Costa Sul - Baía de Guanabara 1:50,000 sea chart from Marinha do Brasil, Diretoria de Hidrografia e Navegação (No. 1501, 4. Edition: September 28, 2001) are used as basis for the digitization. A contour plot of the model bathymetry is shown in *Figure 3.12*.

The temporal discretization is defined by the simulation time step and by the number of time steps in a simulation. The time step is determined by the Courant criterion, which is a stability requirement for the hydrodynamic model. Since, narrow channels and passages exist, the Courant number has not been allowed to exceed 5, which yields a time step of 80 seconds. The simulation period is one year. The main characteristics of the model area and discretization are summarized in *Table 3.10*.

Table 3.10 Model Summary

Model origin	23° 00' S; 43° 19' W
Model extension	33.1 x 39.8 km ²
Grid spacing (DX)	330 m
Grid dimensions	101 x 121
Time step (DT)	80 s

3.4.4 HYDRODYNAMIC AND ADVECTION-DISPERSION MODELING

The hydrodynamic and the advection-dispersion model have been calibrated. Because of the dependency of the AD model to the HD model, the calibration of the two models is largely a combined process.

Firstly, a tidal calibration of the hydrodynamic model was performed. Predicted astronomical tide, based on historical measurements, was prescribed at the open boundary and comparisons of predicted and simulated water levels at Ilha Fiscal and Ilha de Paquetá stations inside the bay was performed. A good agreement between predicted and simulated water levels was obtained. Vector/contour plots of typical ebb and flood tidal current patterns during spring tide as simulated by the model is presented in *Figure 3.13*.

Secondly, daily freshwater inflow for the year 2000 was included in the model and 1-year simulation was performed. At this stage, the advection-dispersion model was included in the modeling in order to calibrate the ability of the joint models to correctly describe the evolution of the salinity distribution. To do so the two models need to correctly simulate the net flow of salt. The net salt flow is partly attributed to the residual currents resolved by the HD model and partly to processes, which are filtered out by the spatial discretization (sub-grid processes) and by the

depth-integration of the flow equations. To account for the mixing effects of these filtered-out processes, the dispersion part of the advection-dispersion model is applied.

The two main issues when calibrating the 1-year HD/AD models are these:

- 1) Specifying the correct volumes and distribution of the freshwater inflow
- 2) Specifying the correct dispersion coefficients.

During the calibration, FEEMA monitored salinity in 8 stations was used for comparison.

3.4.5 WATER QUALITY AND EUTROPHICATION MODELING

Two process models for the simulation of the biological-chemical processes affecting the water quality parameters were established.

The MIKE 21 WQ model is a BOD-DO model describing the DO concentration as function of the anthropogenic load of BOD and NH₄ from land. The WQ model also includes simulation of the bacterial pollution in terms of coliform bacteria. The BOD-DO model exists with different levels of complexity. Depending on the available data on the load and water quality data in the bay, the user has to choose a proper model level. The BOD-DO model does however not include a dynamic description of plankton growth and decay. Preliminary simulations with the WQ model however have shown that it is not useful when simulating the BOD concentration since the model only predict the fate of the BOD load from land. In Guanabara Bay, monitoring data and EU model simulations have shown that a major fraction of the BOD is coming from production of phytoplankton. It is therefore not recommended to use the WQ model for simulations of BOD concentrations in the Guanabara Bay.

Secondary effects in term of blooms of phytoplankton are addressed by the MIKE 21 EU model. The driving forces for this model are the high loads of N and P from land to the bay combined with the water exchange simulated by the hydrodynamic model. The eutrophication model includes descriptions of phytoplankton (C, N & P), zooplankton (C, N & P), chlorophyll, detritus (C, N & P), DO, PO₄-P, and inorganic nitrogen. An example of the carbon cycle is given in *Figure 3.14*. The EU model is used to simulate the BOD, chlorophyll and nutrient concentrations in the bay, and to establish a mass balance for N and P for the bay over a selected period.

