SUPPORTING 6

DEVELOPMENT OF SIMULATION MODEL

TABLE OF CONTENTS

Page

SUPPORTING 6 DEVELOPMENT OF SIMULATION MODEL

LIST OF TABLES

LIST OF FIGURES

SUPPORTING 6 DEVELOPMENT OF SIMULATION MODEL

1. SIMULATION MODEL

1.1 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.

1.2 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 shoved out to be the best model to describe the water quality in the Bay.

Figure 1 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.

For further information on the MIKE 21 modules applied, please refer to Ref./1/ and Ref./2/.

1.3 MODEL DOMAIN AND DISCRETISATION

The basis of the model is the so-called model bathymetry. The model bathymetry defines the model grid, i.e. the spatial discretisation 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 discretisation 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 has included 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; and
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, Directoria de Hidrografía 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 2*.

The temporal discretisation 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 40 seconds. The simulation periods and thus the number of time steps will be defined depending on the actual simulation to be carried out.

The main characteristics of the model area and discretisation are summarized in *Table 1*.

Table 1 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

1.4 HYDRODYNAMIC AND ADVECTION-DISPERSION MODELING

The calibration of the hydrodynamic model and the advection-dispersion model is presently being finalized. 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 has been performed. Predicted astronomical tide, based on historical measurements, has been prescribed at the open boundary and comparisons of predicted and simulated water levels in stations inside the bay have been performed. *Figure 3* shows vector/contour plots of typical ebb and flood tidal current patterns during spring tide as simulated by the model. *Figure 4* shows water level comparisons at the Ilha Fiscal and Ilha Paquetá tidal stations inside the bay. As can be seen in the plots a good agreement between predicted and simulated water levels has been obtained.

Secondly daily freshwater inflow for the year 2000 has been included in the model and 1-year simulation periods have been performed. At this stage the advection-dispersion model has been 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 have been filtered out by the spatial discretisation (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 hereby:

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

During the calibration FEEMA monitored salinity in 8 stations has been used for comparison. *Figure 5* shows a typical simulated salinity distribution. Please notice that this result is only preliminary, since the 1-year HD/AD calibration is not completed.

When fully calibrated, the joint HD/AD models will be able to simulate the evolution in the distribution of a conservative dissolved or suspended substance. The models will thus constitute a solid basis for the water quality and eutrophication models

1.5 WATER QUALITY AND EUTROPHICATION MODELING

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

The MIKE 21 WQ model is a BOD-DO model describing the DO concentration as function of the antrophogenic 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 the model only predict the fate of the BOD load from land. In Guanabara Bay monitoring data and EU model simulations has shown that where a major fraction has 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 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 6*. 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.

