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Finite Element Modelling of the Hydrodynamics and Water Quality of the Patos Lagoon System, Brazil

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ABSTRACT

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The Patos Lagoon and estuary system is of major importance to the communities of the Rio Grande do Sul State, with the consequence of being subject to the influence of multiple and conflicting human impacts, many of which have the potential for pollution. Such activities include recreation and tourism; abstraction of drinking water and the disposal of domestic waste water; the industries of fertiliser production, fish processing, and petroleum refining; artisanal fisheries and aquaculture; agriculture; and navigation. Within the boundaries of the estuary are several shallow embayments, which are degraded environments suffering from the effects of pollution from many of these sources. A 2-dimensional finite element model (TELEMAC-2D) has been calibrated to simulate the hydrodynamics of the entire system and work is in progress to prepare the water quality module (WQFLOW-2D) for the simulation of nutrients, primary production and bacteria. It is intended to use the model as a predictive tool to aid the decision making process for the rehabilitation and management of the shallow embayment of Saco da Mangueira adjacent to Rio Grande; with a specific objective to assess the suitability and capacity of the waters of Saco da Mangueira to support a programme of shrimp aquaculture. The data used for calibration and validation of the model have spanned the last 15 years of research conducted by the Federal University of Rio Grande, and include recent hydrodynamic and water-quality field studies specifically designed to meet the requirements of this research project. Results from the calibration and validation of the hydrodynamic model are presented here, together with initial parameterization of the water quality module.

ADDITIONAL INDEX WORDS: *Nutrients, shallow embayment, eutrophication.*

INTRODUCTION

The Patos Lagoon is located in the state of Rio Grande do Sul on the southern coast of Brazil between 30 to 32°S and 50 to 52°W (Figure 1). The lagoon has a warm temperate climate influenced by the St Helena sub-tropical anticyclone in the South Atlantic, with an average of 223 days/y sunshine (KLEIN, 1997), and average rainfall of 1750 mm/y (KNOPPERS & KJERFVE, 1999). The region is microtidal due to its proximity to an amphidromic point in the South Atlantic, with a mean tidal range of just 0.47m. It is the largest coastal lagoon in South America, extending more than 250km NE to SW, with an average width of 40km, and an area of 10,360km^2 (KJERFVE, 1994; CALLIARI, 1997; KNOPPERS and KJERFVE, 1999). The dominant factors influencing the circulation and residence time of water are non-tidal, i.e. winds, river flow, rainfall and evaporation, which have been demonstrated in studies by MÖLLER *et al*. (1996); MÖLLER (1996) and FERNANDES (2001). The average depth of the lagoon is 5m, however, the bathymetry is highly variable and characterised by natural and artificial channels with depths of 89m, large adjacent areas of >5m, and shallow marginal bays (FERNANDES, 2001). The Patos Estuary is bar-built and has an area of 971km^2. The width of the upper estuary is 30km, which reduces over a distance of 50km from the tidal limit at Ponta da Feitoria to the South Atlantic, where contact is through a single tidal inlet 22km by 2km and 12m deep, reducing to 700m wide and 18m deep at the entrance (MÖLLER & CASTAING, 1996; CALLIARI, 1997; NIENCHESKI *et al*., 1999). The bottom topography of the estuary is dominated by shoals of 15m, with 80% being <2m and 50% <1m (NIENCHESKI *et al*., 1999). There are a number of shallow embayments located in the southern region of the estuary surrounding the city of Rio Grande; one of which, Saco da Mangueira, is an oval semi-enclosed bay situated to the south of the city, with an area of 23km^2 and a maximum depth of just 1.5m (BAUMGARTEN *et al.,* 1995).

The total watershed of the Patos system is 201,626km^2 (including 51,194km^2 from the Mirim lagoon situated to the south-west), of which 75% enters from the north via the Guaiba River (CALLIARI, 1997; WINDOM *et al*., 1999; NIENCHESKI *et al.,* 1999), which receives 85% of its flows from the rivers Jacui and Taquari. The average flow from the Guaiba River is 1500m^3/s. The Mirim and Patos lagoons are connected via the São Gonçalo Channel which is 70km long and discharges an average freshwater flow of 600m^3/s to the Patos Estuary. Another important source of freshwater to the system is the Camaquã River which is situated close to central region of the lagoon and provides an average flow of 300m^3/s.