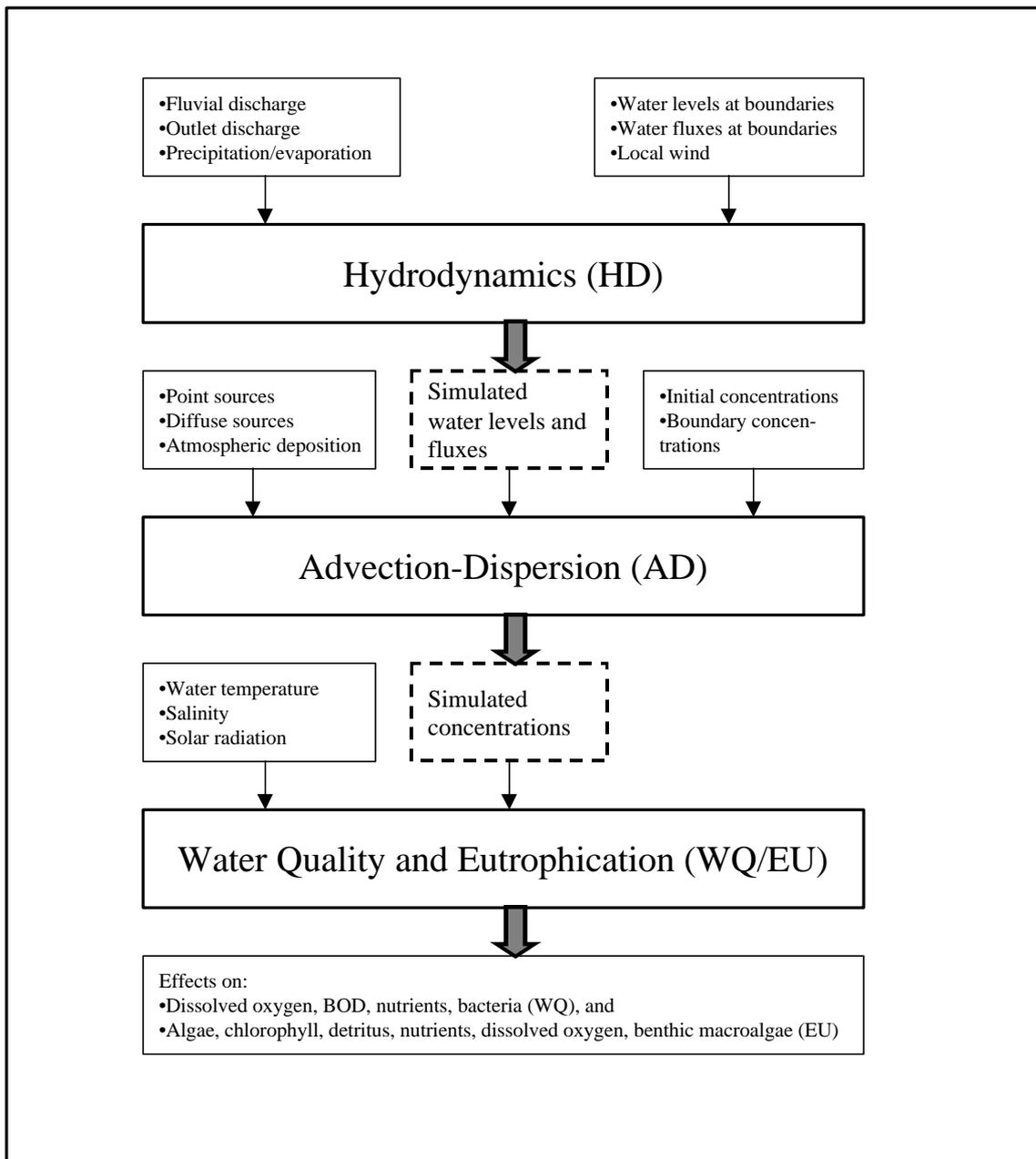


Figure 3.11 Forcing and Inter-Dependency of Applied MIKE 21 Modules

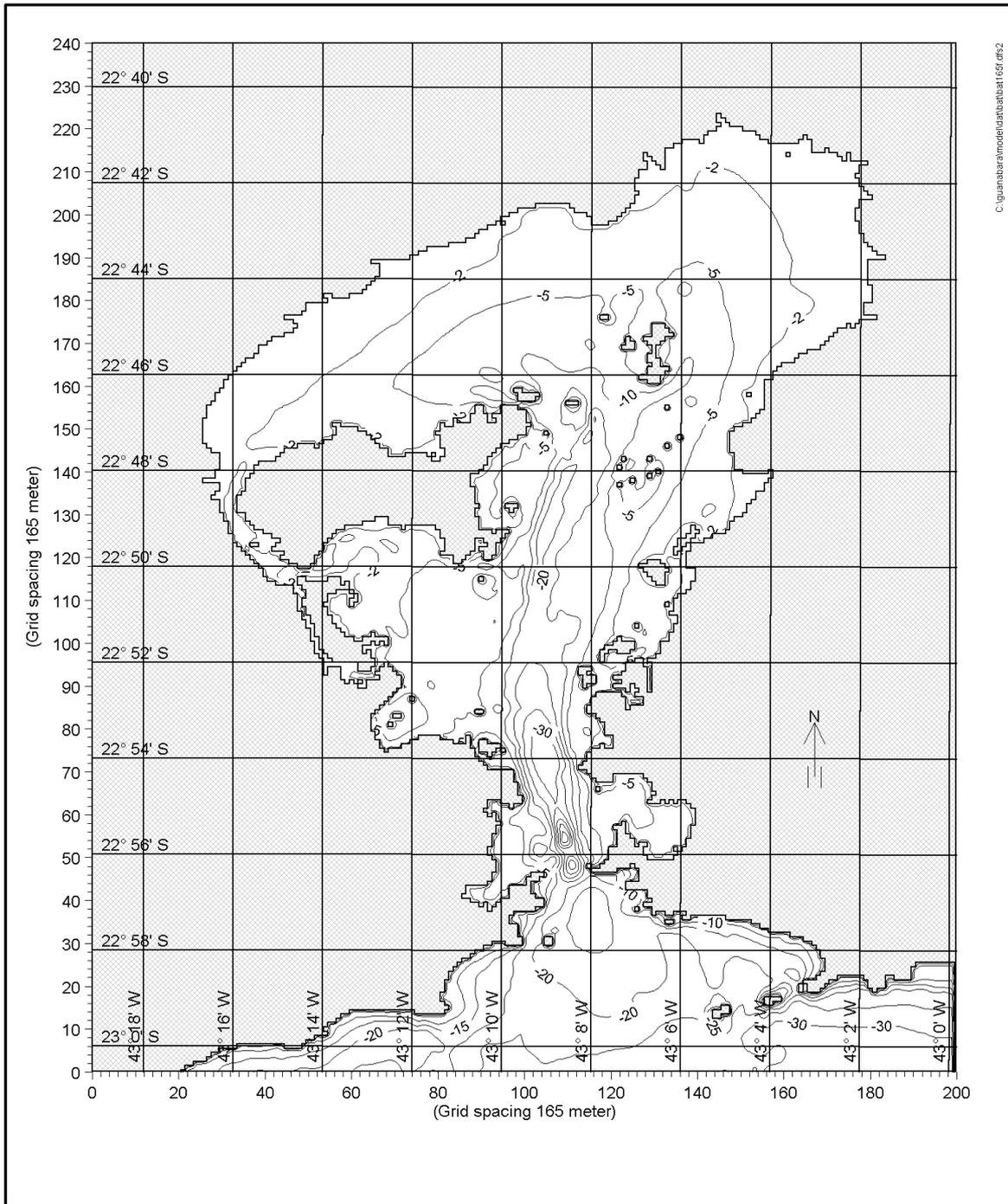


Figure 3.12 Model Bathymetry

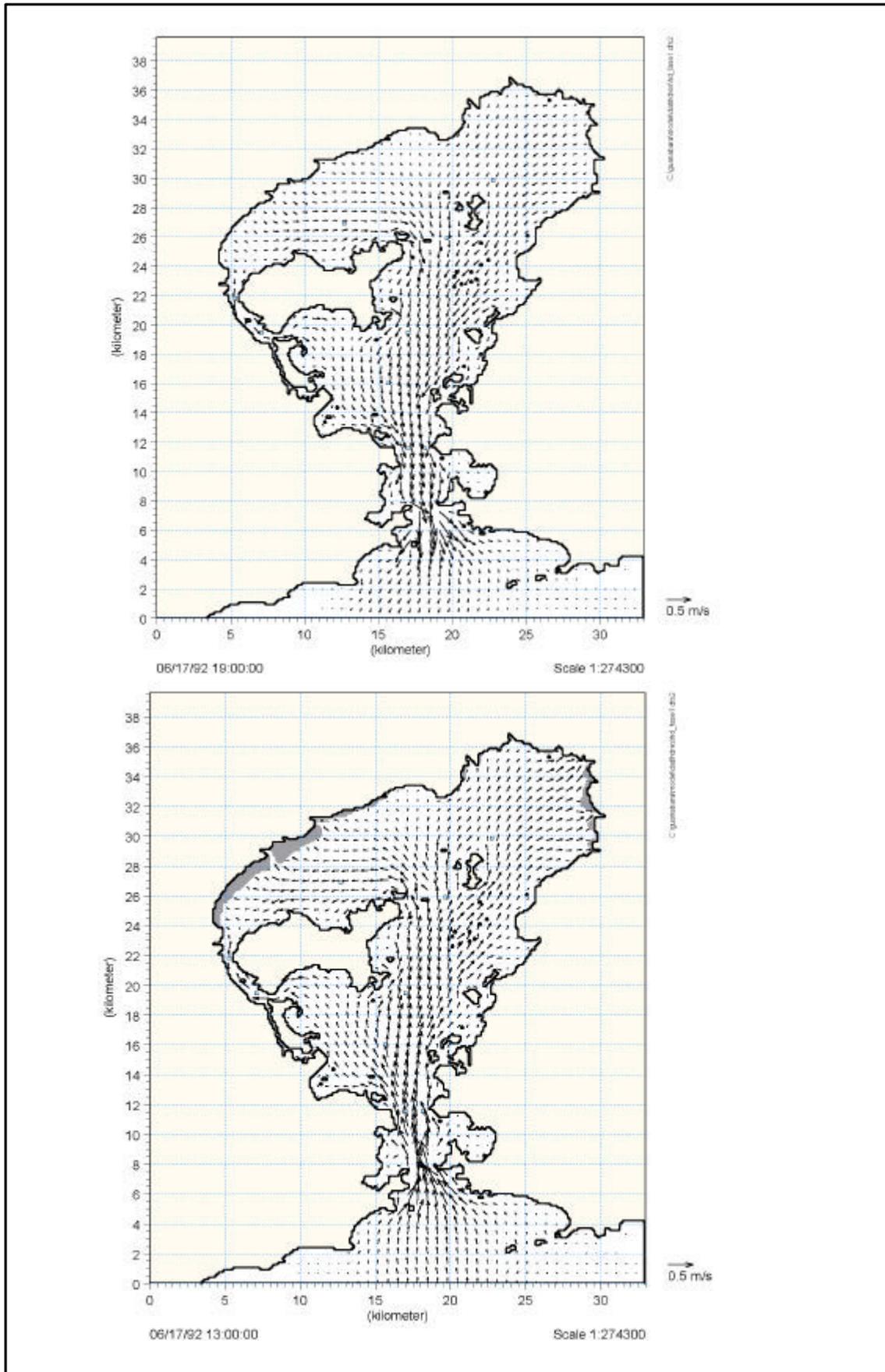


Figure 3.13 Ebb (upper) and Flood (lower) Current Patterns During Spring Tide

In the EU model, detritus carbon (DC) and phytoplankton carbon (PC) are the main state variables in the carbon cycle. The load of BOD from land is converted into a load of detritus carbon or dead organic material using the above ratio. After simulation, total BOD is calculated as the sum of BOD from PC and DC simulated in the Bay. BOD from simulated DC represents in part BOD coming from land and in part BOD from dead phytoplankton C, which enters the pool of detritus. Close to point sources and river mouths, BOD-DC fraction mainly represent BOD discharge from land, whereas simulated BOD-DC concentrations close to the entrance of the Bay mainly consists of BOD from dead phytoplankton.

