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SELF-CLEANING ABILITY OF THE MIDDLE AND LOWER COURSES OF THE UBERABA RIVER, UPGRH-GD8

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Abstract: The multiple and balanced use of water resources has become a difficult task, since the implementation and continuous improvement of management systems still fail to keep abreast of the constant changes occurring in the environment due to human activities. Water planning and management on a river basin scale requires the use of computational tools that allow for joint modeling of water quantity and quality. This study involved an assessment of the self-cleaning ability of the middle and lower courses of the Uberaba River, located in the state of Minas Gerais, Brazil. This river is extremely important because its waters supply a population of approximately 322 500 distributed among the municipalities of Uberaba, Veríssimo and Conceição das Alagoas. The water quality parameters of dissolved oxygen, biochemical oxygen demand, organic nitrogen, ammonia, nitrate and total phosphorus were modeled for the period of October 2012 to September 2013, using the AQUATOOL system. The constants of biochemical reactions were calibrated by the trial and error method. The sensitivity analysis of the initially calibrated constants K_a, K_d, KN_{oa} and KN_{ai} and of the quality parameters of the intermediate inputs did not reveal significant variations in water quality. In the analysis of pollution scenarios, considering the critical flow $Q_{7,10}$, it was found that organic nitrogen, ammonia and nitrate remained within the levels established by Minas Gerais (2008) and Brazil (2005). The concentration of dissolved oxygen would have to increase by 156% when compared with the value of the driest month only in the intermediate input that comprises the entire urban area of the city of Uberaba, whose urban streams receive domestic and industrial effluents. On the other hand, the parameters BOD_5 and P_{total} were the most problematic, with high values in almost all the intermediate inputs, except for the Jataí and Preguiça streams, whose subbasins have minor areas of contribution. This indicates that, in addition to the pollutant loads from the urban area of Uberaba, the use of 70.6% of the total land area of the Uberaba River subbasin for agricultural and pastureland purposes contribute to the high concentrations of BOD_5 and P_{total}.

Keywords: Self-cleaning; constants of biochemical reactions; sensitivity analysis; pollution scenario; Uberaba River

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INTRODUCTION

Advances in technology go hand in hand, albeit in distinct steps, providing benefits to society, but environmental management mechanisms cannot keep abreast of them. The development of society in recent decades has resulted in significant environmental impacts on natural watercourses, whose self-cleaning ability to remove the pollutant loads they receive is limited, requiring longer times and greater space to enable natural processes to re-establish the characteristics they had before they became polluted or contaminated.

In this process, resilience is an important element to be observed, and knowledge about the different characteristics and possible interferences in the environment is necessary. Environmental interactions are diverse and complex, conditioned by various chemical, physical and biological elements that must be analyzed quite frequently. To a certain extent, many environmental elements and factors that interact simultaneously cannot be analyzed due to the high costs involved; hence, mathematical models are an alternative aid in environmental management processes.

To develop a model of river water quality, the user must possess knowledge about the potentialities and limitations of the various computational tools available to enable him to choose the one best suited to his needs. The mathematical models proposed tools for the study of self-cleaning in water bodies evolved from the interactions between the concepts of hydrodynamics, advective-diffusive transport, and biogeochemistry, associated with advances in the computing power of personal computers (Romeiro, 2003; Salla *et al.*, 2013).

According to Fragoso Jr. *et al.* (2009), despite the conceptual advance and processing capacity of computational tools currently available, the absence of monitored stream flow and water quality data impairs the reliability of these tools. Thus, the choice of a mathematical model depends on the objectives and quality parameters of interest.

Several computational tools are widely accepted by the academic and technical communities for modeling water quality in rivers and reservoirs. The QUAL2E models (Chapra *et al.*, 2008; Palmieri & Carvalho, 2006) and their updated versions QUAL2K and QUAL2kw (Chapra *et al.*, 2008; Von Sperling, 2007; De Paula, 2011) are well accepted for river and stream water quality modeling. The WASP (Lai *et al.*, 2012; Yenilmez & Aksoy, 2013; Zhang & Rao, 2012) and WEAP models (Mehta *et al.*, 2013; Weaver *et al.*, 2013) are widely used in water resources planning to assess lake eutrophication and climate change, respectively. On the other hand, the AQUATOX model (Mamaqani *et al.*, 2011; Mcknight *et al.*, 2012) is a powerful tool for assessing ecological risks in aquatic ecosystems.

Much concern today focuses on an integrated approach to study river basins, since unplanned land use causes serious environmental problems that are reflected throughout the water system. According to Salla *et al.* (2013), there are many decision support tools for water management on the river basin scale, which comprise modules for modeling water quantity and quality, as can be seen in Zhang *et al.* (2010), Paredes-Arquiola *et al.* (2010a, 2010b), Zhang *et al.* (2011), Sulis & Sechi (2013), Welsh *et al.* (2013) and Salla *et al.* (2014a, 2014b).

In this context, there was no integrated study of surface water quantity and quality of the Uberaba River, located in the subbasin of the Lower Rio Grande river in the state of Minas Gerais. This water course presents a problem of surface water availability for human consumption during the dry months, and its water quality is also in violation of current legislation, primarily due to the point-wise discharge of raw domestic and industrial effluents into its middle and lower courses. Therefore, the water balance along the Uberaba River was calculated and its water quality modeled, from the point where wastewater treated by the Sewage Treatment Plant (STP) is discharged into this river down to where it flows into the Rio Grande River, during the period of October 2012 to September 2013. To this end, we used AQUATOOL, the tool for integrated water resources management on the river basin scale, by modeling the water quantity (SIMGES module) and quality (GESCAL module). This tool is widely accepted in Europe, Africa and Latin America, as described by Paredes-Arquiola *et al.* (2010a, 2010b), Nakamura (2010), Sulis & Sechi (2013) and Salla *et al.* (2014a, 2014b).

After calibrating the constants of biochemical reactions and the settling velocities of the water quality parameters and then performing the sensitivity analysis, scenarios of the river's self-cleaning ability were predicted in extreme situations of critical flow $Q_{7,10}$.

MATERIALS AND METHODS

Study Area

The Uberaba River subbasin covers an area of 2 374.5 km^2, which corresponds to 12.6% of the lower Rio Grande basin (identified as GD8) and is located between the coordinates 19°31′10.06″ and 20°07′17.09″ °S latitude and 47°41′10.70″ and 48°32′47.64″ °W longitude. The Uberaba River is 181.5 km long and its source is located in the municipality of the same name, in the Serra de Ponte Alta mountain range, at an altitude of 1012 m. It runs through the municipalities of Uberaba, Veríssimo and Conceição das Alagoas and flows into the Rio Grande River (Cruz, 2003). **Figure 1** illustrates the subbasin of the Uberaba River, highlighting the stretch of river under study, the municipalities it runs through, and the internal divisions adopted in this study.

The topography of the watershed consists of flat or slightly undulating surfaces, geologically composed of sedimentary rock, largely sandstone, from the Cretaceous period of the Bauru Formation. In terms of pedology, its soil comprises predominantly latosol of different degrees of fertility, mostly of a medium texture varying from sandy to clayey (Cruz, 2003).

Based on a documentary survey conducted at SUPRAM, the Regional Environmental Superintendency of the Alto Paranaíba and Triângulo Mineiro, this subbasin has a large number of insignificant land use grants, according to Minas Gerais (2004). Among the municipalities in this subbasin, only Uberaba uses water from the Uberaba River for human consumption, at an authorized flow rate of 0.9 m³/s. In the municipalities of Veríssimo and Conceição das Alagoas, water is supplied through tube wells (Copasa, 2012a and 2012b).

A stretch of 96.1 km of the Uberaba River was considered here, starting approximately 100 m upstream from the point where the effluent treated by the STP of the municipality (from 65% of the population) is discharged into this river down to where it flows into the Rio Grande River. To help interpret the findings on water quality, the basin under study, which extends beyond the aforementioned 96.1 km stretch of the Uberaba River, was structured physically, as illustrated in **Fig. 1**.