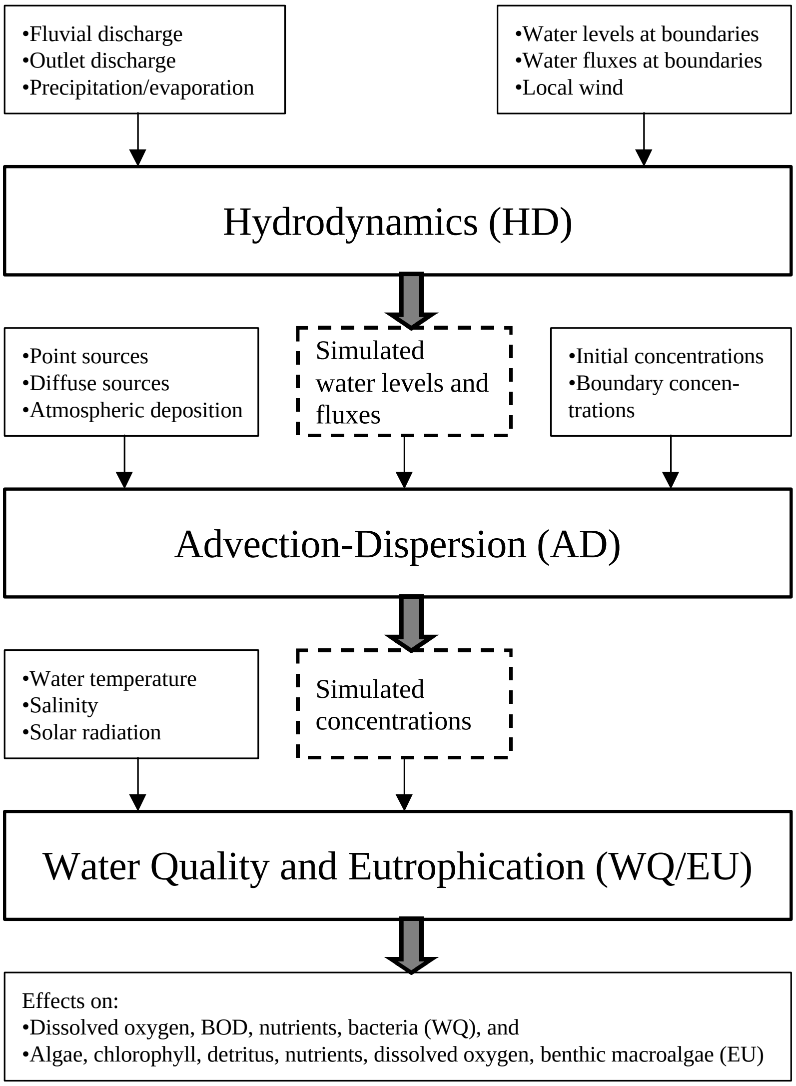

Figure 1 Forcings and Inter-Dependency of Applied MIKE 21 Modules

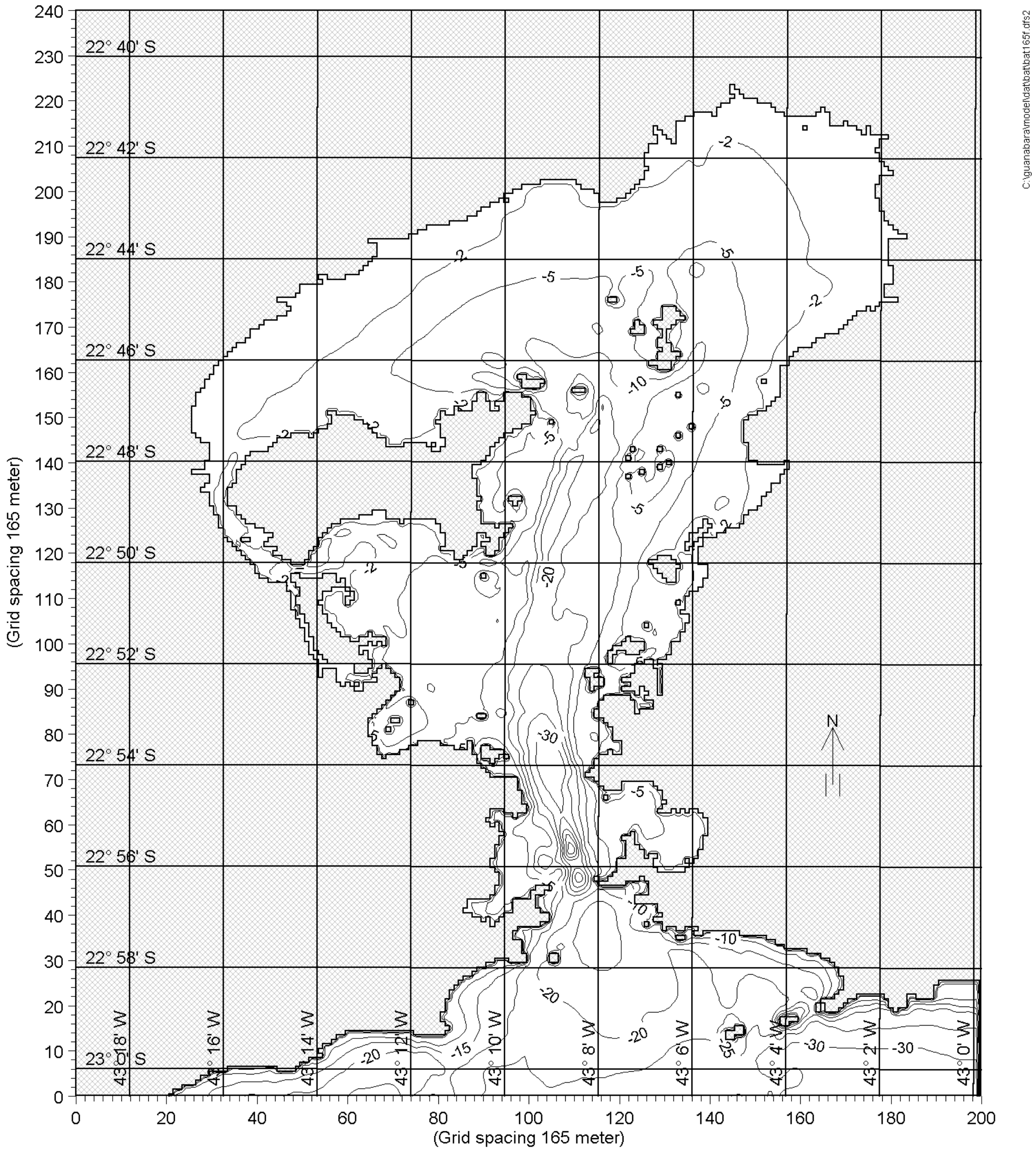

Figure 2 Model Bathymetry

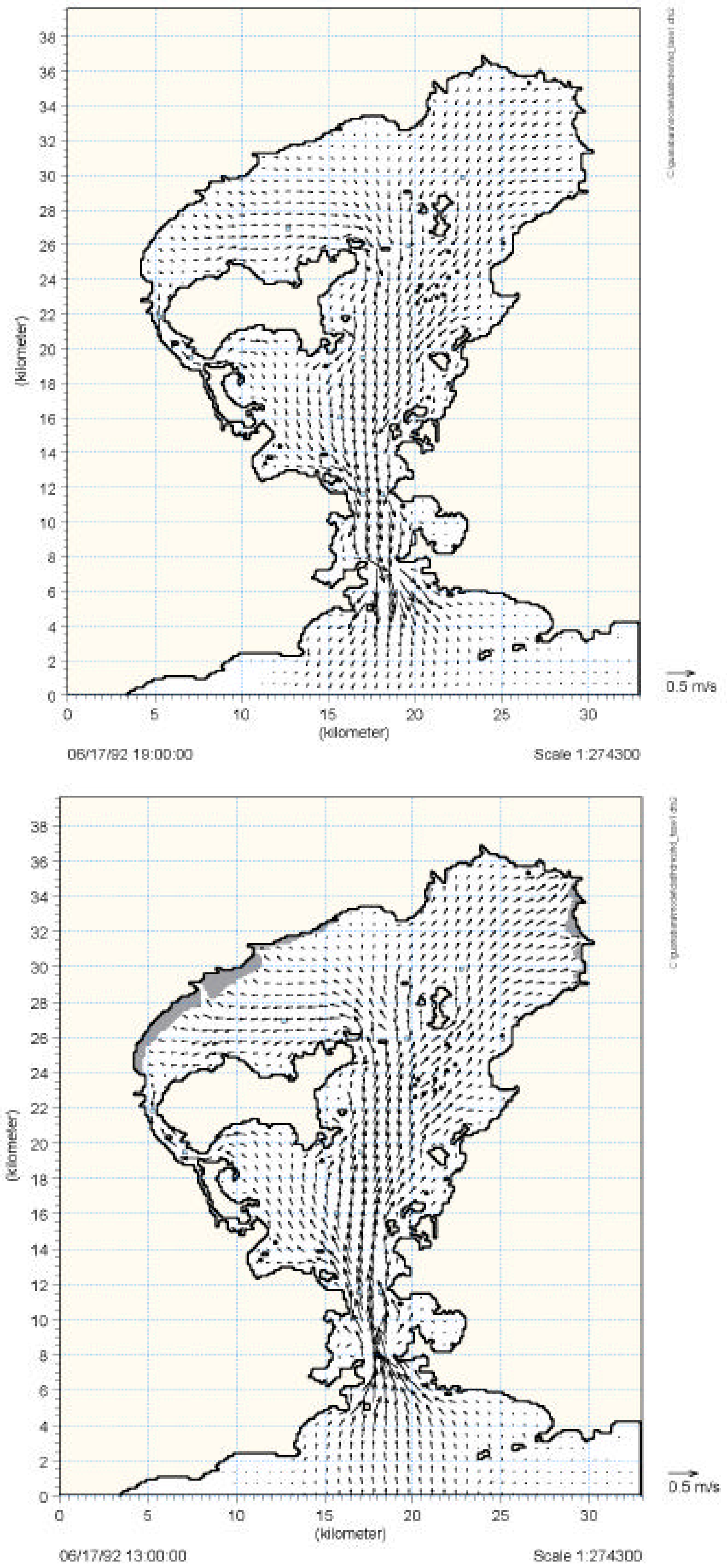