(2) Photosynthetic Active Radiation

The photosynthetic part of the light is estimated using longitude, latitude and precipitation data from hydrological stations close to the bay. 20 % of the light is assumed to be adsorbed in the atmosphere and additional light is adsorbed or reflected proportional to the precipitation. The resulting radiation is presented in *Figure 3.15*.

(3) Water Temperature

In *Figure 3.16*, the monthly average temperature of 7 stations in the bay are presented. The figure reveals a seasonal and a spatial variation of the temperature. The highest temperature is recorded in summer and the lowest temperatures are during winter. In general, the innermost shallow stations located north of Ilha do Fundão have the highest temperatures (st. GN20, GN40, GN42, GN43) and the outermost stations south of Ilha do Fundão have the lowest temperatures (st. GN22, GN26, GN64). The overall average temperature of the bay vary between 27.5° C in January to 23° C in August giving a lag phase of about 1.5 month in the seasonal variation relative to the variation in the sun radiation.

In the model, a time series of the spatial average temperature as shown in *Figure 3.16* has been adopted.

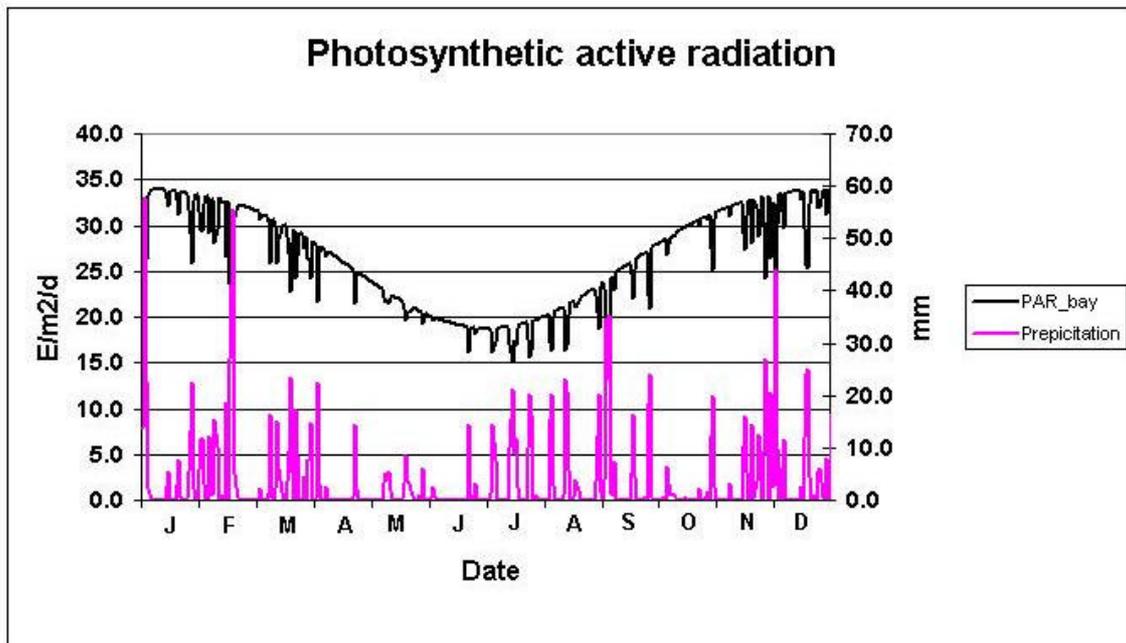


Figure 3.15 Photosynthetic Active Radiation Used for Modeling Growth of Algae

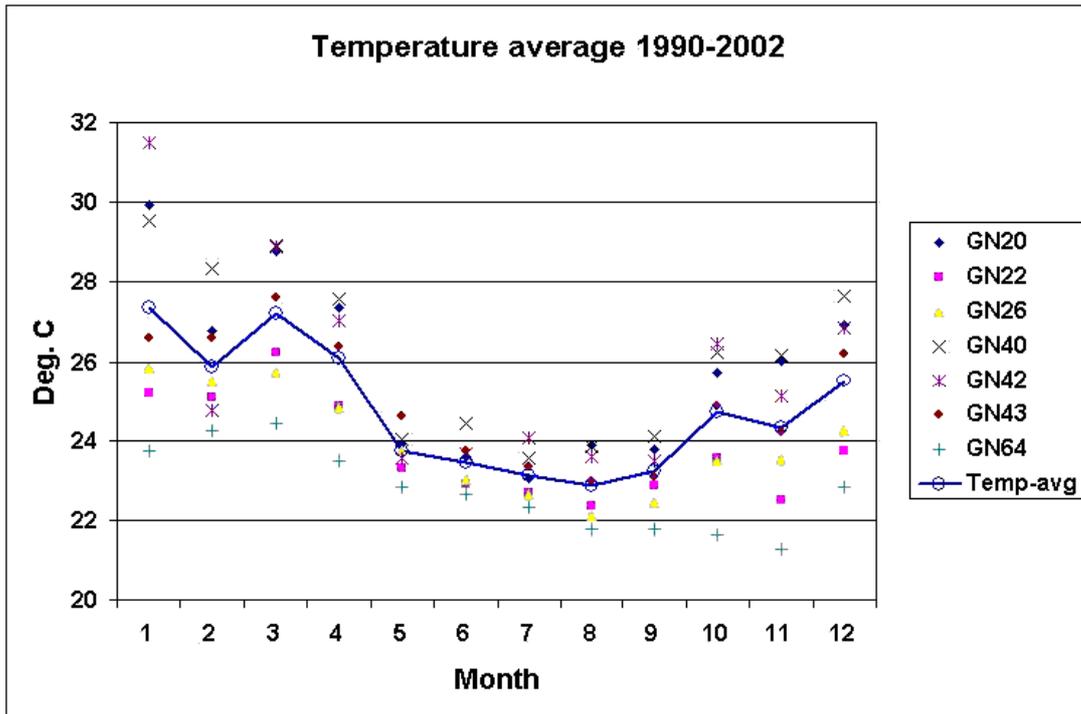


Figure 3.16 Monthly Average Water Temperature at 7 And of All Stations in Guanabara Bay