The upper course of the Uberaba River comprises a 528.1 km² Area of Environmental Protection – AEP, which represents 22.2% of this subbasin. Following the direction of flow of the watercourse, the surface water quality in the urban area of Uberaba is poor due to the illegal discharge of domestic and industrial effluents into the streams of the region. According to PMU (2011), anthropogenic actions are more visible in the Lages and Juca streams, because the former receives raw wastewater from 35% of the population and the latter receives effluent from a poultry slaughterhouse with low removal efficiency of the pollutant load. The river stretch under study, starting from the aforementioned STP, was divided into ten subbasins whose catchment areas are illustrated in **Fig. 1**.

Among all the subbasins, the Veríssimo River receives raw domestic wastewater from the city of Veríssimo (Terra Ambiental, 2013). The municipality of Conceição das Alagoas also discharges raw effluents into the Uberaba River itself. According to the Brazilian Institute of Geography and Statistics – IBGE (2013), the municipalities of Veríssimo and Conceição das Alagoas have a population of 2 733 and 25 139, respectively.

With regard to land use and occupation, we report that 28.1% of the basin's catchment area is occupied by agriculture, 42.5% by pastureland, 3.1% by exposed soil and 23.5% by native vegetation. For this research a ResourceSat satellite image was used. The LISS3 sensor

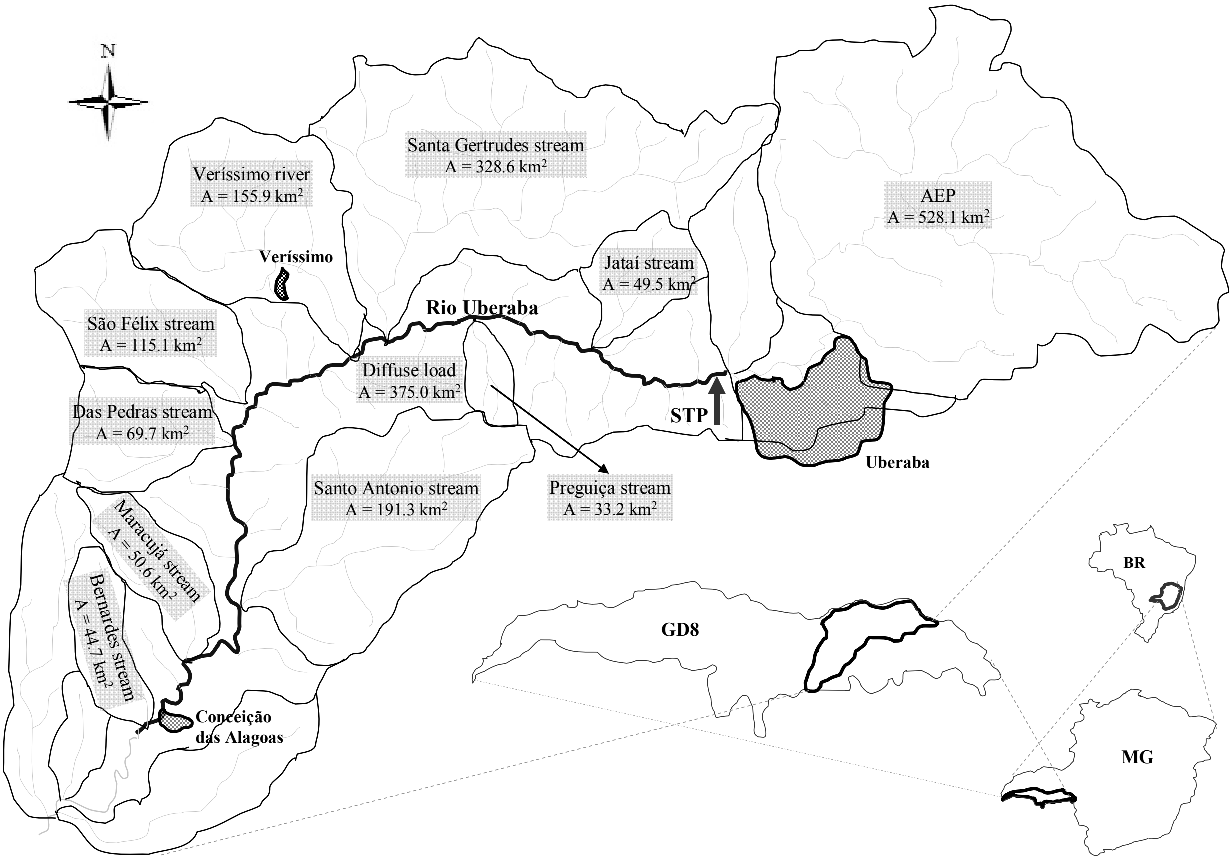


Fig. 1 Location of the Uberaba River subbasin, highlighting the river stretch under study, the municipalities benefited, and the internal divisions adopted.

has a spatial resolution of 24 × 24 m. The images were obtained from the website of National Institute for Space Research and have acquisition dates between May and July 2013. As a single image does not cover the entire study area, a mosaic of six images was created and then clipped in the MultSpec©. Then we proceed a multispectral supervised classification with the maximum likelihood algorithm for the recognition of classes of use and occupation of soil. In this classification, the spectral information is represented by a matrix formed by composing multiple bands. For LISS3 sensor, these bands use frequencies of medium and near infrared, red and green. Taking several pixels of the image as samples of use and occupation classes is possible to define the spectral signature of each class through maximum and minimum limits in each spectral band. The classes were agriculture, exposed soil, riparian forests, reforestation and water. Being possible to define the limits of each class, the classification algorithm extends its analysis of samples to cover all pixels in the image. In this research, the Kappa index that measures the quality of the classification was 94.5%. Finally, the image was classified separately in ArcGIS program to be possible to estimate the number of pixels in each watershed.

AQUATOOL

AQUATOOL is widely accepted in Europe, Africa and Latin America as a decision support system for the integrated management of water resources on a river basin scale (Sulis & Sechi, 2013; Salla *et al.*, 2014a and 2014b). The tool's water quantity (SIMGES) and water quality (GESCAL) modules are interconnected, sharing their georeferenced data through a graphic interface (Paredes-Arquiola *et al.*, 2010a and 2010b).

The SIMGES module was used to estimate flow variations in the subbasin, based on surface input data (point-wise and diffuse inputs from the tributaries and point-wise discharges of effluent) and multiple surface output data (human consumption, industrial supply, livestock watering, and irrigation), by means of the monthly water balance. Surface-water and groundwater interactions were not considered in this study.

After calculating the water balance, water quality simulations were performed in the GESCAL module, using the following parameters: dissolved oxygen, biochemical oxygen demand, organic nitrogen, ammoniacal nitrogen, nitrate, and total phosphorus. The modeling considered permanent, uniform, one-dimensional flow with a constant concentration of any parameter in the transverse direction and stationary conditions of water quality of streams flowing into the watercourse, on a monthly scale.

Potential relationships were used to associate the drainage flow Q with the average velocity V, the average depth y and the width of the cross section b. According to Paredes-Arquiola *et al.* (2009), within a river segment previously discretized, the longitudinal profile of any parameter was modeled using the advection-diffusion equation, **Eq. (1)**. The mass balance was considered to calculate variations in any parameter between segments of river, based on the longitudinal inputs and outputs and lateral intakes. The empirical equation proposed by Fisher (1979) was used to estimate the coefficient of longitudinal dispersion E, as indicated in **Eq. (2)**:

$$0 = \mathrm{d}/\mathrm{d}x(E\ \mathrm{d}C/\mathrm{d}x) - \mathrm{d}(V.C)/\mathrm{d}x + (S_d + \sum W_i)/V_t \qquad (1)$$

$$E = 0.011\ (V^2\ b^2)/(y\ u_*) \qquad (2)$$

where: E is the longitudinal dispersion coefficient (m^2/s); C is the concentration of any parameter (mg/L); x is the longitudinal distance of the river segment (m); V is the mean water velocity (m/s); V_t is the net volume of the studied segment (m^3); S_d is the diffuse input load in the river segment (kg/s); b is the width of the cross section (m); u_* is the shear velocity (m/s), which is equal to $(g\,y\,I_o)^{1/2}$ (g is the acceleration of gravity in m/s^2, y is the average depth, in meters, and I_o is the bottom slope, in m/m); and ΣW_i represents the set of processes that increase or decrease the load of parameter i in the liquid mass, depending on degradation, sedimentation, reaeration and nitrification. Phytoplankton growth and respiration and adsorption were not considered in this study because they are more common processes in lentic environments.