Figure 3 Ebb (upper) and Flood (lower) Current Patterns During Spring Tide

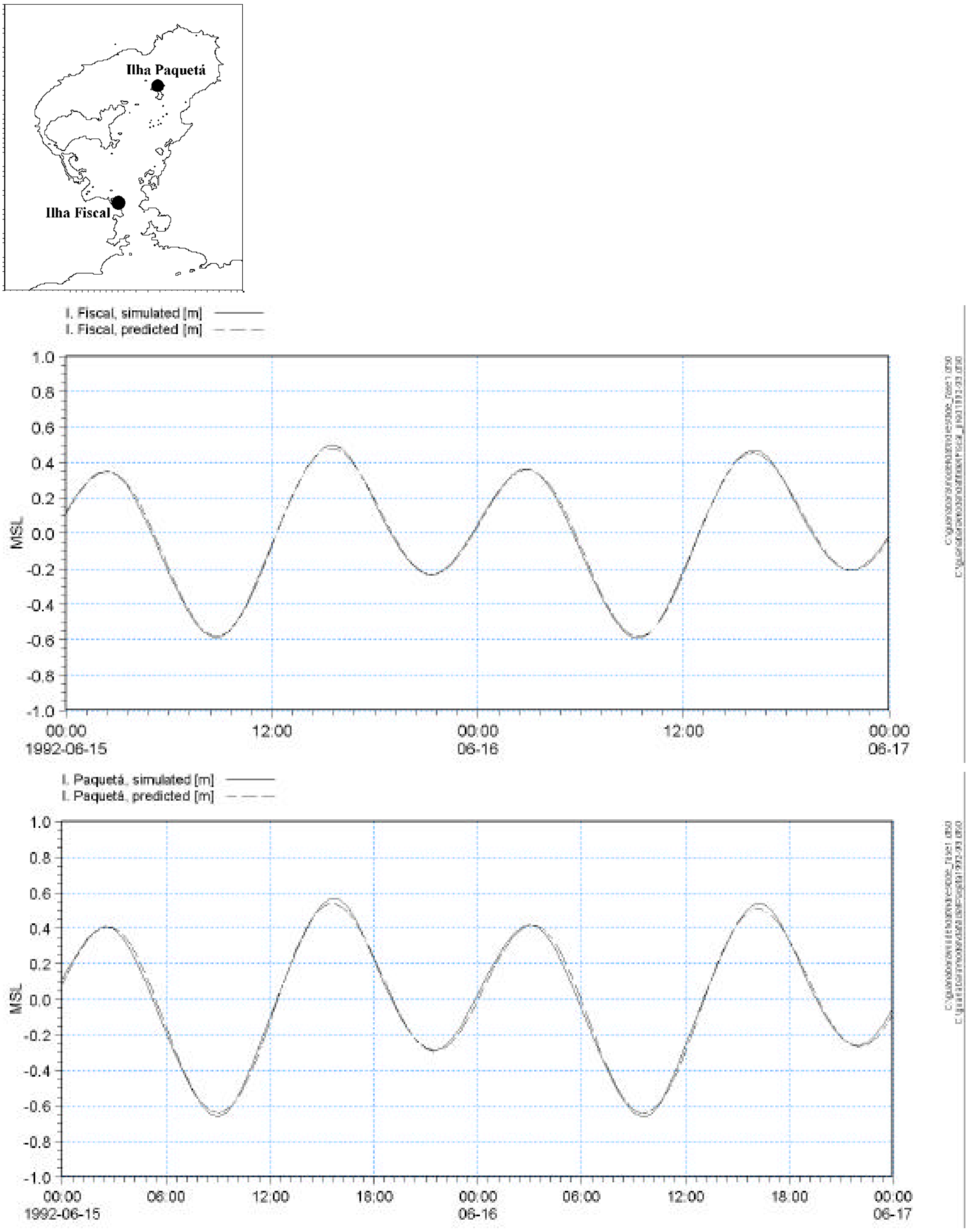

Figure 4 Comparison of Predicted and Simulated Water Levels at Ilha Fiscal and Ilha Paquetá Tidal Stations