(4) EU Model Calibration for Year 2000

The EU model is calibrated against monitoring data of BOD, chlorophyll, total N, inorganic N total P and phosphate at 7 Bay water quality monitoring stations. It is concluded that the Eutrofication model is sufficiently calibrated to simulate the future water quality situation with both increased and decreased load. Please refer to *Supporting 6* on Water Quality Simulation Model for details of Calibration. Only brief description on calibration of BOD is presented here.

The simulated and average of measured BOD from top and bottom samples are presented in *Figures 3.17* and *3.18*. *Figure 3.17* represent a gradient of 3 stations from Rio S. J. do Meriti north of Ilha do Governador, whereas *Figure 3.18* represent a gradient south of Ilha do Governador. The highest concentrations are simulated and measured at station GN40 with a decreasing gradient to station GN42 and stations GN22 & GN26 respectively north and south of Ilha do Governador. Although the variation in the measurements in general is high, the model seems slightly to underestimate the BOD during winter. The time series of BOD loads from the rivers were generated from an average daily load with 20 % of the load made proportional to the discharge and 80 % being constant. The load does therefore not include accidental outlets from treatment plants or industries. With this in mind, the resemblance between simulated and measured are acceptable.

The total BOD is the sum of a BOD from PC and DC. The BOD from DC is presented together in the figures with the total BOD. It is clear from *Figures 3.17* and *3.18* that most of the BOD is coming from the PC (phytoplankton) except at station GN40. This emphasizes the point that the high BOD recorded in the Bay is a combined problem of eutrophication and BOD load discharged from land. The load of BOD and nutrient is highest during the wet summer period where the production of phytoplankton is highest and thereby also the BOD is high. This is reflected in the simulated BOD where the highest BOD values are simulated during summer.

Plan plots of the average total BOD, chlorophyll, total N and total P concentrations in February 2000 are presented in *Figure 3.19*. All the parameters are found to be the highest in the western and north-western part of the Bay.

3.4.7 MASS BALANCE OF BOD, TOTAL N AND TOTAL P

A mass balance for carbon, T-N and T-P covering the Bay was established for the year 2000, and is presented in *Table 3.11*. In total, the load of BOD converted into detritus C is 100,484 tons and the net production of phytoplankton C is 296,848 tons. The load from land, thereby, contributes 25.4 % of the total input of carbon to the bay. In areas close to the polluted rivers in the western and north western part of the Bay, the relative contribution will be higher than 25.4 % whereas in the center of the bay, the contribution will be lower.

The mass balance for nitrogen gives a land based load of 26,280 tons/year of which 22,463 tons is exported to the Atlantic ocean giving a retention or immobilization for N of 14.5 % of the load or 9.97 tons N/km²/year. This denitrification is comparable with denitrification rates found in Narragansett Bay, Ochlockonee Bay and Delaware Bay (Szilgyi *et al*) but higher than denitrification rates of 2 ton N/km²/year found in 9 temperate Danish bays (S. Jansen *et al*, 1995). In these bays, the plankton production was N limited during summer decreasing the NO₃ concentration to low levels. Lower temperatures and lower NO₃ concentration may explain the lower denitrification in these bays relative to Guanabara Bay.

A total P load of 6,716 tons per year enters the Bay from land of which 6,149 tons is exported to the Atlantic Ocean. The mass balance for phosphorus gives a P retention of 8.4 % of the P load or an immobilization of 1.48 kg P/km²/year. This seems reasonable compared to a P immobilization of 0.54 kg/km²/year in the temperate Århus Bay (Denmark), (Danish Environmental Investigations, 2002).

Table 3.11 Mass Balance for Carbon, Total N and Total P Based on an EU Model Simulation for Year 2000

Component	Load from land, Ton/year	Primary production, Ton/year	Export to the Atlantic Ton/year	Imobilization or Retention % of load	Load (Prod.+load) %
Carbon	100,484	296,850	110,100	-	25.4
Total N	26,280	-	22,500	14.5	-
Total P	6,716	-	6,149	8.4	-

The mass balance for nitrogen does not indicate that a significant N fixation occurs in the Bay.