The main cities and ports of the region are located at Porto Alegre (population 1,500,000) at the north of the lagoon, Pelotas (population 300,000) in the upper region of the estuary, and Rio Grande (population 200,000) in the southern region of the estuary (NIENCHESKI *et al*., 1999). One of the most important features of the lagoon system to the livelihood of its inhabitants is the provision of nursery grounds for commercial fish and shrimp in sheltered areas, which sustain a fishery that produces an average of 182 kg/ha/yr (MÖLLER and CASTAING, 1999). As a consequence of the activities of the communities that border the lagoon system, the waters are subject to the influence of impacts which have the potential for pollution. Such activities and impacts summarized by SEELIGER and COSTA (1997) include recreation and tourism; abstraction of drinking water and water for irrigation, which reduces the freshwater flow to the system and results in modifications to flushing, salinity and nutrient balance, which ultimately affects the life cycles of commercially important fish and crustaceans; the disposal of domestic waste water; the industries of fertiliser production, fish processing, and petroleum refining; artisanal fisheries and aquaculture; agriculture; and navigation. The input of nutrients from many of these activities have lead to eutrophication, algal blooms, and blooms of potentially toxic blue-green alga (*Microcystis aeruginosa*). Environmental

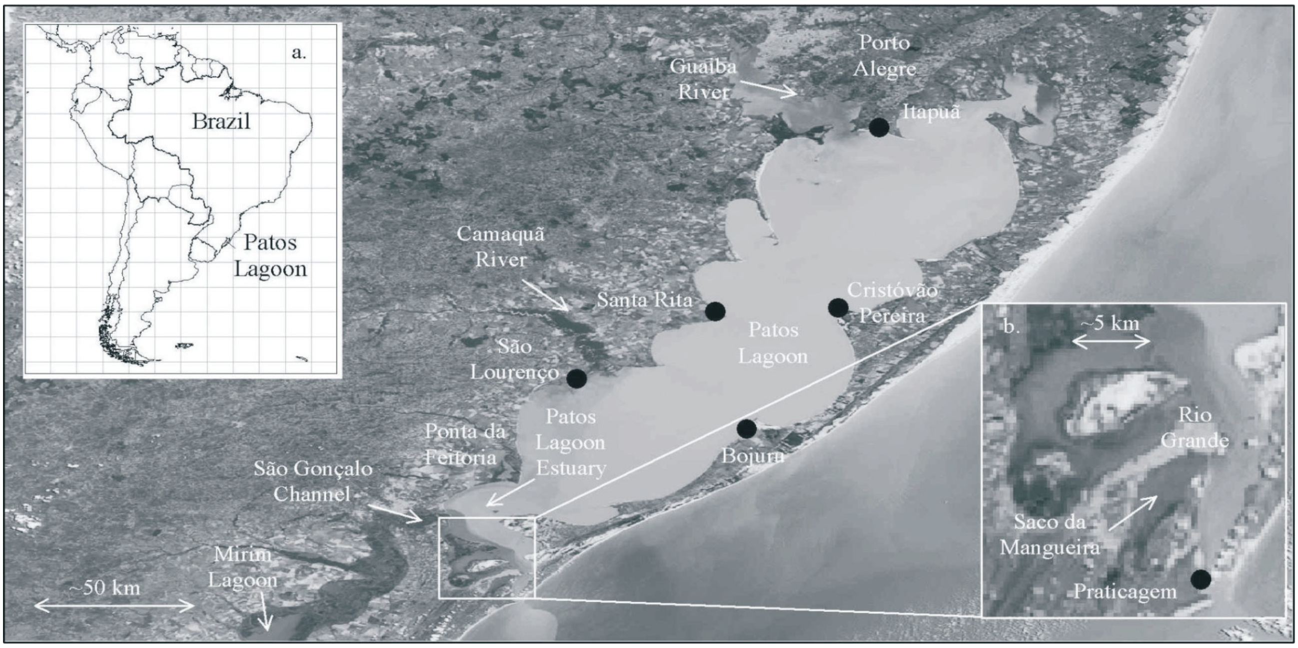

Figure 1. Image of the Patos Lagoon taken by a Multi-angle Imaging SpectroRadiometer aboard the "Terra" Satellite on 27th December, 2001 (NASA/GSFC/LaRC/JPL, MISR Team); a. South America; b. Southern part of Patos Lagoon Estuary showing Saco da Mangueira. Black markers show the locations of water level recorders during 1999.