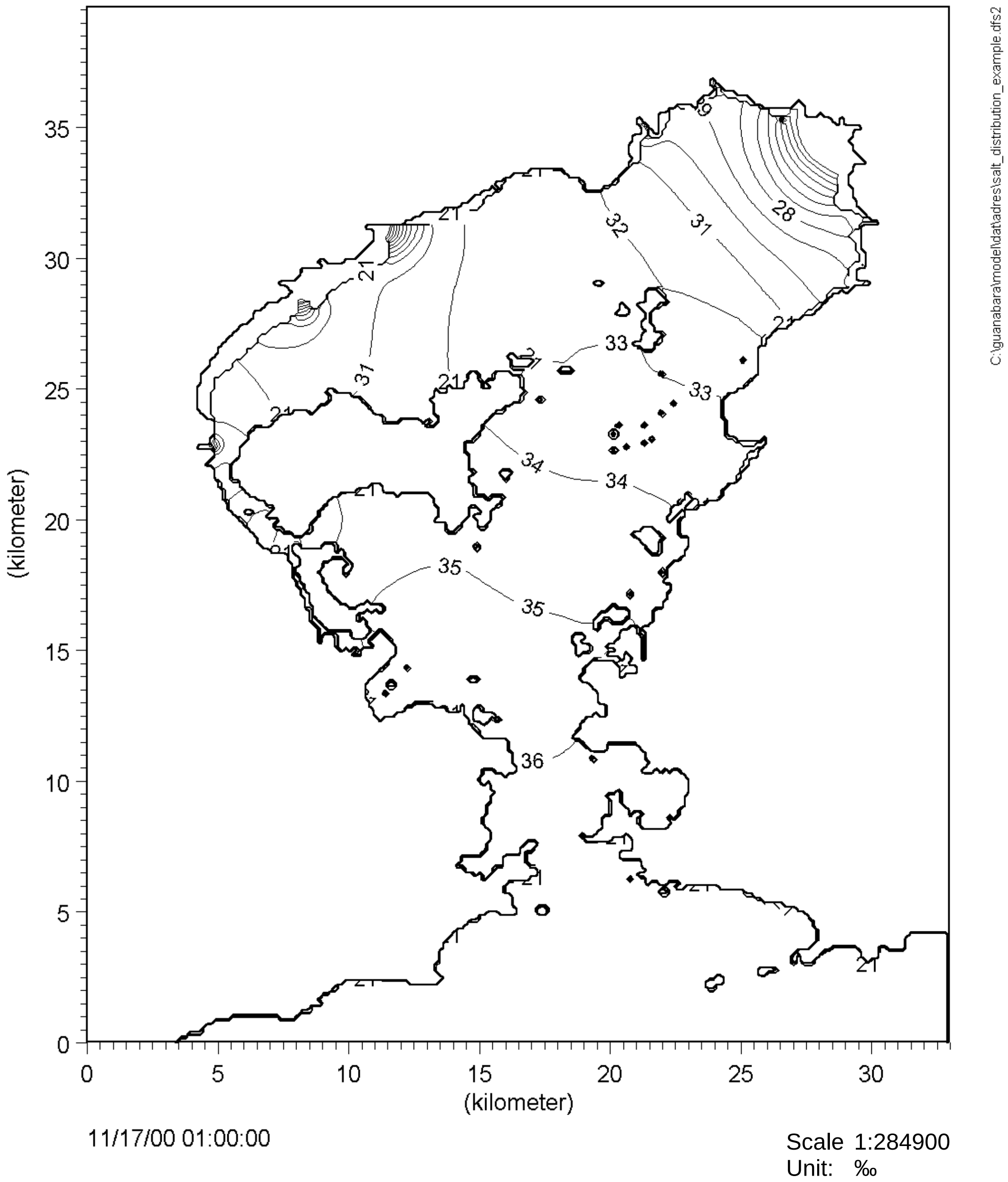

Figure 5 Simulated Salinity Distribution

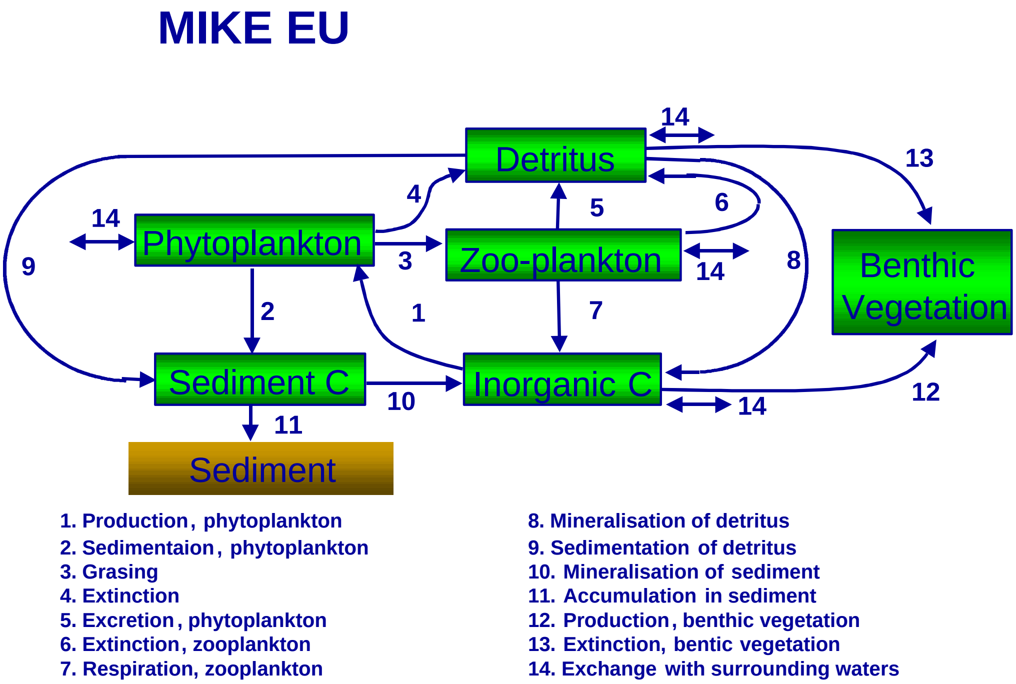

Figure 6 The Carbon Cycle in the MIKE 21 Eutrophication Model

1.6 Eutrophication Modeling

To be able to simulate the present and future water quality in the bay a hydrodynamic model and input data or forcing functions in terms of pollution loads, sun radiation and water temperature are need. In the previous chapters the pollution load and the hydrodynamic model has been described. The sun radiation is used for simulating the production of alga in the water, and the water temperature is a fundamental parameter regulating the speed of most biological processes.

The eutrophication model includes a description of the carbon, nitrogen and phosphorus cycles, however it dos not include BOD as a specific state variable. In addition to the forcing functions a conversion between detritus carbon and BOD and between phytoplankton carbon and BOD therefore has to be defined.

(1) Conversion factors between BOD and Carbon

The COD (chemical oxygen demand) of a water sample represent the oxygen consumption by the carbon possible to oxidize in the sample, and the BOD represent the readily oxidized fraction of the carbon in the sample. The COD converted into carbon unit can therefore be used as input to the EU model. According to ref. /3/ the COD:BOD ratio of different pollutants vary between 2.3 for sewage from “sanitary service” to 3.5 for run off from “agriculture and livestock production”. Converting COD (g O2/m3) into carbon (g C/m3) a COD:C ratio is needed. This COD:C ratio is found to vary between from 2.6 to 3.2 depending on nature of the organic matter. Using a COD:BOD ratio of 3:1 and a COD:C also of 3:1 results in a C:BOD ratio of 1:1 on weight basis (g C:g BOD).

In the present model 1 g BOD is converted to 1 g carbon. This is valid when converting BOD load into carbon load and converting simulated plankton C and detritus C in the Bay back into BOD.

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) Photosyntetic 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 7*.

(3) Water temperature

In *Figure 8* 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 lowest temperatures during winter. In general the innermost shallow stations located north of Ilha do Fundao have the highest temperatures (st. GN20, GN40, GN42, GN43) and the outermost stations south of Ilha do Fundao having the lowest temperatures (st. GN22, GN26, GN64), see *Figure 8*. The over all average temperature of the bay vary between 27,5 C in January to 23 C in August giving an 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 shown in *Figure 8* has been adopted.

