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A System-Based River Simulation: Model Validation and Assessment of Mogi-Guaçu River, São Paulo, Brazil

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ABSTRACT

São Paulo State is located in the southeast region of Brazil, which represents less than 12% of Brazilian water resources and is the biggest water consumer in the nation. Mogi-Guaçu is a São Paulo State watershed and its main river suffers from, i.e., erosion, siltation, flooding and low water quality. Water quality problems are mainly due to non-point pollution from agricultural sources and point discharges from municipal and industrial sources. The Brazilian water quality database is in a developing stage and just a few rivers have been studied for modeling purposes. Therefore, the use of highly complex and data demanding models is not practicable for most watersheds. The systemic model presented here provides an adequate simulation tool suitable for use by the Company of Environmental Sanitation database of São Paulo State. This work makes use of the Energy System Language for modeling. The river is longitudinally modeled as a web of inter-connected compartments and individually described for each control volume by differential equations. The model simulates some ordinary variables (dissolved oxygen, total phosphorus, organic matter) and also includes unusual and biotic variables (turbidity, organic matter in the sediment, benthic organisms and fishes) that were considered indispensable to simulate a turbid river with high sediments and organic matter content. The simulator was coded in Matlab 6.5 and a visual interface was developed in order to guide the users in handling the large variety of incoming data. Results show a good fit between model results and experimental data.

INTRODUCTION

One of the first Brazilian experiences in water resources management was the creation of the water code in 1934, which was a bureaucratic model that was intended to regulate multiple uses of water resources. Since this beginning the management has made significant changes and the model currently adopted is an integrated participative systems model.

The regional distribution of the water resources in Brazil is 70% in the North region, 15% in the central west, 12% to the south and southeast and 3% in the north east region (BNDES, 1997).

São Paulo State is located in the southeast Brazilian region, which represents the biggest water consumption in the nation. The Water Resources Agency of São Paulo State has an advanced process of water resources management with 20 watershed management committees. Groups from different social sectors compose these committees. These committees are a relatively new kind of organization in Brazil and are responsible for developing the watershed management plan. They create documents that contain compiled information on water resources; however, most of them do not contain strategies, plans, action steps or future scenarios of sustainability.

Mogi-Guaçu is a watershed in São Paulo State and erosion, silting, flooding and low water quality are causing problems in its main river. The water quality problems are mainly due to nonpoint sources of pollution from agriculture and municipal and industrial point sources.

The Brazilian water quality database is in a developing stage and few rivers have been studied for modeling purposes. Therefore, the use of highly complex and data demanding models is not practicable. An adequate model suitable to the Brazilian database can be a useful tool for watershed planning.

A system model was applied to evaluate the dynamics of a Brazilian lake (Rivera, E. C. et al., 2007) but there is no system-based studies or model to assess and simulate the water quality and the ecological stability of a river.

In order to support the committees to improve Brazilian Basin Planning this study applied a dynamic systems model to evaluate a watershed and to understand the main aspects of human impact on water quality and biotic variables.

METHODOLOGY

Study Area

Mogi-Guaçu is a watershed situated in the northeast of São Paulo State (Figure 1). The stretch of river studied here is located between two cities (Mogi-Guaçu and Conchal) and has two main tributaries (Mogi-Mirim and Oriçanga) and a point source of pollution (Paper Industry).

The 30km section of river (see Figure 2) was divided into ten (10) compartments. The distances between the upstream point (point 1) and tributaries, river Mogi-Mirim and Oriçanga, are 3.22 and 18.07 km, respectively.

Models Description and Calibration

The model, detailed in Scariot (2007), is based on a systematic evaluation of the river characteristics and is pictured in Odum's energy language (Odum, H.T., 1983, 1996). The river is longitudinally modeled as a web of interconnected compartments individually described for each variable and control volume. The physical model described in this work was inspired in models suggested by Odum (1983) and Schnoor (1996) applied by Whitehead et al. (1997) and Sincock et al. (2003).

Figure 3 shows the web and the compartment model with the multiple inputs, outputs, internal processes and interactions that result in the model.

Differential equations were written for each variable based on previous concepts and on the mathematical expressions associated with the energy language. The differential equations are shown below, and coefficients are defined at Table 1.