degradation has also occurred through the input of hazardous materials such as dissolved trace metals (Cu and Pb) from industrial effluents and mining activities, agrotoxins from pesticides, and hydrocarbons discharged by vessels through washing of tanks. Finally, both natural and human induced processes including dredging activities in the navigation channel, and the construction of jetties at the mouth of the estuary, have lead to modifications to water depths leading to changes in circulation patterns, resulting from inputs of suspended sediments, and shifting sediment deposition patterns.

Of particular relevance to this study is the Saco da Mangueira, which receives effluent from multiple sources identified by ALMEIDA *et al*. (1993) and TAGLIANI and MADUREIRA (2001) including untreated domestic wastewater from housing areas ranging from slums to condominiums; discharges from the industries of meat processing and refrigeration, petroleum refining, fishing, soya oil, and wool processing; and a significant input of phosphates from one of the largest fertiliser plants in South America (~106 tons/y 1995) (NIENCHESKI *et al.,* 1999). In addition, Saco da Mangueira lies adjacent to the main sewage outfall for Rio Grande which discharges untreated effluent from approximately 80% of the population of the city.

Studies by BAUMGARTEN *et al.* (2001, 1995, and 1982), NIENCHESKI and BAUMGARTEN (2000), SANTOS *et al.* (1997), PERSICH *et al.* (1996), PERSICH (1993), COSTA *et al.* (1982), KANTIN *et al.* (1981) have shown that the Saco da Mangueira is a degraded area. Mean levels of nutrients, for example, ammonium 17.47μM and phosphate 4.28μM greatly exceed levels typically found in non-polluted waters i.e. 5μM ammonium (DAY *et al.,* 1987), and 1μM phosphate (POMEROY *et al.,* 1965, AMINOT and CHAUSSEPIED 1983, DAY *et al.,* 1987).

Objectives

A two dimensional depth averaged finite element hydrodynamic model, TELEMAC-2D, has been calibrated to investigate the hydrodynamics of the Patos Lagoon system, and the results have been used to drive the water quality module WQFLOW-2D for the simulation of various chemical parameters with particular geographical focus on the Saco da Mangueira. Calibration and validation of the hydrodynamic model are presented here, together with the results to date from initial sensitivity tests using the water quality module WQFLOW-2D. The work is in progress, with the intention of investigating the effects on water quality from a range of management scenarios such as location of sewage outfalls; improvement in water exchange and flushing; and the suitability and capacity of the waters of Saco da Mangueira to support a programme of shrimp aquaculture.

HYDRODYNAMIC MODELLING

TELEMAC-2D is a two dimensional depth-averaged fluid flow model developed by ElectricitÈ de France, Laboratoire National d'Hydraulique, which solves the Barré de Saint-Venant equations derived from the three dimensional Navier-Stokes equations.

Generation of the Mesh and Boundary Conditions

The mesh was constructed from triangular finite elements, with the space discretisation based principally on the density of the soundings, which were digitised from various Brazilian nautical charts and supplied by the Federal University of Rio Grande (FURG). The mesh is presented in Figure 2 (3734 nodes and 6717 triangles).

A coarse resolution of 6000m was imposed in the body of the lagoon since this area was not the main focus of the modelling study, but would be used to provide inputs to the southern part of the Patos system. A more refined grid was required for the Guaiba river, estuarine and navigation channel areas, with inter-node distances closer to the mean distance between soundings. A maximum resolution of around 200m was selected for Saco da Mangueira reducing to just 30m at the narrow entrance (175m) from Saco da Mangueira to the estuary.

The open boundary conditions were defined by prescribed velocity (U, V) and free elevation (ζ) for the freshwater inputs Guaiba River, Camaquã River, and the São Gonçalo Channel; and prescribed elevation and free velocity at the ocean boundary at Praticagem.