References for Section 3.4

1. MIKE 21 Coastal Hydraulics and Oceanography, User Guide, 2001
2. MIKE 21 Environmental Hydraulics, User Guide, 2001
3. Maria Louredes San Diego-McClone, Stephen V. Smith, Vivian F. Nicolas. Stoichiometric Interpretations of C:N:P ratios in organic waste materials. Marine Pollution Bulletin Vol. No. 4 pp 325-330, 2000.
4. Ferenc Szilagy, Hydrobiological investigations on Guanabara Bay, RJ, Brasil. Final report (Project: BRA/90/010)
5. Henning S. Jensen, Peer B. Mortensen, Frede Ø. Andersen, Erik K. Rasmussen, Anders Jensen. Phosphorus cycling in a coastal marine sediment, Aarhus Bay, Denmark. Linnol. Oceanogr. 40(5), 1995, pp. 908-917.
6. Carbon and nutrient cycles in seabed. Report from Danish Environmental Investigations no. 42. April 2002. (in Danish)

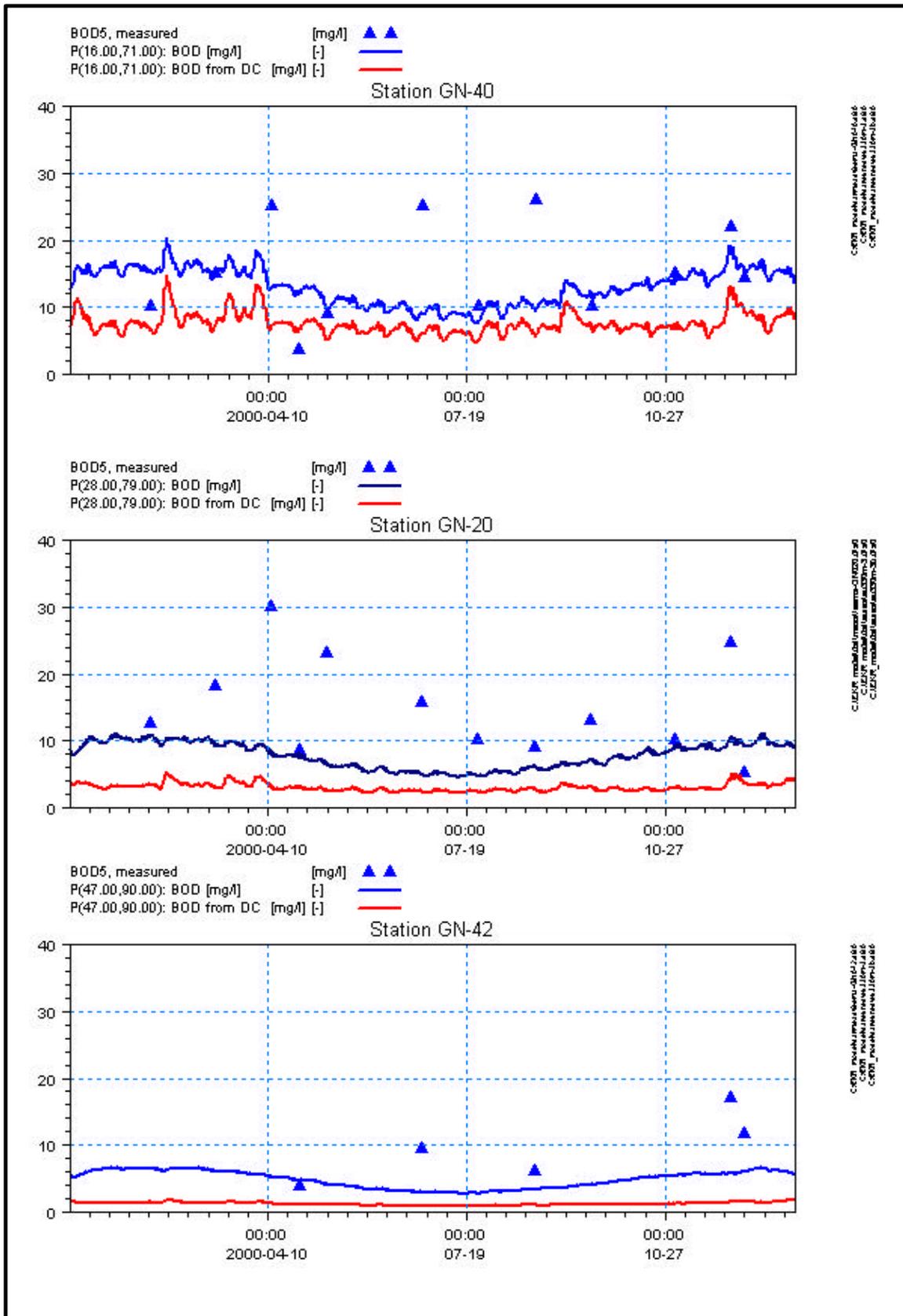


Figure 3.17 BOD Total and BOD from DC at 3 Stations Making a Gradient from Rio S.J. de Meriti, north of Ilha do Governador