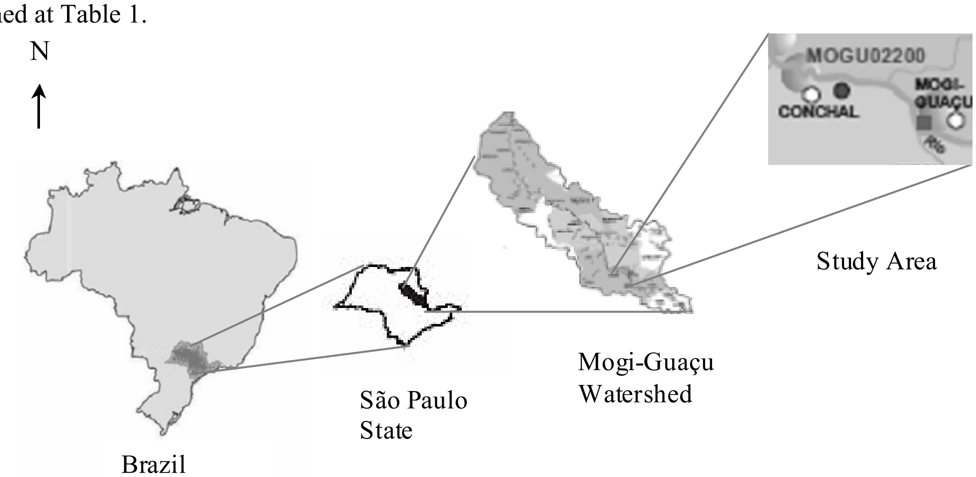

***Figure 1**. Location of the Study Area.*

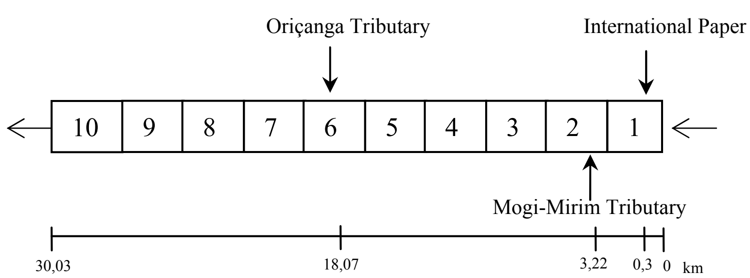

***Figure 2**. Distances between the main tributaries and point sources of pollution.*

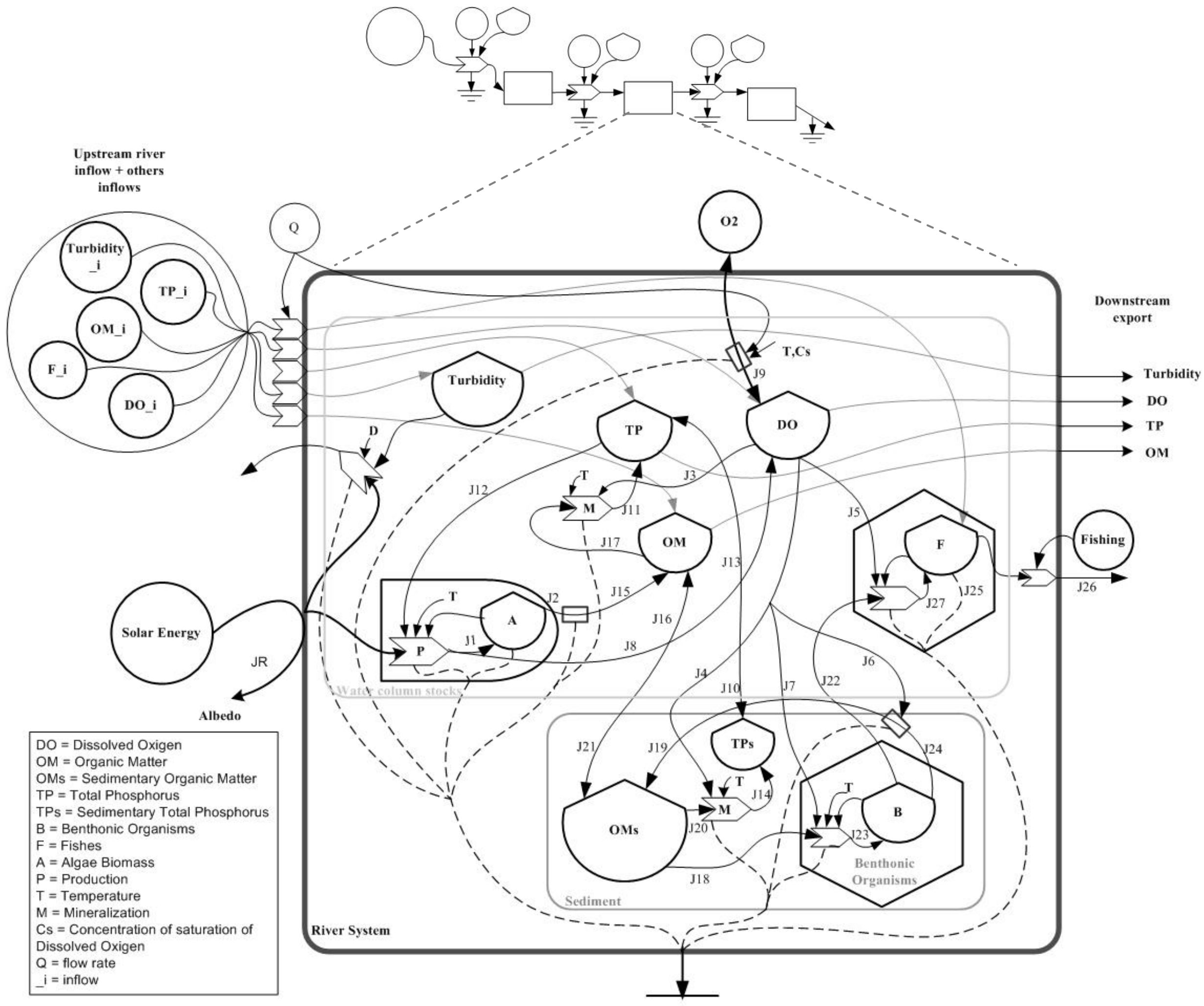

Figure 3. *Systemic Diagram for a river compartment.*

Total Phosphorus:

$d(TP)/d(t)= TP\_i*kpi-TP*kpo+TP*kpres - TPs*kps - kmax*A*(JR/JR+Imi)*(TP/Kmp+TP)+ OM*DO*kom;$

Sedimentary Total Phosphorus:

$d(TPs) / d(t) = TP*kps - TPs*kpres + OMs*DO*koms;$

Dissolved Oxygen:

$d(DO) / d(t) = DO\_i*ki - DO*ko + krea*(Cs -DO)+ kmax*A*(JR/JR+Imi)*(TP/Kmp+TP)*ko - DO*OM*kres - DO*B*F*kf - DO*OMs*krs - DO*B*F*kfo - DO*OMs*B*kbp;$

Algae Biomass:

$d(A) / d(t) = kmax*A*(JR/JR+Imi)* (TP/Kmp +TP) *kb - A*kom;$

Organic Matter:

$d(OM)/d(t) = OM\_i*ki - OM*ko + A*krOM - OM*ks - OM*DO*kom$

Sedimentary Organic Matter:

$d(OMs)/d(t) = OMs*DO*B*kbc + B*DO*kbi - OMs*DO*krOM + OM*ksOM$

Benthic Organisms:

$d(B)/d(t) = B*DO*kfish + OM*DO*B*kbp - B*DO*kdom$

Fish population:

$d(F)/d(t) = B*DO*F*kpf - F*kfishing$

The calibration involves many parameters rates and transfer coefficients. Results of calibration are shown in Table 1 and all the calculations are presented at the end of this paper.

Graphical User Interface

A graphical user interface was created (see Figure 4) to enhance the model efficiency and ease of use. The user interface offers some options for simulation and permits the user to choose the best parameters and equations as needed. Experimental data can be uploaded to be compared with simulated data.

Point and non-point sources of pollution can be classified and inserted in the model in each compartment. Point sources can be of different origin: industrial, urban sewage or a tributary. Non-point sources were classified according to the land use. The runoff is automatically calculated from rainfall data and watershed physical characteristics using the McMath (McMath, 1887) or other rational methods (Dooge, 1957), (Kuichling, 1889) and the mean concentrations are estimated from the literature (Larentis, 2004). Flow rate and rainfall data are used to recalculate inflow concentrations by mean of a mass balance.