Sensitivity Analysis of River Flow, Wind Influence, and Free Surface Elevation

An initial set of 30 short simulations was completed to investigate the sensitivity of the system to variations in tidal

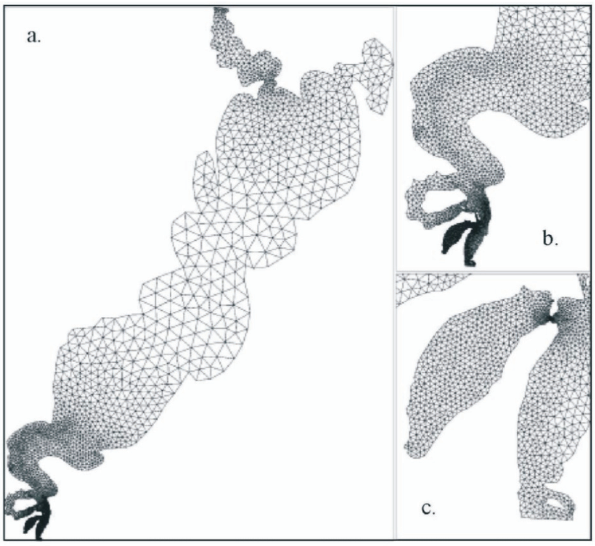

Figure 2. Space Discretisation for Model; a. Entire Domain; b. Estuary; c. Saco da Mangueira and Access Channel.

elevation (a constant elevation of 0.3m, and an artificial semi-diurnal elevation with a range of 0.3m); river flow (10,000, 3162, and 1000m^3/s); and wind (0, 5, and 10 m/s SW, 5 and 10 m/s NE). The results for these simulations firstly demonstrated the diminutive importance of tides on the barotropic circulation, compared to wind and river flow, which concurs with previous studies conducted by, for example, MÖLLER & CASTAING (1996). Secondly, a positive gradient was evident from Feitoria to Itapua, for all flows influenced by a SW wind, and a negative gradient for strong winds from the NE, i.e. water piling up downwind. Strong winds appeared to be the dominant factor over low and medium river flows, which was in agreement with the explanation given by MÖLLER (1996) for the local wind dominating the circulation through a set-up/set-down mechanism of oscillation for the central and inner lagoon.

Calibration of the Source Terms

The sensitivity of the model to the parameters of friction, eddy viscosity, and Coriolis force, had previously been evaluated in detail by FERNANDES (2001), with the indication that variations of both the eddy viscosity and the Coriolis force had little effect on the circulation of the lagoon. However, since the extent of the domain and the resolution of the mesh used for this study differed significantly from the work of Fernandes, it was necessary to re-evaluate the sensitivity of the model to the principal source terms of bed and surface friction.

The sensitivity and initial calibration of the model to bed friction was investigated using coefficients defined by the laws of Chezy (C), Manning (n), and Nikuradse (k_s). A range of model simulations for the 3 day period 6th to 8th August 1999 were completed for friction coefficients: C = 80, 60,40; n = 0.01, 0.015, 0.02, 0.025, 0.03, 0.035; K_s = 0.001, 0.004, 0.06, 0.1, 0.13, 0.25. Tidal elevation and wind data measured at Praticagem were used to force the model, together with mean monthly river flows (Table 1). Wind data at Praticagem were

Table 1. *Mean Monthly River Flows in 1999.*

Month	Guaiba River (Taquari + Jacui) (m^3/s)	Camaquã River (m^3/s)	São Gonçalo Channel (m^3/s)
April	1074	243	457
May	611	159	260
June	2255	458	958
July	2469	497	1050
August	1257	277	534
September	1735	364	737
October	2148	439	913

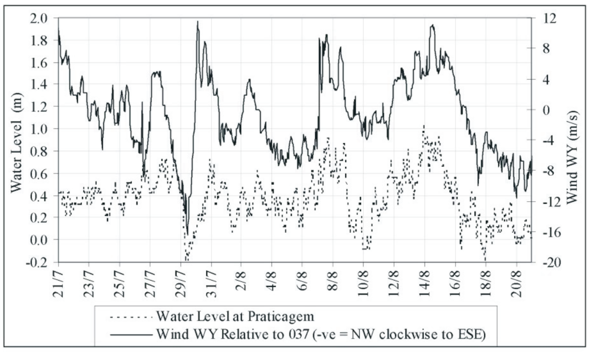

Figure 3. Observed Elevation and Wind at Praticagem 21st July to 21st August 1999.

considered representative of the whole model domain, since comparison with a concurrent set of data measured at Santa Rita gave a correlation coefficient (R^2) of 0.83.