The mathematical representations of ΣW_i for modeling the biochemical oxygen demand BOD, organic nitrogen No, ammonia Na, nitrate N_{O3}, total phosphorus P and dissolved oxygen OD are shown, respectively, in **Eqs (3)**, **(4)**, **(5)**, **(6)**, **(7)** and **(8)**:

$$\sum W_{DBO} = -k_d \theta_d^{(T-20)}\ [O/(O+k_{d1/2})]\ DBO - VS_{DBO}/y)DBO \qquad (3)$$

$$\sum W_{No} = -k_{Noa}\theta_{Noa}^{(T-20)}\ N_o - (VS_{No}/h)\ N_o \qquad (4)$$

$$\sum W_{Na} = +\ k_{Noa}\theta_{Noa}^{(T-20)}\ N_o - k_{Nai}\theta_{Nai}^{(T-20)}\ [O/(O+k_{N1/2})]\ N_a \qquad (5)$$

$$\sum W_{NO3} = +\ k_{Nai}\theta_{Nai}^{(T-20)}\ [O/(O+k_{Nai1/2})]\ N_a \qquad (6)$$

$$\sum W_P = -k_P \theta_P^{(T-20)}\ P - (VS_P/h)\ P \qquad (7)$$

$$\sum W_{OD} = +\ k_a \theta_{ka}^{(T-20)}\ (O_{sat} - O) - k_d \theta_d^{(T-20)}\ L - r_a\ \{k_{Nai}\theta_{Nai}^{(T-20)}\ [O/(O+k_{Nai1/2})]\}\ N_a \qquad (8)$$

where: K_d is the deoxygenation constant at 20ºC (1/d); $K_{d1/2}$ is the semi-deoxygenation constant at 20ºC (1/d); K_{Noa} is the ammonification constant (1/d); K_{Nai} is the constant of nitrification of ammonia to nitrate (1/d); $K_{n1/2}$ is the nitrogen semi-saturation constant (mg/L); K_P is the total phosphorus decay constant (1/d); K_a is the reaeration constant (1/d); θ is the temperature correction constant (dimensionless); VS is the settling velocity (m/s); T is the water temperature (°C); O is the dissolved oxygen concentration (mg/L); O_{sat} is the dissolved oxygen saturation concentration (mg/L); P is

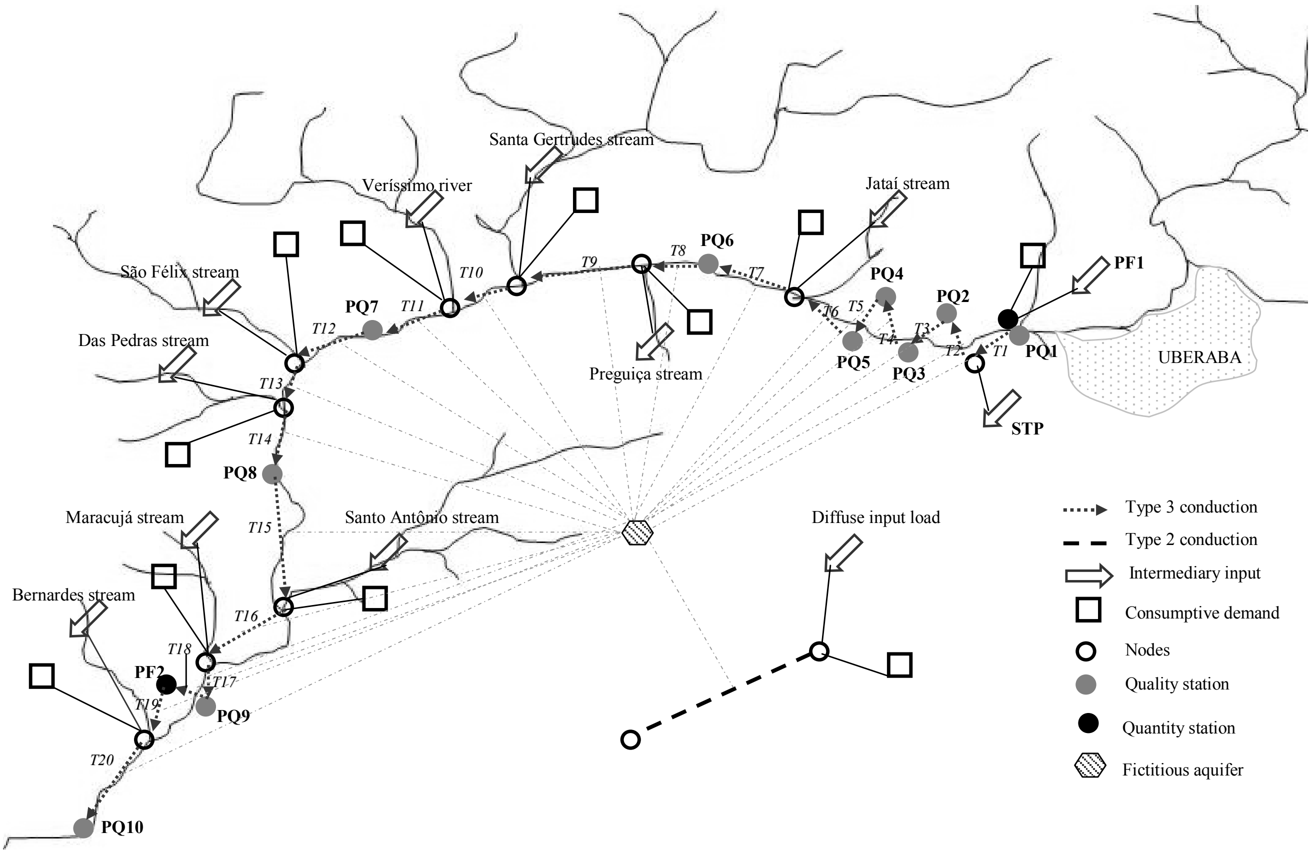


Fig. 2 Topology of the model created with AQUATOOL.

the total phosphorus concentration (mg/L); and r_a is the consumption of oxygen by oxidation of ammonia (mgO/mgN).

Topology of the model

The topology was sketched directly in AQUATOOL, in which all the elements of the model were arranged without the need to maintain a scale, as illustrated in **Fig. 2**.

In this study, alternative elements were adopted for the diffuse surface inputs, such as a "dummy" unicellular aquifer and Type 2 and 3 conductions, as shown in **Fig 2**. An alpha runoff coefficient (1/month) equal to 1 and an initial volume (hm^3) equal to zero were considered in the introduction of the "dummy" unicellular aquifer. A single segment with Type 2 conduction was then added, which was used for the dummy infiltration of the total diffuse incremental flow of all the river segments. To this end, the description of this Type 2 conduction included the linked unicellular aquifer, and the coefficients *A*, *B* and *C* of the equation $I = A+B.Q^C$ were defined as 0, 1 and 1, respectively (*I* is the total infiltrated flow and *Q* is the total surface flow). Lastly, the sub-segments were represented by Type 3 conductions, in which the entire flow returned incrementally to the river segment. The description of the Type 3 conduction, in each sub-segment, included the unicellular "dummy" aquifer connected to it, as well as the distribution coefficient of the connection. The distribution coefficient is the ratio of the length of the sub-segment to the total length of the stretch under study.

It was not necessary to add the return element to any consumptive demand, since most of these demands are insignificant. As for the water demand for human consumption in the city of Uberaba, the intermediate input of the effluent treated by the municipality's STP eliminated the need to introduce the return element for this demand as well.

Input flow

The water balance was calculated monthly, from October 2012 to September 2013. Flow rates were considered in the Uberaba River just upstream of the point where wastewater treated by the STP enters the river (identified as PF1 in **Fig. 2**), from the STP, in the streams corresponding to the subbasins, and in the diffuse input.