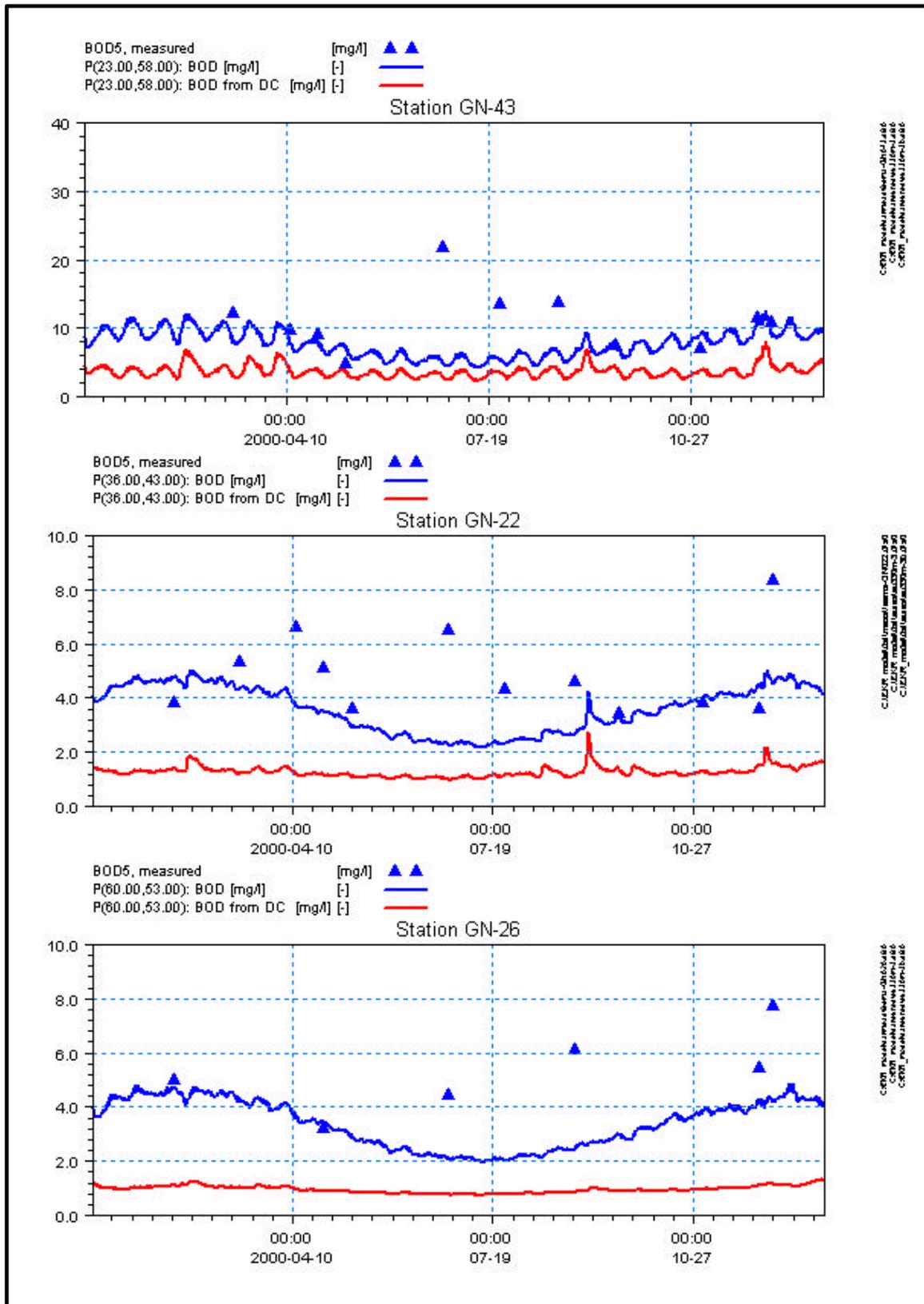


Figure 3.18 BOD Total and BOD from DC at 3 Stations Making a Gradient South of Ilha do Governador