Results showed the magnitude of velocity to decrease with increasing magnitude of both Manning and Nikuradse friction coefficients, and conversely, decreases with decreasing Chezy coefficients; as would be expected from the formulation of these laws.

Comparisons between model predictions and measured data were quantified using two measures of correlation: R^2, and Var_{pred}, the predictable variance, which is the proportion of the observations the model is able to predict, given as a percentage. Measured data were available from five water level recorders located throughout the lagoon during 1999 (see Figure 1), and current velocities measured at Praticagem. Optimal agreements between model output and observations were produced with a Chezy coefficient of 80 (R^2 = 0.82, Var_{pred} = 84%); a Nikuradse coefficient of 0.001 (R^2 = 0.82, Var_{pred} = 84%); and a Manning value of 0.015 (R^2 = 0.82, Var_{pred} = 83%). This is compared with the results of FERNANDES (2001) where the best correlation was achieved using a Manning coefficient of 0.0100.025; Chezy coefficient of 50; and Nikuradse coefficient of 0.008-0.01.

The sensitivity of the model to the effects of wind were evaluated by varying the coefficient of wind influence under conditions of a constant bed friction coefficient of k_s=0.001. A series of five simulations were completed with coefficients of wind influence computed from winds of 2.5, 5, 7.5, 10, and 12m/s. The model was run for a period of 31 days from 21st July 1999 to 21st August 1999 using the wind and water elevations presented in Figure 3. This period was considered to represent typical winter conditions of an underlying wind direction from the northerly sectors, punctuated by several clearly defined frontal systems passing through from the SW, e.g. for the 7th to 9th and 11th to 16th August.

Figure 4 shows the model output and longitudinal velocity observations for the wind coefficient of 1.61 x 10^{-6}, which gave the closest agreement (R^2 = 0.90, Var_{pred} = 88%).

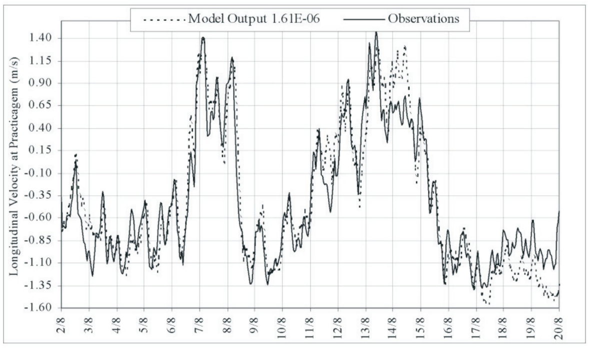

Figure 4. Modelled and Observed Longitudinal Velocity at Praticagem 2nd to 20th August 1999 Wind Coefficient 1.61x10^{-6}.

Model Validation

Following the successful calibration of TELEMAC-2D, the final step was to test the robustness by a process of validation using a further independent data set, modelled with the source terms derived from the calibration. The model was run for a period of 165 days from 19th April to 1st October 1999, using flows presented in Table 1 and the set-up shown in Table 2. Measured elevations and wind at Praticagem for the same time period were again used to force the model.

The results for modelled and measured elevations at two of the five gauging stations are presented in Figure 3. The R^2 and predictable variance values for the entire period were calculated: Farol de Itapuã (R^2=0.60, Var_{pred}=60%); Santa Rita (R^2=0.69, Var_{pred}=68%); São Lourenço do Sul (R^2=0.59, Var_{pred}=59%);

Bojuru (R^2=0.55, Var_{pred}=55%); and Rincão do Cristóvão Pereira (R^2=0.63, Var_{pred}=63%). The correlation for the longitudinal velocities at Praticagem for the period 2nd to 21st October were also very good (R^2=0.76, Var_{pred}=69%).