Water flows in PF1 were monitored using the Acoustic Doppler Current Profiler (ADCP) methodology associated with echo sounding. The device measures water flow velocity based on the Doppler effect, transmitting sound waves in water and quantifying the change in echo frequency generated by the particles in suspension. As these particles and water move at the same velocity, the water flow velocity can also be determined. The cross section of PF1 was determined by means of an echo sounder coupled to the ADCP. The mean velocity and cross section data were fed into the River Surveyor program to determine the drainage flow.

The flows of the tributaries and the diffuse inputs were estimated based on the specific discharge concept (hm^3/month km^2), taking into account the runoff data monitored at PF1 and PF2, respectively, by means of **Eqs (9)** and **(10)**. Gauging station PF2 is located in the municipality of Conceição de Alagoas and operated by the hydroelectric power company Furnas Hidrelétrica, by means of a key curve method.

$$Q_i = [(Q_{rioUberaba\ PF2} - Q_{rioUberaba\ PF1})/\sum A_n]\ A_i \quad (9)$$

$$Q_{difusa} = [((Q_{rioUberaba\ PF2} - Q_{rioUberaba\ PF1})/\sum A_n)\ A_{difusa}] \quad (10)$$

where: Q_i is the estimated influent flow i (in hm^3/month); Q_{difusa} is the estimated diffuse flow (in hm^3/month); A_n is the total area of contribution between gauging stations PF1 and PF2 (in km^2); A_i is the area of contribution of tributary i (in km^2); and A_{difusa} is the total diffuse area (in km^2).

The flow rates from the STP of Uberaba were monitored by the Municipal Water and Wastewater Authority, by means of an ultrasonic level meter installed at the station entrance.

Consumptive demands

The surface water demands granted and georeferenced for human consumption, irrigation, industry, and watering livestock were obtained from SUPRAM, based on registered data for 2012 and 2013. The highest consumptive demand is that of surface water for the public supply of Uberaba, whose fixed monthly amount is 2.33 hm^3/month. The demand for water from the other rural tributaries varied from 0.004 to 0.954 hm^3/month, keeping in mind that most of the water grants are for negligible use. The total diffuse consumptive demand was 1.53 hm^3/month, which was determined by the sum of each of the water grants registered in the Minas Gerais Water Management Institute – IGAM.

Qualitative input data

The simulated water quality parameters along the middle and lower courses of the Uberaba River were: DO, BOD, organic nitrogen, ammoniacal nitrogen, nitrate and total phosphorus. This involved linking a water quality, during the simulation period, to all the aforementioned intermediate inputs illustrated in **Fig. 2**.

The first intermediate input was the PQ1 station (**Fig. 2**), whose water quality data were measured monthly. The water quality data of the effluent treated in the STP were also measured by the technical staff of the Municipal Water and Wastewater Authority of Uberaba (Minas Gerais).

In the Veríssimo River subbasin, despite the impact caused by the discharge of raw domestic sewage from this municipality into the Veríssimo River, water quality was not monitored; hence, the water quality had to be estimated. As for the quality of rural tributaries, conditioned by the feasibility of access, only monthly measurements were taken in the Preguiça and Das Pedras streams. The quality parameters for the other intermediate inputs were estimated.

These estimates were made in two stages. In the first stage, the best fit was found between measured and simulated data from the PQ water quality gauging stations immediately downstream of each intermediate input, based on the calibrations of the constants of biochemical reactions, considering that the parameters of water quality in the tributaries would assume limit values for Class 2 of the river, according to Brazil (2005). In the second stage, after setting the calibrated constants, the values of water quality parameters, initially set for the tributaries, were altered to improve the fit between the measured and simulated quality data at each PQ.

Other input data

To complete the structure of the topology, besides the aforementioned quantitative and qualitative data, AQUATOOL requested additional information such as the longitudinal length of each river segment, temperature curves in each river segment, and the hydraulic ratios $v = f(h)$ and $Q = f(h)$ obtained from the key curves at gauging stations PF1 and PF2.

Monitoring the water quality monthly at gauging stations PQ1 to PQ10 from October 2012 to September 2013 was instrumental for the calibration of the constants of biochemical reactions in the various segments of the Uberaba River. The ten monitored water quality gauging stations are depicted in **Fig. 2**. The parameters of water temperature and DO were analyzed in the field using portable devices, while the BOD, organic nitrogen, ammoniacal nitrogen, nitrate and total phosphorus were analyzed in the laboratory.

Calibration of the constants of biochemical reactions

Water quality data monitored at stations PQ2 to PQ10 were used as a reference for adjustments of the simulated data, from October 2012 to September 2013, to calibrate the constants mentioned in **Eqs (3)** through **(8)**, keeping in mind that a monthly scale was adopted. Based on the data collected from the PQ stations, the constants of biochemical reactions of the segments upstream from each station were calibrated by the trial and error method. The purpose of this calibration was to find the best fit between the measured data and the data simulated by the GESCAL module. The calibrated constants include: K_d – deoxygenation constant (1/d); K_{Noa} – ammonification constant (1/d); K_{Nai} – constant of nitrification of ammonia to nitrate (1/d); K_P – total phosphorus decay constant (1/d); and K_a – reaeration constant (1/d). The real biochemical reaction rate of carbonaceous organic matter removal in the water course is higher than the reaction rate obtained in the laboratory, from a water matrix sample collected from the river after mixing with raw wastewater (Von Sperling, 2007). This is due to the sedimentation of organic matter adsorbed on particulate matter in the river and the sediment oxygen demand. Because the domestic wastewater released into the Uberaba River undergoes secondary treatment, the real reactions and those performed in the laboratory show similar rates. Thus, it was possible to measure the K_d based on the laboratory analysis of the decay of organic carbonaceous matter over a period of 20 days. This argument is underpinned by the low concentration of suspended solids in the treated wastewater discharged by the STP, whose suspended solids removal efficiency is on average 89%. The adoption of measured values is closer to the reality of the water course than a simple calibration of the K_d by trial and error.

The low concentration of suspended solids in the effluent discharged by the STP also allowed for low values of settling velocities of carbonaceous organic matter, organic nitrogen and total phosphorus to be considered in this study.

Sensitivity analysis

The variations in the constants of biochemical reactions initially calibrated (K_a, KN_{oa}, KN_{ai} and K_p) and the quality parameters of the tributaries that were initially estimated were subjected to sensitivity analyses.

The sensitivity analysis of the constants of biochemical reactions was performed by the factorial method, based on a variation of +10% and -10% of the calibrated value. In the sensitivity analysis of the quality parameters of the tributaries, the most critical situation was considered the one in which there were changes of +10% (for BOD_5, nitrogen series and total phosphorus) or −10% (for dissolved oxygen), were detected individually in each tributary and simultaneously in all the tributaries, using a method called relative or relative sensitivity. The quality data measured in PQ2 through PQ10 were used as parameters of comparison in all the sensitivity analyses.

Pollution scenarios

This phase of the study involved an evaluation of the self-cleaning ability of the middle and lower courses of the Uberaba River, from a segment immediately upstream of the confluence of the STP with the Uberaba River to the vicinity of the latter's confluence with the Rio Grande river, based on qualitative and quantitative interventions. The minimum flow $Q_{7,10}$ (minimum average flow of seven consecutive days with a recurrence period of 10 years) was considered as the critical situation of effluent dilution capacity. The objective was to analyze the minimum water quality of all the intermediate inputs that would meet the minimum requirements of Minas Gerais (2008) and Brazil (2005) for Class 2 of the Uberaba River.

The $Q_{7,10}$ flow was determined based on historical data monitored at the PF2 gauging station from January 1995 to December 2009. These data were obtained from the Hidroweb site managed by the National Water Agency (Hidroweb, 2013). $Q_{7,10}$ was quantified by log-normal distribution (Von Sperling, 2007). Based on the concept of specific discharge, the monthly flows in the tributaries and gauging station PF1 were estimated using **Eq. (11)**,

$$Q_i = [Q_{rio\ Uberaba\ PF2}/\sum A_n]\ A_i \qquad (11)$$

where: Q_i is the estimated flow in tributary i (in m^3/s) flow; A_n is the total area of contribution in the Uberaba River subbasin (in km^2); and A_i is the area of contribution of tributary i (in km^2).