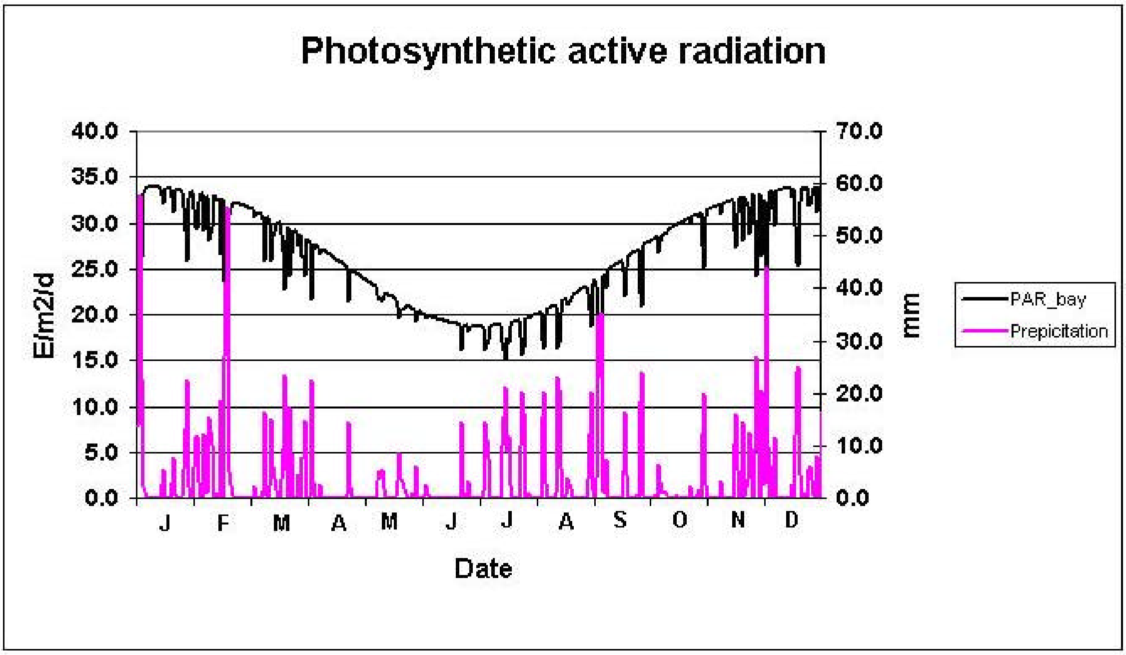

Figure 7 Photosynthetic Active Radiation Used for Modeling Growth of Algae

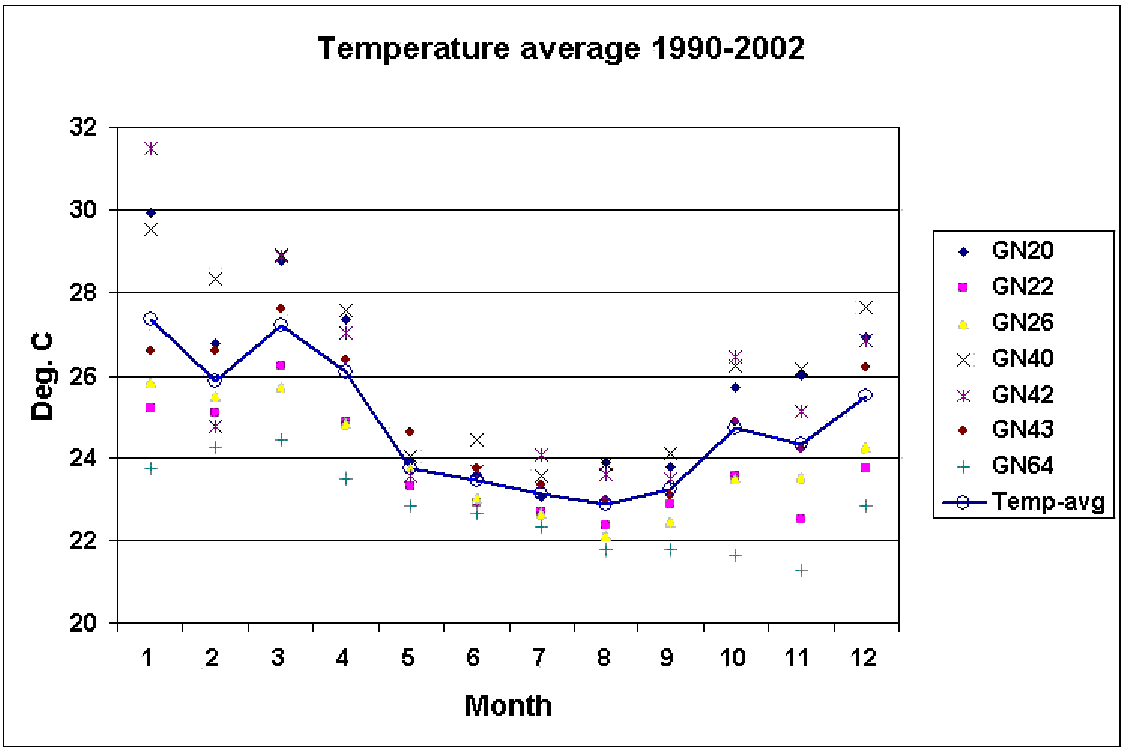

Figure 8 Monthly Average Water Temperature in Guanabara Bay of 7 Stations and of All the Stations

(4) EU model calibration

The EU model is calibrated against monitoring data of BOD, chlorophyll, total N, inorganic N total P and phosphate for the 7 monitoring stations, for location of the stations see *Figure 8*.

The simulated and average of measured BOD from top and bottom samples are presented in *Figures 9 to 11*. *Figure 9* represent a gradient of 3 stations from Rio S. J. Martini north of Ilha do Govandor, whereas *Figure 10* represent a gradient south of Ilha do Govanodor. *Figure 11* represent the cleanest station at the entrance to the Bay. 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 Ihla do Govanador. Though the variation in the measurements in general is high the model seems slightly to underestimate the BOD during winter. At station GN40 3 measurements are well above the simulated values and 7 measurements close to the simulated BOD and 2 measurements are below the simulated BOD. On a station GN 26 and GN64 closer to the entrance the ratio is 3 measurements above and 3 measurements close to the simulated BOD concentrations. The time series of BOD loads from the rivers are generated from an average daily load with 20 % of the load made proportional to the discharge and 80 % being constant. The load dos 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 the plots that most of the BOD is coming from the PC (phytoplankton) except at station GN40. This stress that the high BOD recorded in the Bay is a combined problem of eutrophication and BOD load discharged from land. A plan plot of the average total BOD in February and BOD from DC are presented in *Figures 12* and *Figures 13*. The load of BOD and nutrient is highest during the wet summer period where the production of phytoplankton is on its highest and thereby also the BOD being high. This is reflected in the simulated BOD where the highest BOD values are simulated during summer.

The simulated and the measured chlorophyll in the surface are presented in *Figures 14 to 16.* As for the BOD there is a great variation in the measurements. This partly can be due to especially cyanobacteriea (blue-green algae) ability to move up and down in water column optimizing the light regime. In the JICA study from 1994 vertical variations of chlorophyll concentrations was observed.

Besides from station GN26 where the simulated values are to high and an exceptional high measurement of chlorophyll measurements at station GN64 the simulated chlorophyll fall in between the measured chlorophyll.