WATER QUALITY MODELLING

WQFLOW-2D is a finite element depth-averaged water quality module developed by HR Wallingford Ltd., used alongside TELEMAC-2D to simulate transport and mixing processes; biochemical interaction of solutes and suspended matter; oxygen and nutrient balance; and algal growth in estuaries, lakes and coastal waters (Figure 6). The advection-diffusion equation is solved separately for each parameter, with source terms provided by outfalls, river inputs and by the result of reactions between variables:

$$\frac{\partial(dC)}{\partial t}+\frac{\partial(duC)}{\partial x}+\frac{\partial(dvC)}{\partial y}=\frac{\partial}{\partial s}\left(dDs\frac{\partial C}{\partial s}\right)+\frac{\partial}{\partial n}\left(dDn\frac{\partial C}{\partial n}\right)-kCd-Fc-\frac{Lc}{\Delta s^2}+\frac{S}{\Delta s^2} \qquad (1)$$

where

- C = concentration of solute (kg/m^3)
- u, v = components of velocity (m/s)
- D_s = longitudinal dispersion coefficient (m^2/s)
- D_n = lateral dispersion coefficient (m^2/s)
- (x, y) = Cartesian coordinates in the horizontal plane (m)
- (s, n) = intrinsic coordinates parallel with and normal to the mean flow (m)
- t = time (sec)
- d = water depth (m)
- Δs = model grid size

Table 2. *Model Set-Up for Validation 19/04/99 to 01/10/99.*

Time Step	20 s
Number of Time Steps	712800 (165 days)
Coriolis Coefficient (rad/s)	-7.73 x 10^{-5} (at latitude 32 South)
Coefficient of Wind Influence	1.61 x 10^{-6} (wind speed = 10 m/s)
Air Pressure	No surface pressure field
Friction Coefficient and Law	k_s = 0.001
Velocity Diffusivity (m^2/s)	10
Tidal Flats	Option 2 - Submerged/exposed areas are removed from the computation
Type of Advection	U+V method of characteristics, H - conservative scheme + SUPG

- k = first order decay rate (s^{-1})
- F_c = flux of solute between water and bed ($kg/m^2/s$)
- L_c = loading of solute (kg/s)
- S = source/sink term (kg/s)

WATER QUALITY SOURCE TERMS

Initial water quality simulations are being conducted using the parameters summarised in Table 3. The concentrations of nutrients and dissolved oxygen imposed throughout the domain for the initial and boundary conditions were measured from water samples collected in 1999 for the period coincident with the hydrodynamic data used for the flow model. Unfortunately, there were no measured concentrations of pollutants from the domestic and industrial waste water inputs that enter the system, therefore, estimates have been calculated based on known values for crude sewage e.g. TEBBUTT, 1998, with a typical water consumption rate for Brazil of 160 litre/head/day.

Two sewage outfalls have been included for the initial tests: the main domestic wastewater outfall serving Rio Grande located close to the entrance of Saco da Mangueira; and a second smaller sewage outfall within the bay. Industrial inputs including the discharge from the fertiliser factory are also to be included in the sensitivity analysis.

CONCLUSIONS

The TELEMAC-2D hydrodynamic model has been successfully calibrated and validated, for a range of flow regimes and meteorological events that typically occur in the study area. Further hydrodynamic simulations designed for the comparison of La Niña and El Niño periods are to be completed when data from 2002 are available. Water quality modelling sensitivity analysis is currently in progress and results