RESULTS

AQUATOOL input data

In the study of self-cleaning in a river segment, AQUATOOL requires several input data for modeling, not only to calibrate biochemical constants based on monthly quantitative and qualitative data but also to analyze pollution scenarios based on a stationary critical flow.

Flows in intermediate inputs

Table 1 lists the statistical data on flow rates in intermediate inputs from October 2012 to September 2013, and on the critical flow rates.

Water quality of the intermediate inputs

Table 2 lists the statistical data on water quality in the intermediary inputs and at the monitoring stations along the Uberaba River.

Other input data

The hydraulic ratios were: $V=0.041Q^{0.814}$, $B=25.026Q^{0.018}$, $y=1.017Q^{0.176}$ at gauging station PF1 and $V=0.398Q^{0.323}$, $B=22.046Q0^{.0110}$, $y=1.086Q^{0.583}$ at station PF2. In the period under study, the water temperature in this region of Minas Gerais varied from 10.7 to 28.8°C, with maximum values between December 2012 and February 2013, and minimum values between July and September 2013.

Modeling water quality

Water quality was modeled in the GESCAL module, based on calibrations by trial and error of the constants of biochemical reactions in the twenty segments identified in **Fig. 2** (*T1* to *T20*). **Table 3** lists the calibrated constants of biochemical reactions, as well as the low values considered for the settling velocities of

Table 1. Statistical data on flow rates in intermediate inputs and critical flow rate

Flow rate (hm^3/month)	PF1	STP	Jataí Stream	Preguiça Stream	Sta Gertrudes Stream	Veríssimo River
Oct 2012 to Sep 2013	5.13±0.10[a] 4.96–5.24[b]	0.59±0.08[a] 0.46–0.73[b]	2.14±1.52[a] 0.28–5.05[b]	1.44±1.02[a] 0.19–3.39[b]	14.29±10.09[a] 1.89–33.60[b]	6.79±4.79[a] 0.90–15.95[b]
$Q_{7,10}$	3.45	—	0.22	0.09	1.60	0.72
Flow rate (hm^3/month)	São Félix Stream	das Pedras Stream	Sto Antônio Stream	Maracujá Stream	Bernardes Stream	Diffuse input
Oct 2012 to Sep 2013	5.01±3.54[a] 0.66–11.77[b]	3.04±2.14[a] 0.41–7.13[b]	8.68±5.88[a] 1.45–19.92[b]	2.35±1.55[a] 0.44–5.33[b]	2.89±1.37[a] 1.20–5.51[b]	17.79±11.52[a] 3.63–39.82[b]
$Q_{7,10}$	0.47	0.32	0.91	0.39	0.18	2.10

[a]mean±standard deviation; [b]minimum-maximum

Table 2. Statistical data on water quality in the intermediary inputs and at the monitoring stations along the Uberaba River

	DO (mgO_2/L)	BOD_5 (mgO_2/L)	ON (mgN/L)	Ammonia ($mgNH_4^+$/L)	Nitrate ($mgNO_3^-$/L)	P_{total} (mgP/L)
Intermediary Inputs						
PQ1	4.2 ± 2.5	34.9 ± 14.4	1.6 ± 1.1	1.3 ± 0.9	0.2 ± 0.1	0.9 ± 0.9
STP	5.1 ± 1.2	21.0 ± 3.4	5.9 ± 0.0	17.4 ± 5.0	0.2 ± 0.0	2.4 ± 0.5
Preguiça Stream	5.8 ± 1.8	25.6 ± 20.5	0.7 ± 0.6	0.2 ± 0.4	0.1 ± 0.1	0.8 ± 0.7
das Pedras Stream	6.0 ± 1.5	17.7 ± 21.4	0.5 ± 0.8	0.5 ± 0.6	0.2 ± 0.1	0.8 ± 0.5
Jataí Stream	4.5 ± 1.1	17.8 ± 16.3	0.7 ± 0.6	1.5 ± 1.2	0.1 ± 0.1	0.1 ± 0.0
Sta. Gertrudes Stream	5.5 ± 2.0	9.6 ± 8.2	1.7 ± 1.1	0.4 ± 0.5	0.1 ± 0.1	0.1 ± 0.0
Veríssimo River	5.5 ± 2.0	9.6 ± 8.2	1.7 ± 1.1	0.4 ± 0.5	0.1 ± 0.1	0.1 ± 0.0
São Félix Stream	6.2 ± 1.4	5.0 ± 0.0	0.7 ± 0.6	0.3 ± 0.4	0.1 ± 0.1	0.8 ± 0.9
Sto. Antônio Stream	4.9 ± 0.8	5.4 ± 1.4	0.5 ± 0.7	1.1 ± 0.4	0.4 ± 0.3	0.6 ± 0.9
Maracujá	4.9 ± 0.8	5.4 ± 1.4	0.5 ± 0.7	1.1 ± 0.4	0.4 ± 0.3	0.6 ± 0.9
Bernardes Stream	5.7 ± 1.2	16.8 ± 12.2	1.2 ± 0.9	1.0 ± 0.3	0.4 ± 0.3	0.6 ± 0.8
Diffuse	5.0 ± 0.0	5.0 ± 0.0	0.6 ± 0.7	0.9 ± 0.4	0.3 ± 0.2	0.1 ± 0.0
Water quality monitoring stations						
PQ2	4.6 ± 2.3	33.3 ±10.7	2.8 ± 0.7	2.3 ± 1.9	0.2 ± 0.1	1.0 ± 1.1
PQ3	5.0 ± 1.2	32.2 ± 8.8	2.4 ± 1.4	4.3 ± 0.7	0.2 ± 0.1	1.0 ± 1.1
PQ4	4.9 ± 1.0	28.2 ± 9.6	2.3 ±1.3	3.7 ± 1.4	0.2 ± 0.1	0.9 ± 1.0
PQ5	6.4 ± 0.7	27.2 ± 8.6	2.0 ±1.3	3.4 ± 2.4	0.2 ± 0.2	0.8 ± 0.7
PQ6	7.2 ± 0.6	19.7 ± 5.8	2.1 ± 0.7	1.8 ± 0.9	0.6 ± 0.7	0.7 ± 0.8
PQ7	6.8 ± 0.7	10.8 ± 7.6	1.7 ± 0.2	0.4 ± 0.5	0.6 ± 0.6	0.5 ± 0.5
PQ8	6.8 ± 1.0	9.6 ± 5.4	1.2 ± 0.9	0.9 ± 0.8	0.5 ± 0.5	0.5 ± 0.6
PQ9	6.2 ± 1.2	9.9 ± 7.7	1.3 ± 0.6	0.3 ± 0.4	0.4 ± 0.4	0.4 ± 0.4
PQ10	6.4 ± 0.7	11.8 ± 5.2	1.1 ± 0.7	0.8 ± 0.3	0.4 ± 0.3	0.5 ± 0.5

mean ± standard deviation

Table 3. Constants of biochemical reactions and calibrated settling velocities

Segments	Between stations	K_a (1/d)	K_d (1/d)	VS_d (m/d)	KN_{oa} (1/d)	VS_{No} (1/d)	KN_{ai} (1/d)	K_P (1/d)	VS_P (m/d)
T1 and T2	PQ1 + PQ2	4.0	0.12	0.01	0.1	0.001	0.05	0.01	0.001
T3	PQ2 + PQ3	4.0	0.12	0.01	0.05	0.001	0.005	0.01	0.001
T4	PQ3 + PQ4	1.5	0.12	0.01	0.05	0.001	0.005	0.01	0.001
T5	PQ4 + PQ5	3.3	0.12	0.01	0.05	0.001	0.005	0.01	0.001
T6 and T7	PQ5 + PQ6	2.8	0.11	0.01	0.001	0.001	0.0005	0.01	0.001
T8 to T11	PQ6 + PQ7	2.4	0.12	0.01	0.001	0.001	0.005	0.01	0.001
T12 to T14	PQ7 + PQ8	2.4	0.10	0.01	0.001	0.001	0.01	0.01	0.001
T15 to T17	PQ8 + PQ9	1.6	0.11	0.01	0.001	0.001	0.01	0.01	0.001
T18 to T20	PQ9 + PQ10	1.6	0.11	0.01	0.001	0.001	0.0005	0.01	0.001

carbonaceous organic matter, organic nitrogen and total phosphorus.