Figure 4 shows the main interface. Each button opens a new window that allows one to insert or to upload model data. Results can be visualized in the main interface or be opened in another window which permits the user to change specifications and to save figures in different formats. The program offers the most important figures; if another format is desired it can be plotted using the Matlab command window.

RESULTS

In model validation, the variables dissolved oxygen (DO) and total phosphorus (TP) were compared with experimental data obtained from river sampling by CETESB[1]. Both the dissolved oxygen and total phosphorus are involved in many interactions that occur within the system, as shown by Figure 1; so these variables were assumed to be representative of the whole system.

Model was calibrated using 2006 data and validation was performed with calibrated parameters (Table 1) for 2003, 2004 and 2005. Results shown in Figure 5, for the years 2003 to 2006, demonstrate an agreement between calculated and observed data.

The variation of dissolved oxygen concentration in two dimensions (Figure 6), time and space, shows the substantial decrease of DO during summer[2] time and a recovery during the winter. It is also possible to see a day/night fluctuation in DO, with a DO decay during night and recovery during the day reaching acceptable levels (5 mg/L). This remarkable day/night DO fluctuation is characteristic of tropical climate rivers.

Figures 6 and 7 show both a longitudinal behavior along the river compartments and along time. First and second compartments receive large quantities of nutrients and organic matter that result in a decay of dissolved oxygen which tended to recover in the downstream compartments.

Dissolved oxygen concentration is around the limit required by legislation and this demonstrates the unsteadiness of the system. This fragile threshold between stability and instability of the system can be overlooked when the understanding of the processes depends only on experimental measures. In Brazil data taken over time is normally scarce and samples are often acquired during the peak production of dissolved oxygen by the algae biomass (from 11:00 to 13:00 h), such as the data measured by CETESB.