As for the BOD the highest chlorophyll values are simulated in western and north-western areas of the Bay in February, see *Figure 17.*

The simulated and measured total N and inorganic N (NH4+NO2+NO3) are presented in *Figures 18 to 20*. A good resemblance between measured and simulated inorganic N is reached on all stations except St. GN43, where the simulated IN are to high. The variation of the measured total N is generally high. On the stations closest to the entrance (GN22, GN26 and GN64) measurements of high TN concentrations are impossible to simulate provided a sensible mass balance for total N in the Bay has to prevail.

In ref /4/ it has been suggested that N fixation by cyanobacteria could give a significant contribution to the N load of the bay. N-fixation can however not explain the above described high TN concentrations because N-fixation only occurs in situations with excess of phosphorus. The TN:TP ratio at these measurements are around 20:1 far exceeding Redfield ratio for N:P in algae (7.4:1) or the TN:TP ration in sewage of 5,5:1, see ref. /3/. The high TN: TP ratio in these measurements show a potential P limitation situation for the phytoplankton where no N-fixation will happen. Other factors have to explain the high TN values.

In *Figure 21* the simulated concentration of total N in February 2000 are presented. As for BOD and chlorophyll the highest concentrations are found in the western and north-western area of the Bay.

The simulated and measured total P and phosphate are presented in the *Figures 22 to 24*. The simulated TP and phosphate concentrations fits in between the measured values for all stations except station GN43 and GN42 where the simulated values are slightly to high. A planplot of the simulated average total P concentration in February is presented in *Figure 25*. As for the other presented parameters the concentration is highest in the western and north-western part of the Bay.

It may be concluded that the Eutrofication model is calibrated sufficient to simulate the future water quality situation with both increased and decreased load.

(5) Mass balance of BOD, TN and TP

A mass balance for carbon, TN and TP covering the Bay has been established for the year 2000, see *Table 2*.

The mass balance for carbon is presented in *Table 2* In total the load of BOD converted into detritus C is 100.484 ton and the net production of phytoplankton C is 296.848 tons. The load form land thereby contributes with 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, 22463 tons is exported to the Atlantic 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, see ref. /4/ but higher than denitrification rates of 2 ton N/km2/year found in 9 temperate Danish bays, ref /5/. 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 6716 ton pr. year enters the Bay from land of which 6149 tons is exported to the Atlantic. 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), ref /6/.

Table 2 Mass balance for carbon, total N and total P based on an EU simulation of 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 dos not indicate that a significant N fixation occur in the Bay.

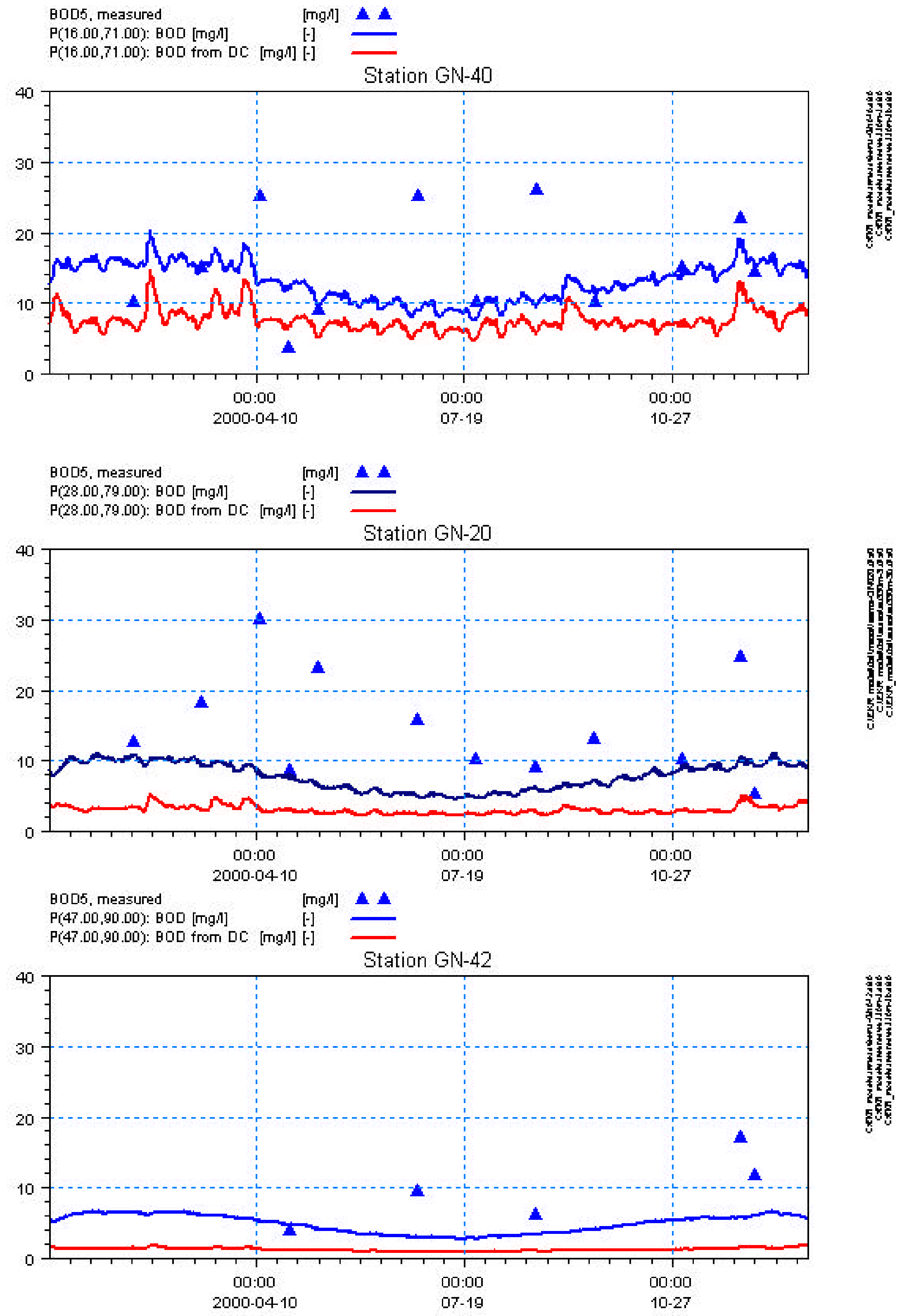

Figure 9 BOD total and BOD from DC at 3 stations making a gradient from Rio S.J.Meriti north of Ilha do Governador