The carbonaceous matter decomposition constant K_d was fixed at 0.10 to 0.12 1/d, determined from the laboratory analysis performed at water quality monitoring stations PQ1 to PQ4. Data reported in the literature confirm that the K_d values are consistent. Formentini (2010) obtained a K_d of 0.15 to 0.27 1/d in the Vacacaí Mirim River (Rio Grande do Sul), Nunes (2008) found 0.07 to 0.42 1/d in the Turvo Sujo River (Minas Gerais), and Almeida (2013) reported 0.02 to 0.39 1/d in the Uberabinha River (Minas Gerais).

In general, the total phosphorus decay constant (K_P) and the settling velocities of carbonaceous organic matter (VS_d), organic nitrogen (VS_{No}) and phosphorus (VS_{phosph}) showed no significant changes. The highest values of the constant of nitrification of ammonia (KN_{ai}) in segments T1 to T2 and T12 to T17 correspond, respectively, to the discharge of treated effluent from the STP and the poor water quality of Veríssimo River, which receives raw wastewater from the municipality of Veríssimo. The highest values of ammonification constant (KN_{oa}) were detected only segments T1 and T2, due to the discharge of treated effluent from the STP. The K_{Noa} coefficient shows considerable variations in several studies reported in the literature, e.g., 0.25 1/d according to Garcia & Tucci (2000), 5.2 to 3.3 1/d according to Soares *et al.* (2012), and 0.02 to 0.4 1/d according to Paredes-Arquiola *et al.* (2007).

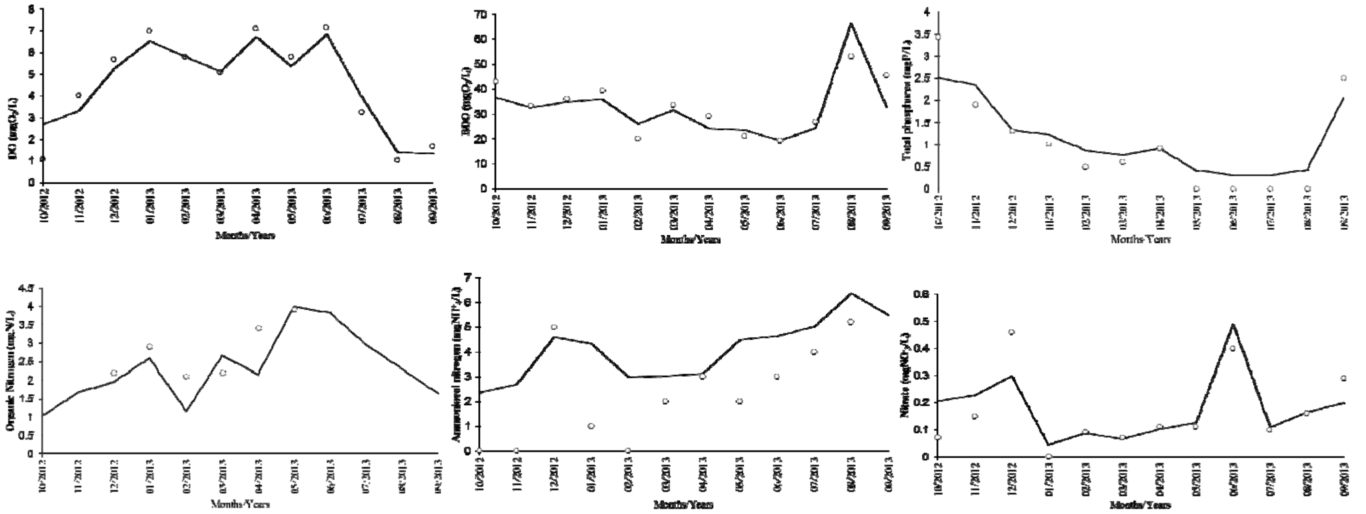
Because the primary effluent discharged into the stretch of the Uberaba River under study comes from a STP, the sediment oxygen demand S_{OD} (in g/m^2 day) was not considered. In **Table 3**, the values of the reaeration constant K_a are correlated directly with the average liquid level y, the mean velocity V and the longitudinal slope of the channel I_o. There are three regions with distinct bottom slopes between segments T1 and T20, i.e., 0.0041 m/m between T1 and T6, 0.0028 m/m between T7 and T14, and 0.0009 m/m between T15 and T20. Simply for the sake of conceptual information about channel hydraulics, for the same flow regime, an increase in the longitudinal slope causes the average velocity to increase and the liquid level to decrease. The empirical equations in the literature indicate that an increase in the reaeration coefficient K_a is directly proportional to the average velocity V and the longitudinal slope I_o and inversely proportional to the average liquid level y. This conceptual information explains the tendency of the value of K_a to decrease along the middle and lower courses of the Uberaba River.

The K_a values show a variation between 1.5 and 4.0 1/d, which are similar to those found by Chapra (2003), Von Sperling (2007), Paredes-Arquiola *et al.* (2009), Nakamura (2010), Barros *et al.* (2011), Salla *et al.* (2013) and Teodoro (2013).

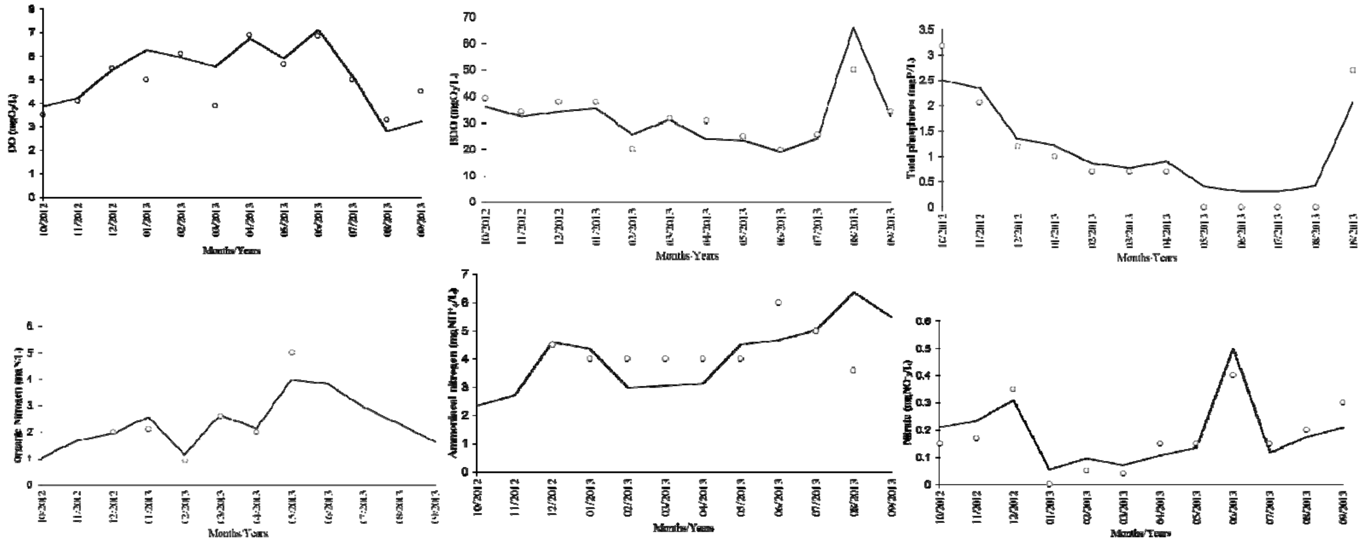
The series of simulations and observed data of the water quality parameters at the quality gauging stations PQ2 to PQ10 showed good fits. The calibration reached satisfactory results for the parameters of OD, BOD_5, organic nitrogen, nitrate and total phosphorus, even though some of the data were scattered, mainly for the parameters of organic nitrogen and total phosphorus at stations PQ6 and PQ7. However, no satisfactory fit was achieved between the series of simulated and observed data for the parameter of ammonia at any of the quality monitoring stations, since this fit was compromised by the need to adjust the parameter nitrate based on variations of the coefficients KN_{oa} and KN_{ai}. **Figure 3** illustrates the fits between simulations and data observed at quality gauging stations PQ2 to PQ10.