Urbanization can greatly influence both quantitatively (use of water resources) and qualitatively (different kind of pollutions) the water body and its ecosystem. Total phosphorus concentration (TP) (Figure 7) is above the legislated limit (0.025 mg/L) mainly in the first and second compartments of the river. The uptake of nutrients by the photosynthetic process is higher during summer which promotes a decline of TP in the water. The river receives two polluted tributaries (compartments 2 and 6), diffuse pollution from agricultural areas and urban centers and an industrial source in the first compartment. These pollution sources can be seen on the respective compartments (Figures 6 and 7) as an increase of TP and a decrease of DO. Pollutants undergo a natural self-depuration in which the water quality parameters recover longitudinally.

[1] Brazilian Technology Company of Environmental Sanitation

[2] Mogi-Guaçu River is located in the Southern Hemisphere where seasons are opposite with the Northern Hemisphere.

Table 1. Transfer Coefficients, Literature Data Sources and Final Calibrated Values.

N°	Rates	Values (mg L^{-1} h^{-1})	Description	Symbol	Literature Values (h^{-1})	Calibrated Values (h^{-1})	References
A: Algae Biomass							
1	J1=kmax*A*FI*FP	$2.3x10^{-2}$	Biomass Production	ka	$1.1x10^{-1}$	$1.1x10^{-1}$	Feresin,1994
2	J2=A* k_{rA}	$2.4x10^{-3}$	Biomass Respiration	k_{rA}	$1.2x10^{-2}$	$1.2x10^{-2}$	Odum, 1983
DO: Dissolved Oxygen							
3	J3=DO*OM*kresp	-	OM Mineralization	kresp	$5.3x10^{-3}$	$5.3x10^{-3}$	Bitar , 2002
4	J4=DO*OMs*krs	- $8.3x10^{-3}$	OMs Mineralization	krs	$5.5x10^{-3}$ $1.7x10^{-5}$	 $1x7x10^{-5}$	Bitar , 2002 Zheng, 2004
5	J5=DO*B*F*kf	$1.8x10^{-2}$	Fish Production	kf	$7.1x10^{-6}$	$7.1x10^{-6}$	Wetzel, 2001
6	J6=DO*B*kbd	-	Benthos Degradation	-	-	-	Herzfeld, 2001
	J7=kbp*DO*OMs*B	-	Benthos Production	-	-	-	Zheng, 2004
	J6+J7=	$1.7x10^{-3}$	Production Benthos - Degradation	kbp+ kbd	$4.4x10^{-6}$	$4.4x10^{-6}$	By difference
7	J8=kmax*A*FI*FP	$8.4x10^{-2}$	DO Production by biomass	kbo	$4.4x10^{-1}$	$4.4x10^{-1}$	Deas, 2000 Stoichiometric relation
8	J9=Equation 1	-	Reaeration	krea	-	-	Chapra
TP: Water Column Total Phosphorus							
9	J10=TP*kp_s	-	TP Sedimentation	kps	$5.9x10^{-5}$	$5.9x10^{-5}$	Deas, 2000
10	J11=DO*OM*kom	$8.3x10^{-7}$	Inlet - OM mineralization	kom	$2.7x10^{-8}$	$2.6x10^{-7}$	Stoichiometric relation
11	J12=kmax*A*FI*FP	$5.2x10^{-4}$	Consumption by biomass production	kmax	$5.5x10^{-3}$	$5.5x10^{-3}$	Stoichiometric relation Feresin E.G.,1994
TPs: Sedimentary Total Phosphorus							
12	J13=TPs*kp_{res}	-	TPs Resuspention	kpres	-	$1.9x10^{-3}$	Wetzel, 2001
13	J14=DO*OM_s*k_{oms}	$8.3x10^{-7}$	Inlet- OMs mineralization	koms	$1.7x10^{-9}$	$3.0x10^{-7}$	Stoichiometric relation
OM: Organic Matter							
14	J15=A*k_{rA}	$5.2x10^{-3}$	OM Production by biomass respiration	k_{rA}	$1.7x10^{-4}$	$1.7x10^{-4}$	Odum, 1983
15	J16=OM*k_{sOM}	$1.5x10^{-3}$	OM Sedimentation	ksom	$3.4x10^{-4}$	$3.4x10^{-4}$	Wetzel, 2001
16	J17=OM*DO*komd	- $2.6x10^{-3}$	OM Mineralization	komd	$8.2x10^{-4}$ $4.6x10^{-5}$	$4.2x10^{-5}$	Bianchini Jr.,2002 Wetzel, 2001
OMs: Sedimentary Organic Matter							
17	J18=OMs*DO*B*k_{bc}	$7.3x10^{-4}$	OMs Consumption by Benthos	kbc	$1.9x10^{-6}$	$1.9x10^{-6}$	Wetzel, 2001
18	J19=B*k_{bi}	$1.2x10^{-4}$	OMs from Benthos degradation	kbi	$2.4x10^{-7}$	$2.4x10^{-7}$	Wetzel, 2001
19	J20=OMs*DO*k_{rOMS}	- $1.7x10^{-4}$	OMs Mineralization	kroms	$9.9x10^{-4}$ $3.5x10^{-7}$	$9x10^{-5}$	Bianchini Jr.,2002 Wetzel, 2001
20	J21=OM*k_{sOM}	$1.5x10^{-3}$	OM Sedimentation	ksom	$3.4x10^{-4}$	$6.4x10^{-4}$	Wetzel, 2001
B: Benthic Organisms							
21	J22=B*k_{fish}	$2.5x10^{-4}$	Consumption of benthic organisms by fishes	kfish	$4.6x10^{-7}$	$3.05x10^{-7}$	Estimated