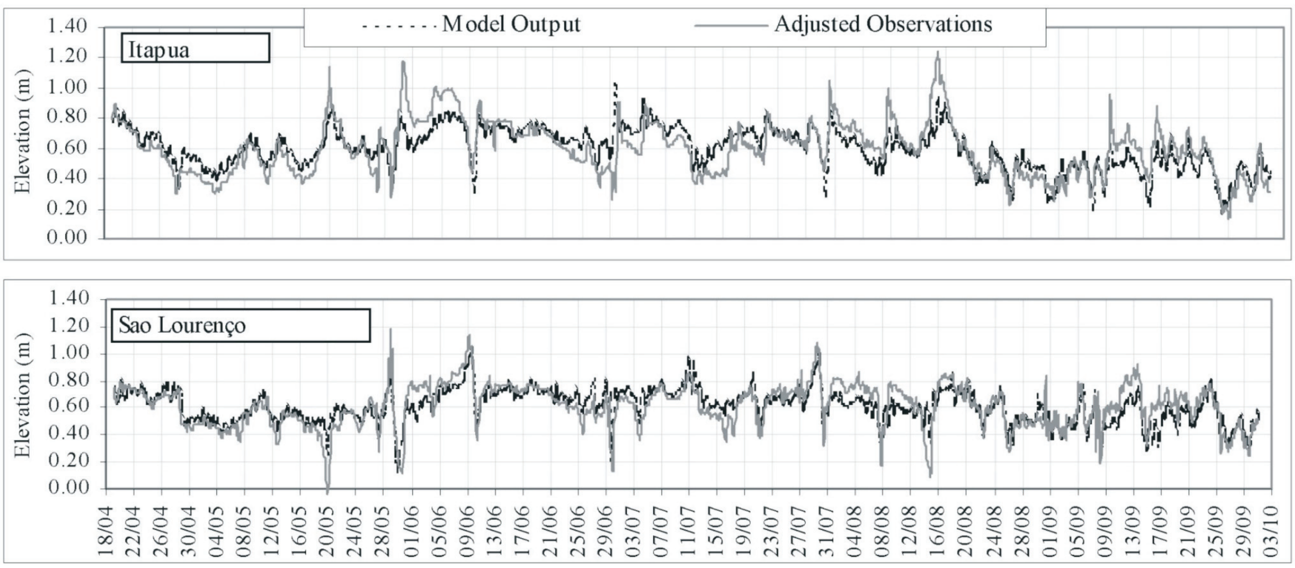

Figure 5. Model Output and Adjusted Observations 19th April to 1st October 1999.

Table 3. *Source Terms for Initial Water Quality Simulations.*

	Initial Conditions	Boundary Conditions	Rio Grande Outfall 1	Rio Grande Outfall 2
Population			144000	18000
Flow (m^3/s)			0.5	0.0625
Suspended Solids (kg/d)			21600	2700
Dissolved Oxygen (kg/d)	10	9.8		
Fast BOD (kg/d)			8640	1080
Fast Organic Nitrogen (kg/d)			1080	135
Ammonium (kg/d)	0.1	0.15	1728	216
Nitrite (kg/d)			4.32	0.54
Nitrate (kg/d)	0.12	0.23	8.64	1.08
Phosphate (kg/d)	0.015	0.015	432	54
Silicate (kg/d)	0.15	2.4	864	108
Coliforms (10^6/d)			$1.3x10^{10}$	$1.6x10^9$

comparing flood and drought conditions with respect to nutrients and bacteria will be discussed in the near future.

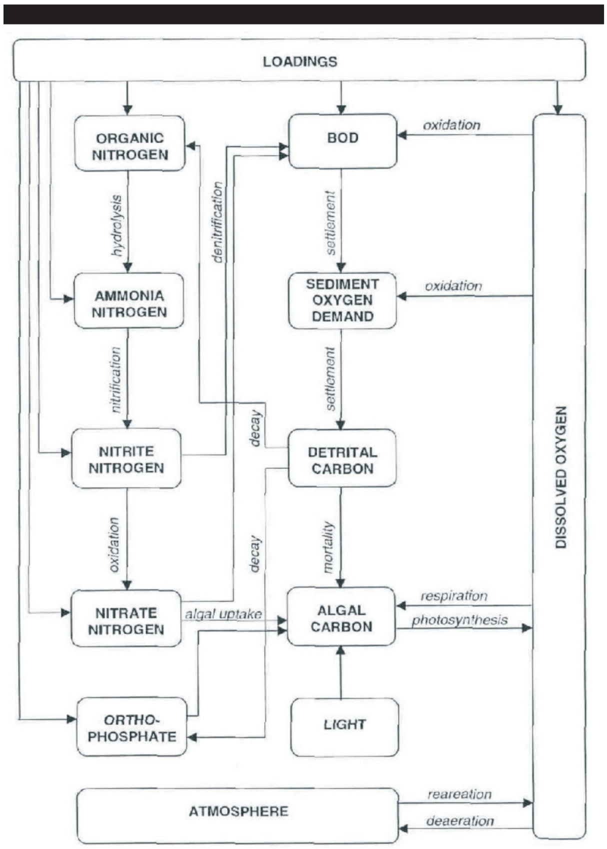

Figure 6. Flow Chart of the Water Quality Processes Included in WQFLOW-2D (from Hydraulics Research Wallingford, 2000, WQFLOW-2D User Guide).

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