Figure 4 shows the longitudinal profiles of the quality parameters simulated for the wettest and driest months, along with the data measured at the PQ monitoring stations. An overall analysis of these numbers reveals that the parameters of DO, BOD_5 and total phosphorus are in violation of Minas Gerais (2008) and Brazil (2005). It should be kept in mind that water body classification in Brazilian territory is determined by Brazil (2005). In addition to this resolution, the state of Minas Gerais has its own ND for the quality parameters under study (Minas Gerais, 2008), which is similar to Brazil (2005). According to Minas Gerais (2008), the Uberaba River is classified as a Class 2 river, which must comply with the following limits: DO $\geq$ 5.0 mgO_2/L; $BOD_5 \leq$ 5.0 mgO_2/L; ammonia $\leq$ 3.7 $mgNH_4^+$/L; nitrate $\leq$ 10.0 $mgNO_3^-$/L; phosphorus (lotic environment) $\leq$ 0.1 mgP/L.

Throughout the middle and lower courses of the Uberaba River, the parameter of total phosphorus in the drier season (0.9 to 2.5 mgP/L) remained consistently higher than in the wetter period (0.2 to 0.9 mgP/L), due to the decreased ability for natural self-cleaning and dilution of pollutants in reduced flows. This situation also applies to the middle course of the Uberaba River for the parameter BOD_5, from station PQ1 down to the point where the Veríssimo River empties into the River Uberaba. The increase in the average flow velocity, which leads to increased surface turbulence in the river, increases the DO concentration in the rainiest month (6.3 to 8.2 mgO_2/L) throughout the longitudinal profile when compared to the DO concentration in the driest month (2.1 to 7.2 mgO_2/L). The parameter DO was not in compliance with either Brazil (2005) or Minas Gerais (2008) only in the driest month in the first 5 segments (*T1* to *T5*). The poor water quality in this initial region is attributed mainly to the lack of urban infrastructure planning in the city of Uberaba. It is clear that there are point-wise discharges of raw domestic and industrial wastewater upstream of PQ1.



(a) PQ2



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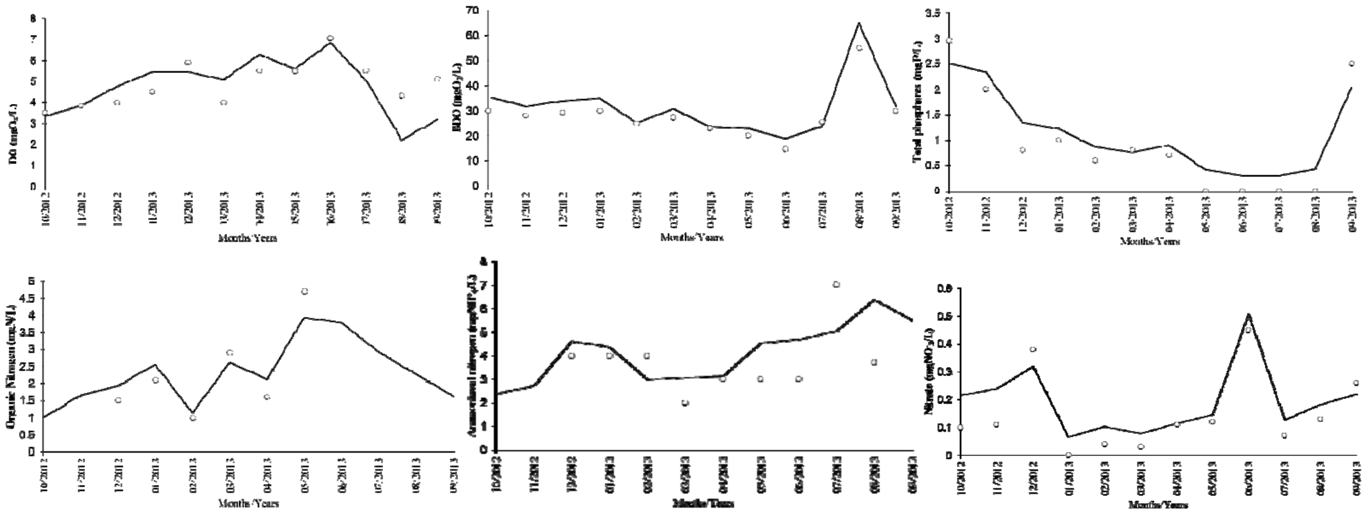
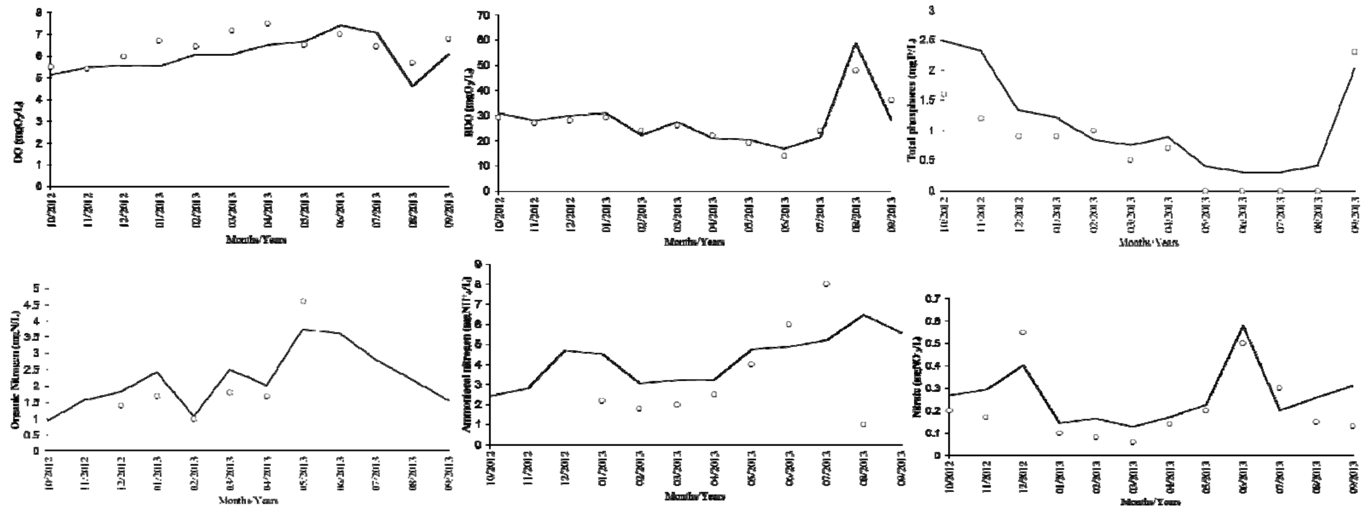
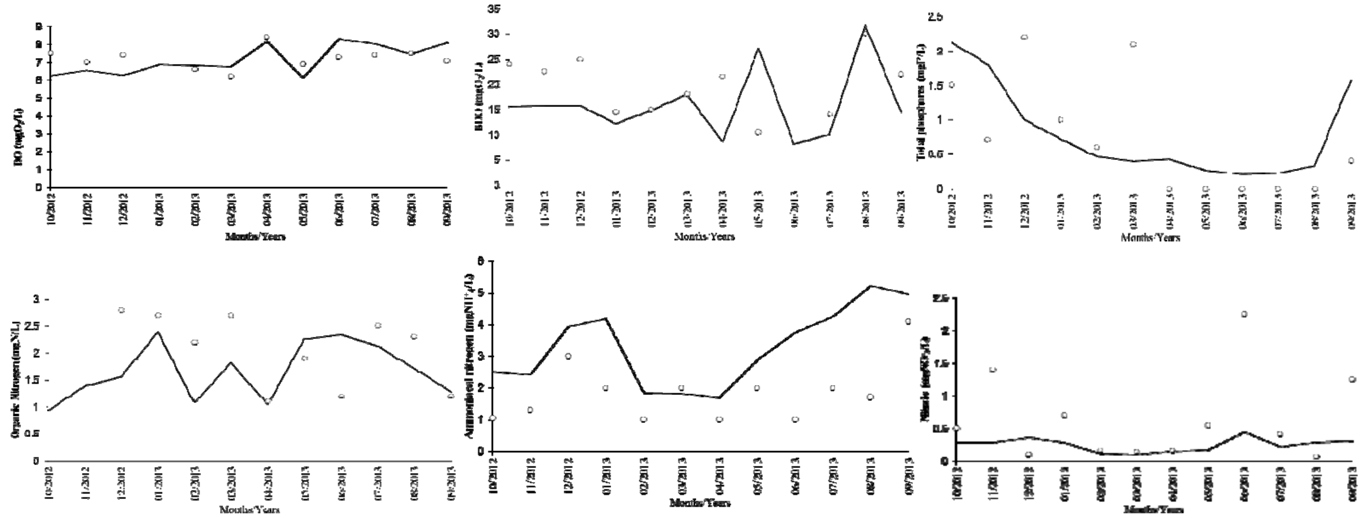