Table 1. Continued.

N°	Rates	Values (mg L^{-1} h^{-1})	Description	Symbol	Literature Values (h^{-1})	Calibrated Values (h^{-1})	References
22	$J23=OMs*DO*B*k_{bp}$	$5.6x10^{-4}$	Production of benthic organism	kbp	$1.5x10^{-6}$	$8.5x10^{-5}$	Wetzel, 2001
23	$J24=B*DO*kdom$	$1.2x10^{-4}$	B Degradation	kdom	$4.0x10^{-7}$	$2.4x10^{-7}$	Wetzel, 2001
F: Fishes							
24	$J25= F*k_{fi}$	-	Mortality	kfi	-	$1.0x10^{-8}$	Estimated
25	$J26=F*k_{fishing}$	-	Fishing outlet	kfishing	-	$2.0x10^{-8}$	Estimated
26	$J27=B*DO*F*k_{pf}$	-	Production	kpf	$1.04x10^{-3}$	$1.04x10^{-4}$	Chen, 1976

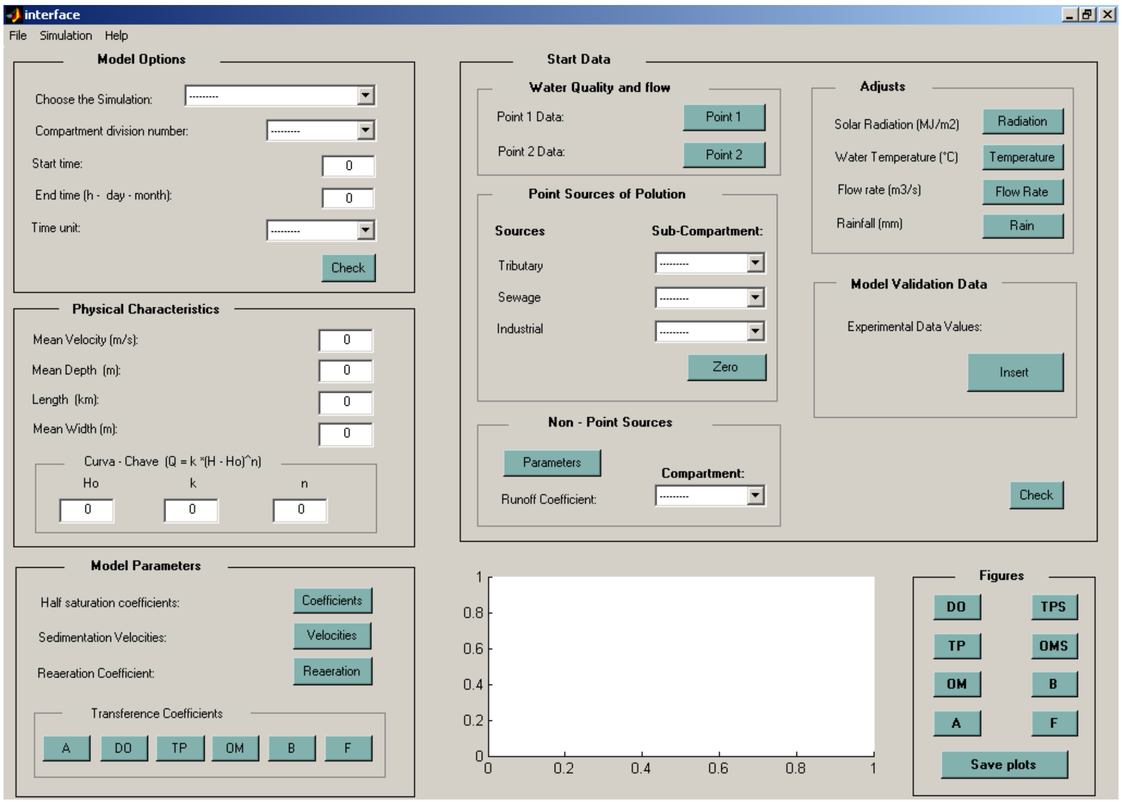

***Figure 4**. Graphical User Interface.*

CONCLUSIONS

Low dissolved oxygen and high total phosphorus concentrations show that the process of local development strongly affects the water quality of this river stretch and the probable consequences are ecosystem degradation and instability.