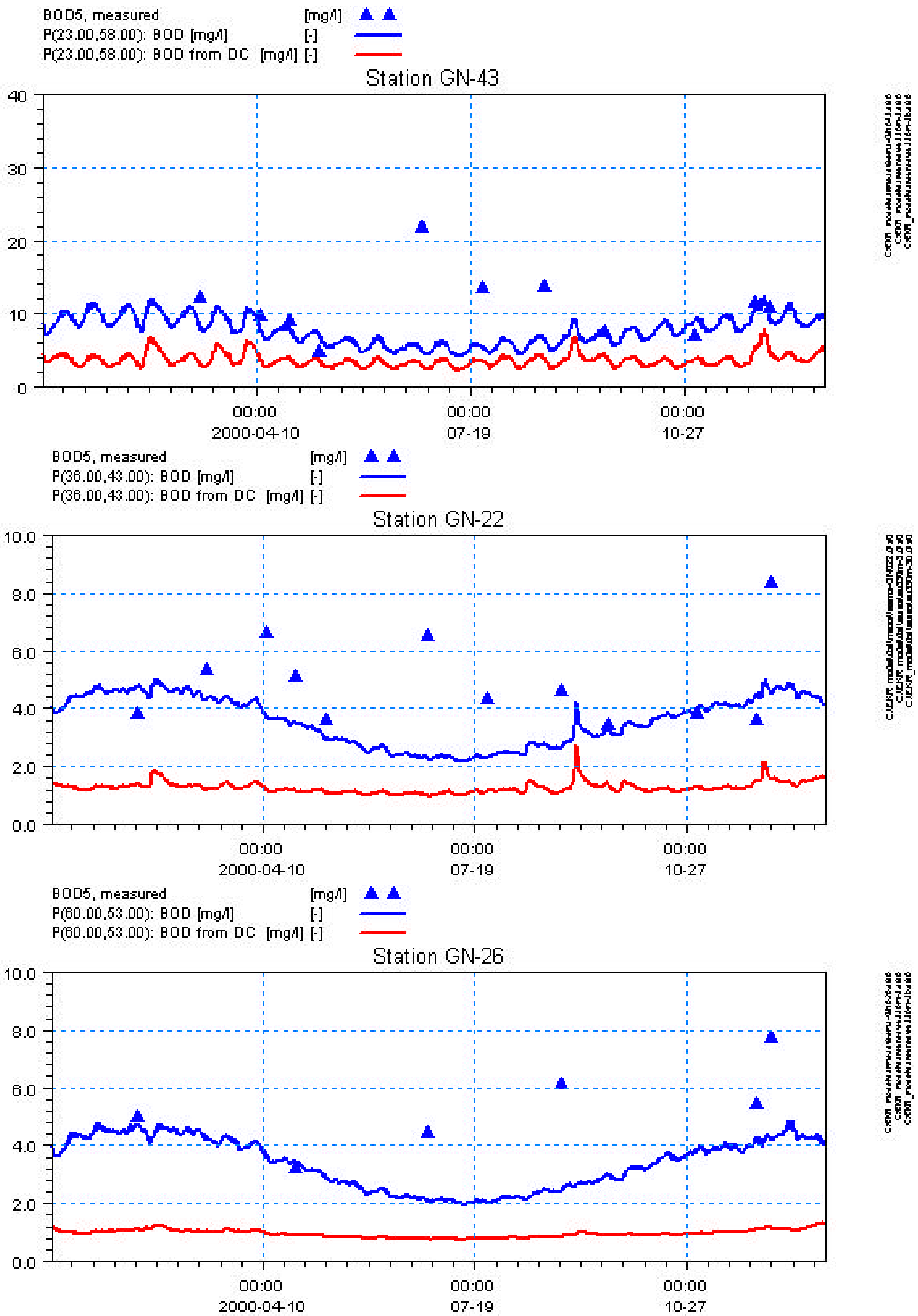

Figure 10 BOD total and BOD from DC at 3 stations making a gradient south of Ilha do Governador