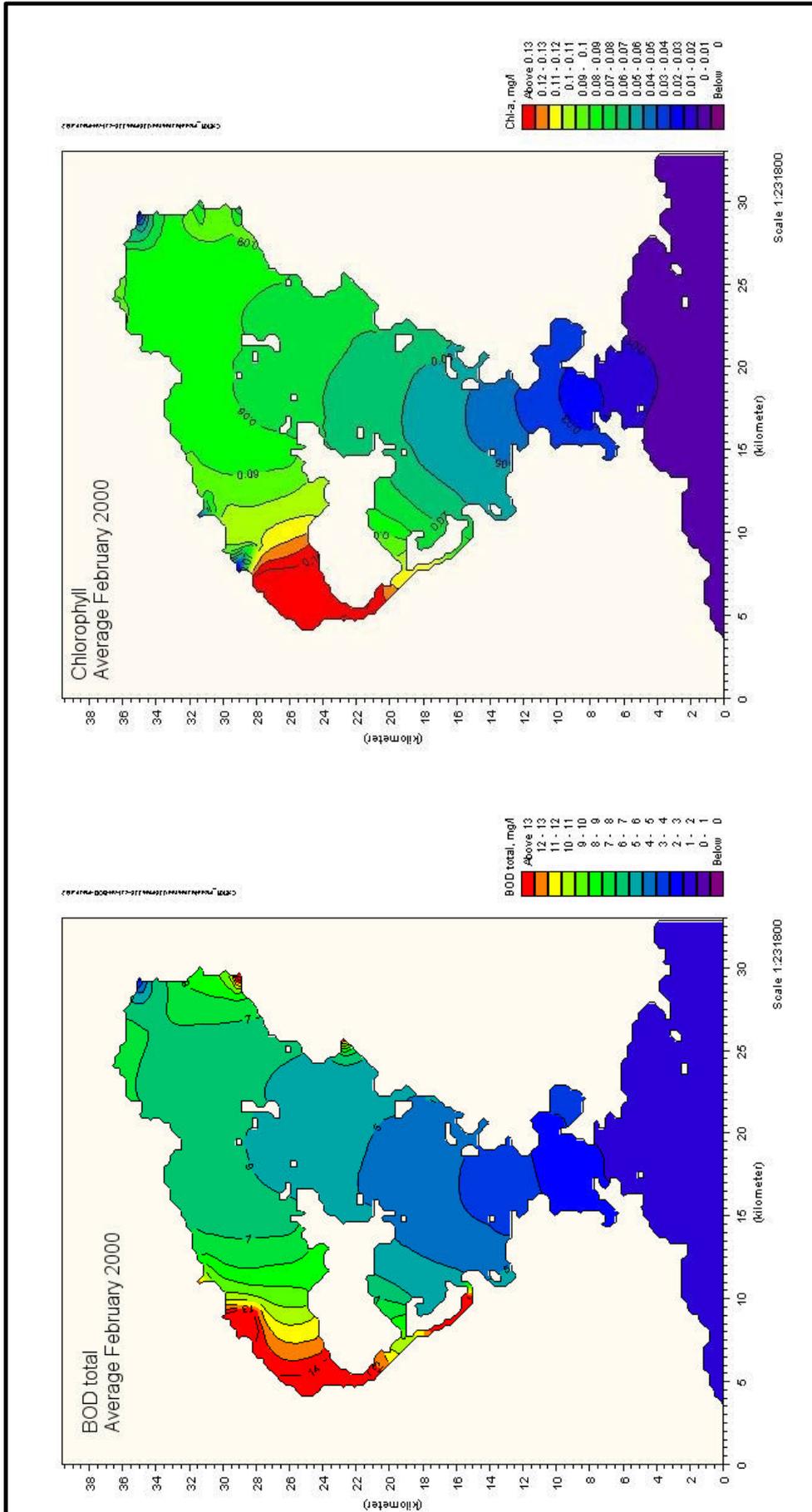


Figure 3.19 Simulated Average Total BOD, Chlorophyll, Total N and Total P Concentrations in February 2000 (1 of 2)

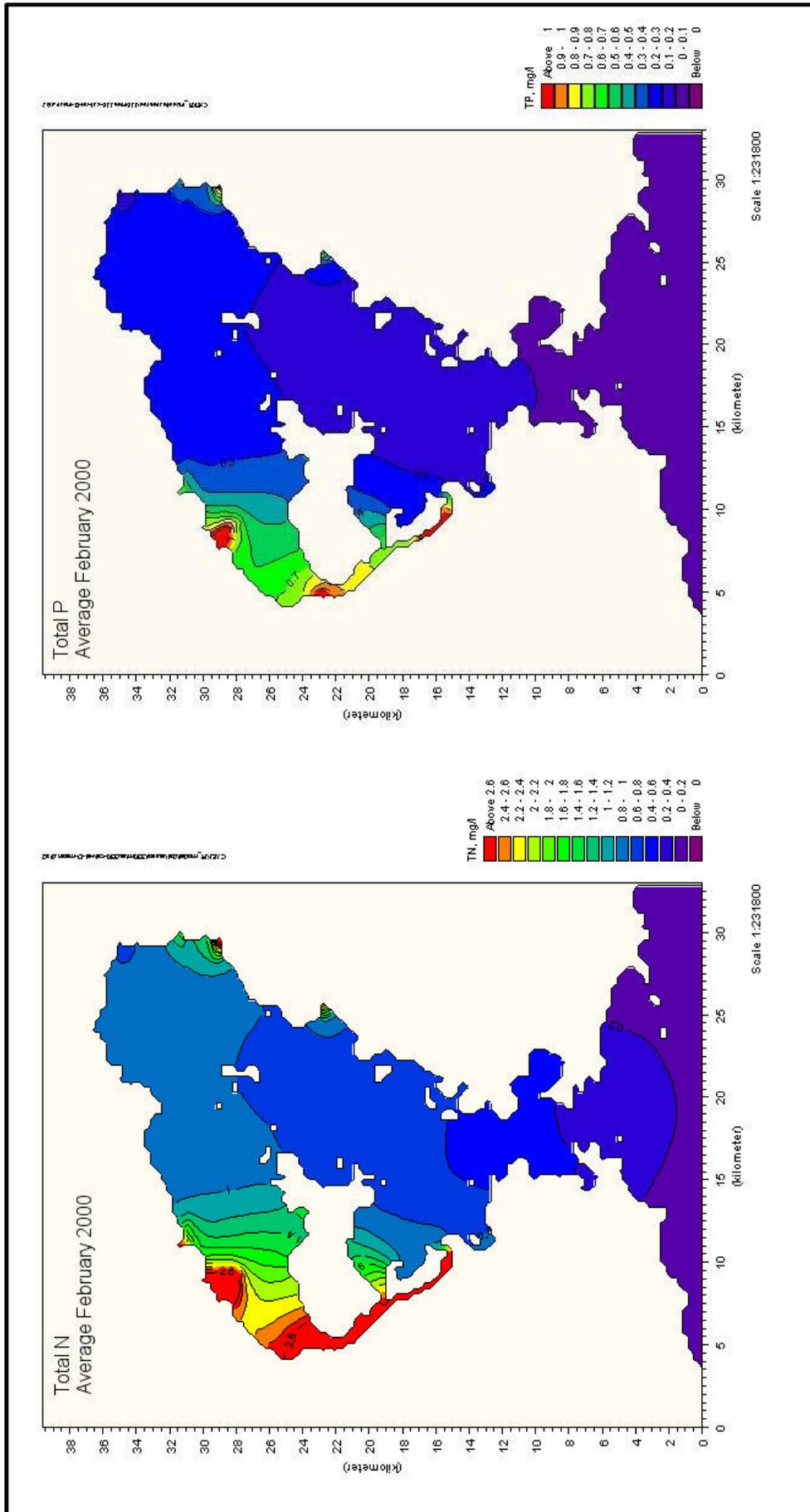


Figure 3.19 Simulated Average Total BOD, Chlorophyll, Total N and Total P Concentrations in February 2000 (2 of 2)