This stretch of Mogi-Guaçu River is in such a stage of degradation that, during most of the summer, pollution exceeds the Brazilian water quality standards set by legislation. In this case, conservation measures are no longer being sufficient, what is needed is a recovery action plan.

The lack of planning and data monitoring by government institutions generates data incompatible with the simulation user interests. Another problem preventing the broad application of water quality models is the lack of knowledge about point sources of pollution. For example, there is no current

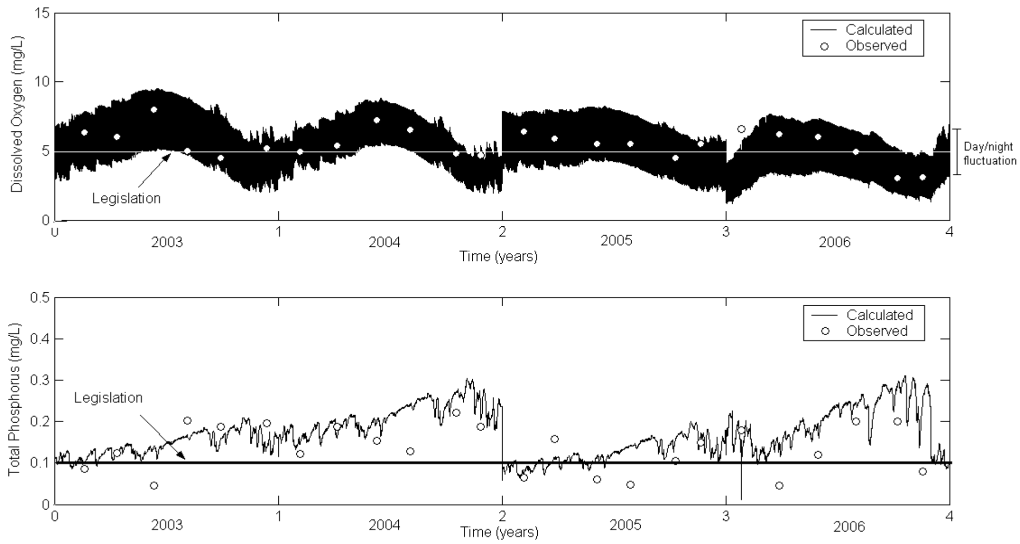

Figure 5. *Dissolved Oxygen and Total Phosphorus Validation.*

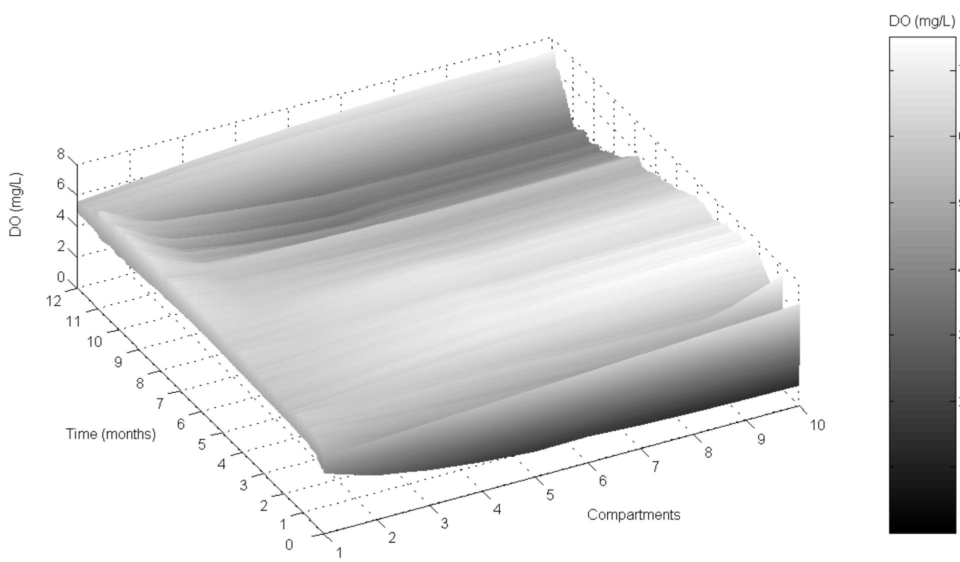

Figure 6. *Dissolved Oxygen longitudinal and time variation (2006).*

database of urban sewage pollution and of industrial effluents water quality. Therefore model results cannot be expected to exactly represent reality, if the initial conditions were estimated using average data.

To have an effective process of planning for multiple uses of water, it is fundamental to increase the monitoring points and this increase must be planned with knowledge of the pollution point sources, in addition to the tributaries. This knowledge is essential since water quality and the river ecosystem respond quickly to different sources of pollution.

One of the potential uses of models is to understand complex dynamics such as the water quality of a river. Despite the difficulties with its implementation, it is expected that the model will be used in a considerable number of Brazilian rivers.