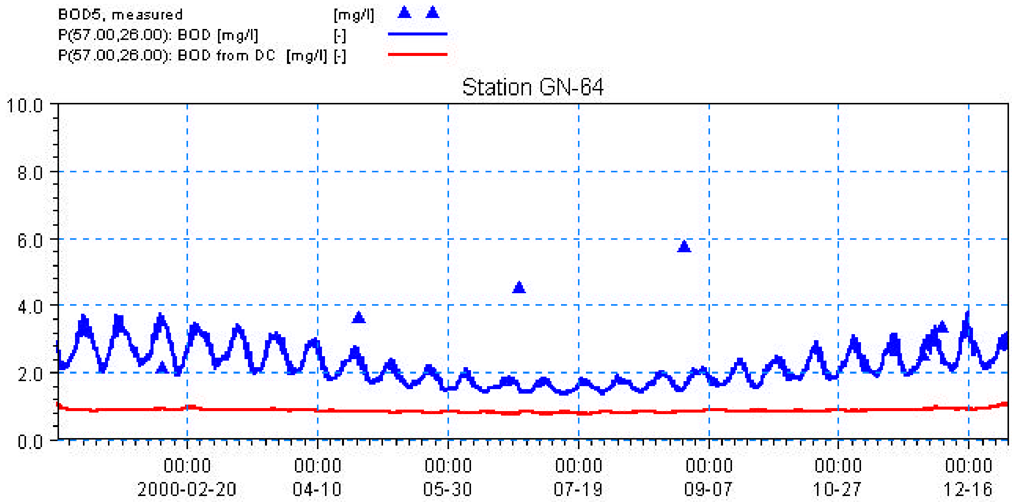

Figure 11 BOD total and BOD from DC at the entrance to Guanabara Bay

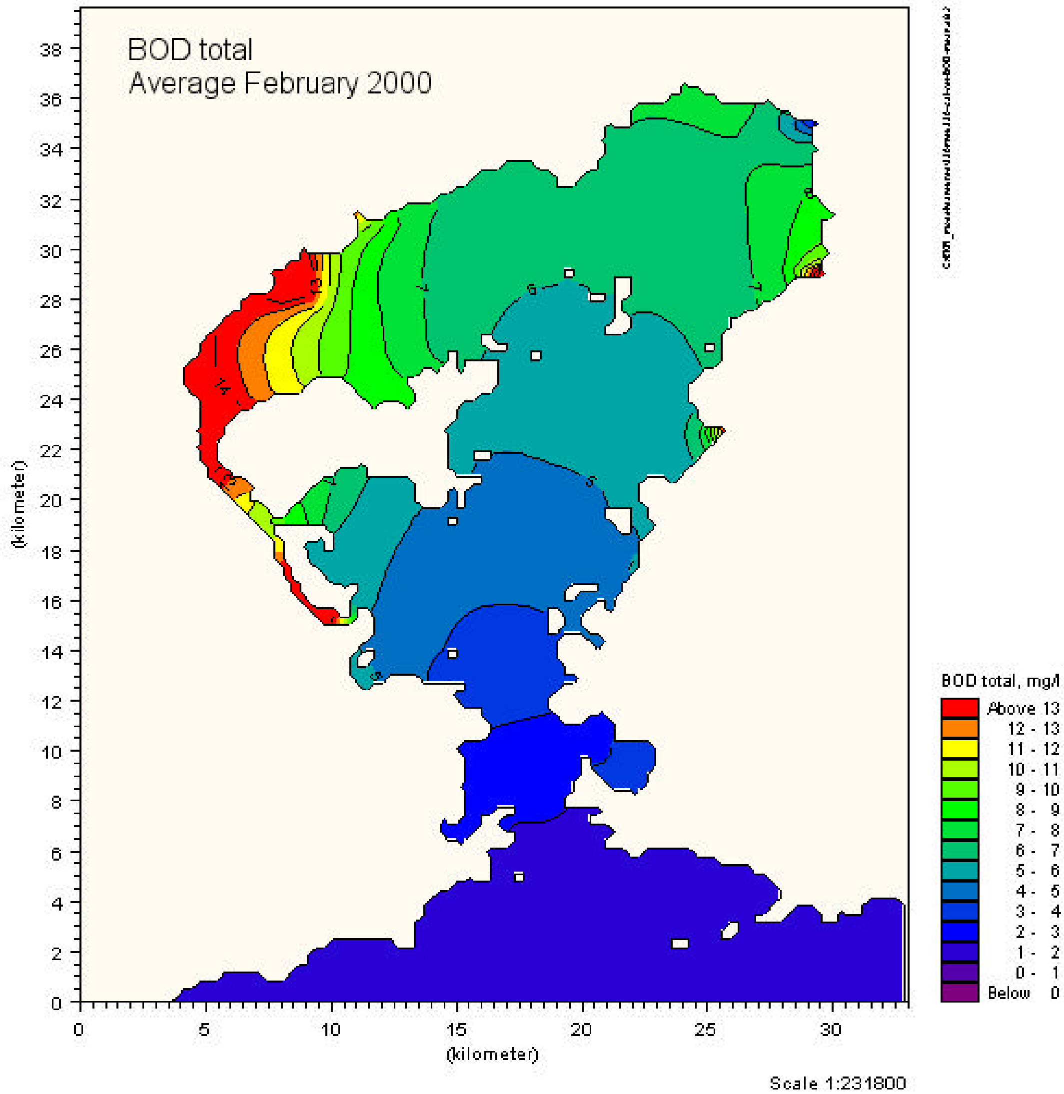

Figure 12 BOD total average of February year 2000

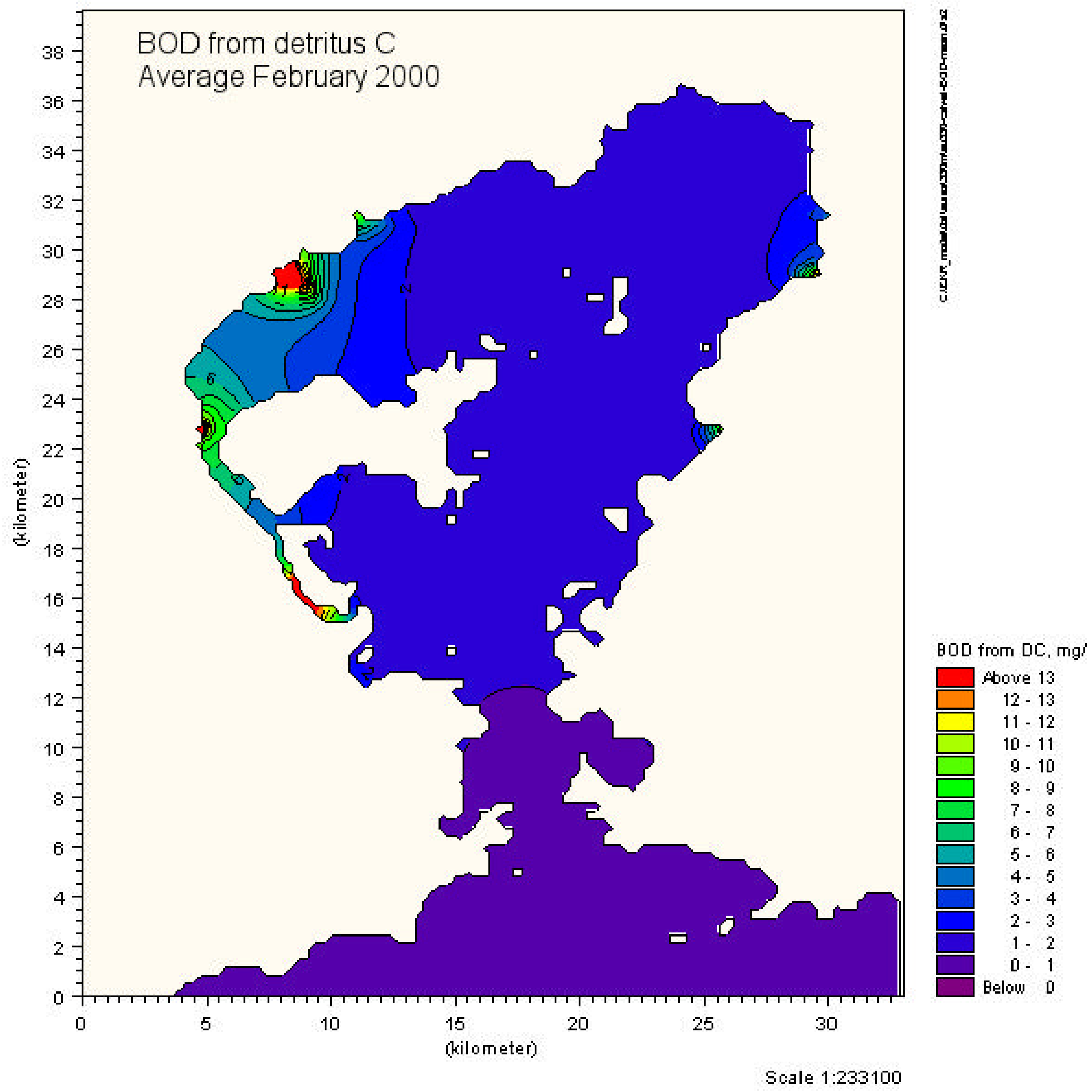

Figure 13 BOD from DC, average of February year 2000