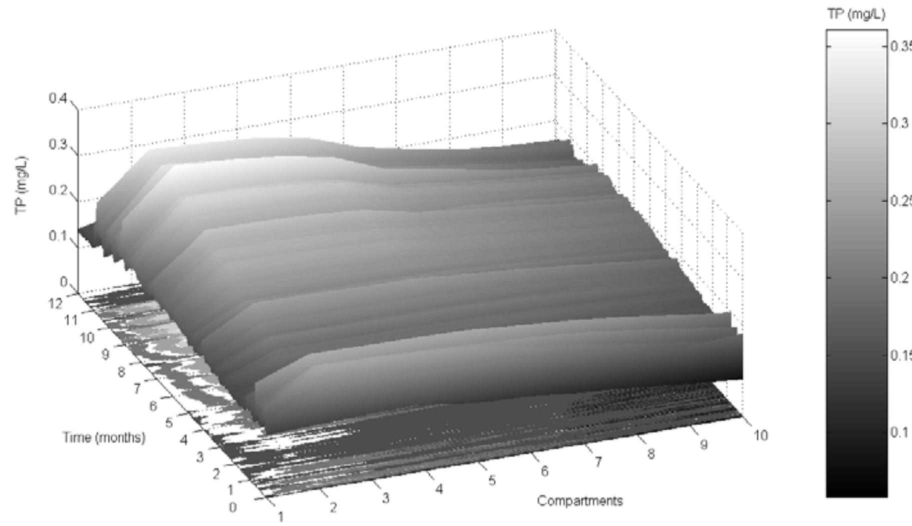

Figure 7. *Total Phosphorus longitudinal and time variation (2006).*

The next step is to use the model to evaluate river impacts of different future scenarios considering the economic and population growth, technical changes in agriculture, and the impact of environmental and social policies for watershed management.

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CALCULATIONS

A: Algae Biomass

1) Primary production – Data from Feresin (1994) points toward a primary production of 30 mgC $m^{-2}.h^{-1}$. Converting from mgC to mg de **Algae Biomass** (A), the equation to the **Algae Biomass is :** $C_{106}H_{263}O_{110}N_{16}P_1$ = 3550g of **Algae Biomass** correspond to 1272g of carbon (C106). Transforming the unities and considering the depth of 1.8 m; the primary production value is about: 5.23 10^{-2} mg A L^{-1} h^{-1}.

2) Respiration represents about 10% of primary production, so the respiration value is 2.27 10^{-3} mg L^{-1} h^{-1}.

DO: Dissolved Oxygen

3) Coefficient related to the oxygen consumption by the organic mater in the water column was calculated by Bitar (2002) as: 0.126 day^{-1}, this value was obtained from experimental data in the Mogi-Guaçu river floodplain.

4) Coefficient related to the oxygen consumption by the sedimentary organic mater, was calculated by Bitar (2002) as: 0.132 day^{-1}. In accord to Zheng (2004) and Herzfeld (2001), the oxygen demand by the sediment is (1.2 - 2.5) g m^{-2} day^{-1}, taking account that 2 g $m^{-2}day^{-1}$, and considering a sediment thickness of 10^{-1} m; the rate is: $8.3.10^{-3}$ mg L^{-1} h^{-1}.

5) Data from Wetzel (2001) shows a total production rate of fish (multi-species) for a tropical zone of $1.8.10^{-2}$ mg L^{-1} h^{-1}.

6) Data from Zheng (2004) shows that a liquid consumption from sediment of dissolved oxygen is about 2.5 g m^{-2} day^{-1}, assuming a sediment thickness of 10^{-1} m, results a consumption of 1.0 10^{-2} mg L^{-1} h^{-1}. The difference between the gross consumption and the sedimentary organic matter consumption (8.3 10^{-3}) gives the total oxygen consumption benthic organisms (1.7 10^{-3} mg L^{-1} h^{-1}).

7) Concerning that dissolved oxygen (DO) produced by algae biomass is 1.6 mg (OD) for each gram of algae biomass, therefore the OD production is 8.37 10^{-2} mg L^{-1} h^{-1}.

8) The reaeration rate was calculated by the following equations:

TR = krea*(Cs - DO); where Cs is the saturation oxygen concentration in the water column. Cs is a temperature function calculated by:

$Cs = 14.652 - 0.41022*T + 0.0079910*T^2 + 0.000077774*T^3$; where T (°C) is the water temperature.

The re-aeration coefficient was calculated by the followings empiric relations (Chapra, 1997):

	O'Connor-Dobbins (1956)	Churchill (1962)	Owens and Gibbs (1964)
Equation	$krea = \frac{3{,}93v^{0,5}(\theta)^{(T-20)}}{D^{1,5}}$	$krea = \frac{5{,}026v^{1}(\theta)^{(T-20)}}{D^{1,67}}$	$k_{rea} = \frac{5{,}32 * v^{0,67} * (\theta)^{(T-20)}}{D^{1,85}}$
Velocity	0.15 – 0.49	0.55 – 1.52	0.03 – 0.55
Depth	0.3 – 9.14	0.61– 3.35	0.12– 0.73

where v(m/s) is the mean velocity of the water flow rate, D(m) is the mean depth, T(°C) is the water temperature and TETA is the temperature correction coefficient.

TP: Total phosphorus

9) Total phosphorus sedimentation rate was calculated from the sedimentation velocity divided by the mean depth. According to Deas (2000) the phosphorus sedimentation velocity is the interval (0.002 – 0.2) m day^{-1}, assuming an equilibrium between sedimentation and ressuspention.

10) According to Reichert P. (2000) the chemical formulation of the organic matter mineralization process can be known using the elements conservation principle for C, H, O, N, P. Resulting:

CαC/12 HαH OαO/16 NαN/14 PαP/31 +

The coefficients, to available dissolved organic substances fast degraded by heterotrophic organisms, are: αC=0.57, αH=0.08, αO=0.28, αN=0.06, αP=0.01. The stoichiometric relation results:

$1MO + 0.056\ O_2 + 0.0036\ H^+ => 0.033 H_2O + 0.047\ CO_2 + 0.0043\ NH_4^+ + 0.00032\ HPO_4^{2-}$

Thus, each 1gMO produce 3.2 10^{-4}g of total phosphorus in the organic matter mineralization process. The mineralization rate is 2.6 10^{-3} mg OM L^{-1} h^{-1} and the phosphorus production rate is 8.3 10^{-7} mg TP L^{-1} h^{-1}.

11) Stoichiometric proportion for the phosphorus used in the primary production is 0.01 mg of total phosphorus for each 1mg of algae biomass. Therefore, the rate uses of total phosphorus in the primary production is 5.23 10^{-4} mg TP L^{-1} h^{-1}.

TPs: Sedimentary Total Phosphorus

12) Equilibrium between sedimentation and ressuspention was assumed according to Gayle and Odum (1975) item 9.

13) From process described in item 10, mineralization rate of sedimentary organic matter is 2.6 10^{-3} mg OM L^{-1} h^{-1} and total phosphorus production is 8.3 10^{-7} mg TP L^{-1} h^{-1}.

OM: Organic Matter

14) Assuming respiration 10% of primary production, therefore, the respiration rate is 5.23 10^{-3} mg TP L^{-1} h^{-1}.

15) Wetzel (2001) work points toward a rate value for sedimentary organic matter of 21.7 gC m^{-2} $year^{-1}$. From stoichiometric relations of organic matter mineralization, the organic carbon conservation is given by: orgC= αC. OM where (αC = 0.57g C), therefore, the organic matter sedimentation rate is 1.65. 10^{-3} mg OM L^{-1} h^{-1}.

16) Organic matter mineralization was measured by Santino (2002). Coefficient value of aerobic mineralization of stable organic matter (fúlvic ácid (AF) + húmic ácid (AU)) is 8.2.10^{-4} h^{-1}. Data from Wetzel (2001), shows that the mineralization rate of dissolved organic carbon (DOC) is 20.6 gC m^{-2} $year^{-1}$. From stoichiometric relations it is possible to find a organic matter mineralization rate of 2.6 10^{-3} mg OM L^{-1} h^{-1}.

OMs: Sedimentary Organic Matter

17) According to Wetzel (2001) the carbon consumption of benthic organisms is 100 mgC $m^{-2}day^{-1}$, converting to organic matter the value is 7.3 10^{-4} mg OM L^{-1} h^{-1}.

18) According to Wetzel (2001) the benthic organisms degradation rate is 16 mgC m^{-2} day^{-1}, converting to organic matter the value is 1.16 10^{-4} mg OM L^{-1} h^{-1}.

19) Santino (2002) calculate the coefficient of aerobic mineralization of unstable organic matter from empirical data, the value is 9.9 10^{-4} h^{-1}. Data from Wetzel (2001) point toward a mineralization rate of particulate organic carbon of 8.6 g C m^{-2} $year^{-1}$. Converting to organic matter the value is 1.7 10^{-4} mg L^{-1} h^{-1}. According to Wetzel (2001), the velocity of simple organic solutions uses is larger in the sediment than in the water column.

20) Described in (15).

B: Benthic Organisms

The benthic community of Mogi-Guaçu river is basically formed by *Annelida Cl. Oligochaeta* and *Fam. Chironomidae*. The values were estimated from Brigante (2003).

21) Estimated.

22) Data from Wetzel (2001) shows a benthic production of 49 g m^{-2} $year^{-1}$ or 5.6 10^{-4} mg L^{-1} h^{-1}.

23) Described in (18).

F: Fishes

24) Estimated; 25) Estimated; 26) Chen (1976) propose a value of 0.01 day^{-1}.