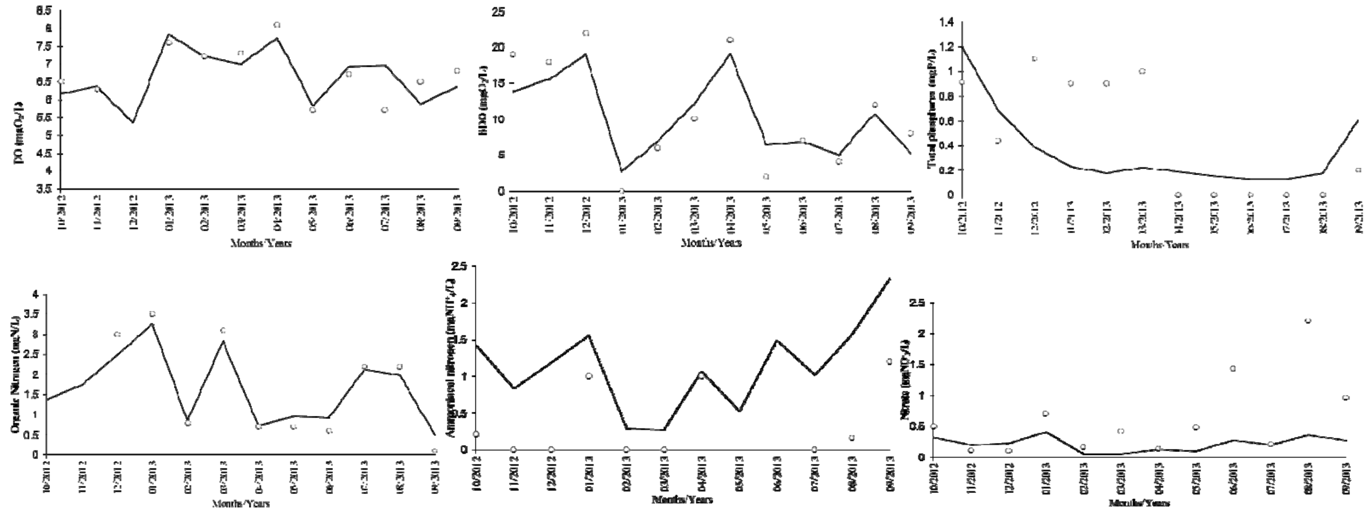
(c) PQ4



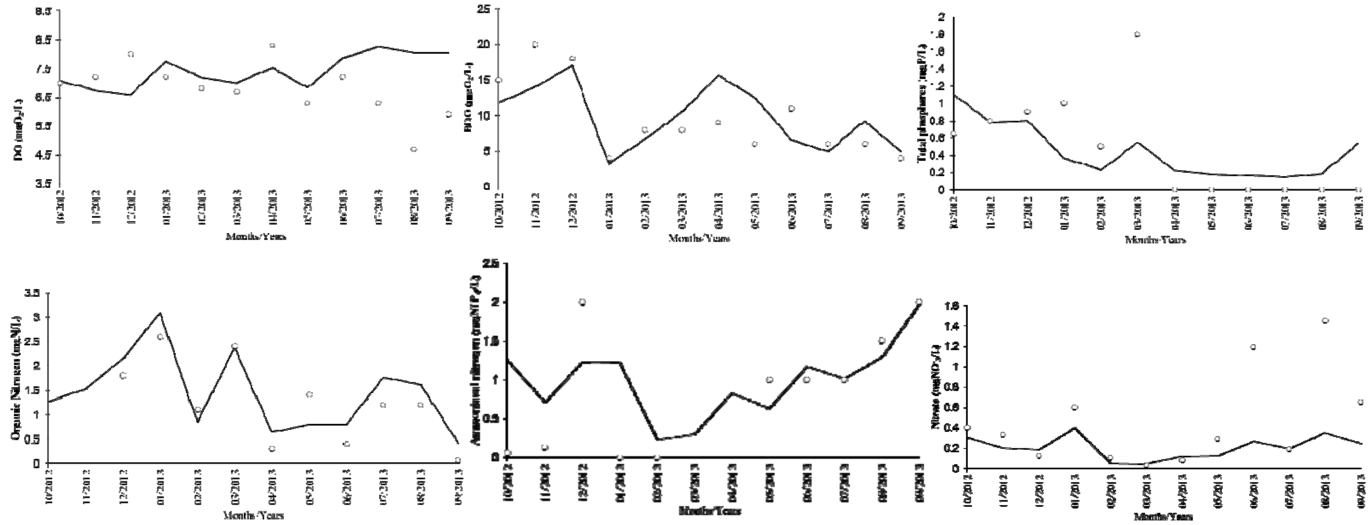
(d) PQ5



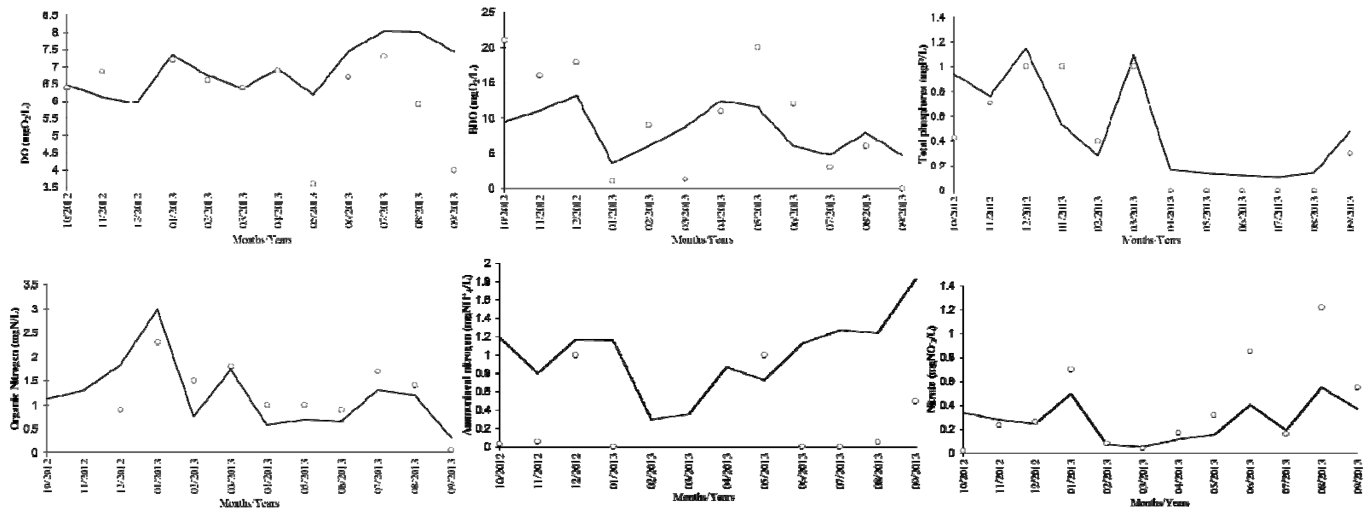
(e) PQ6



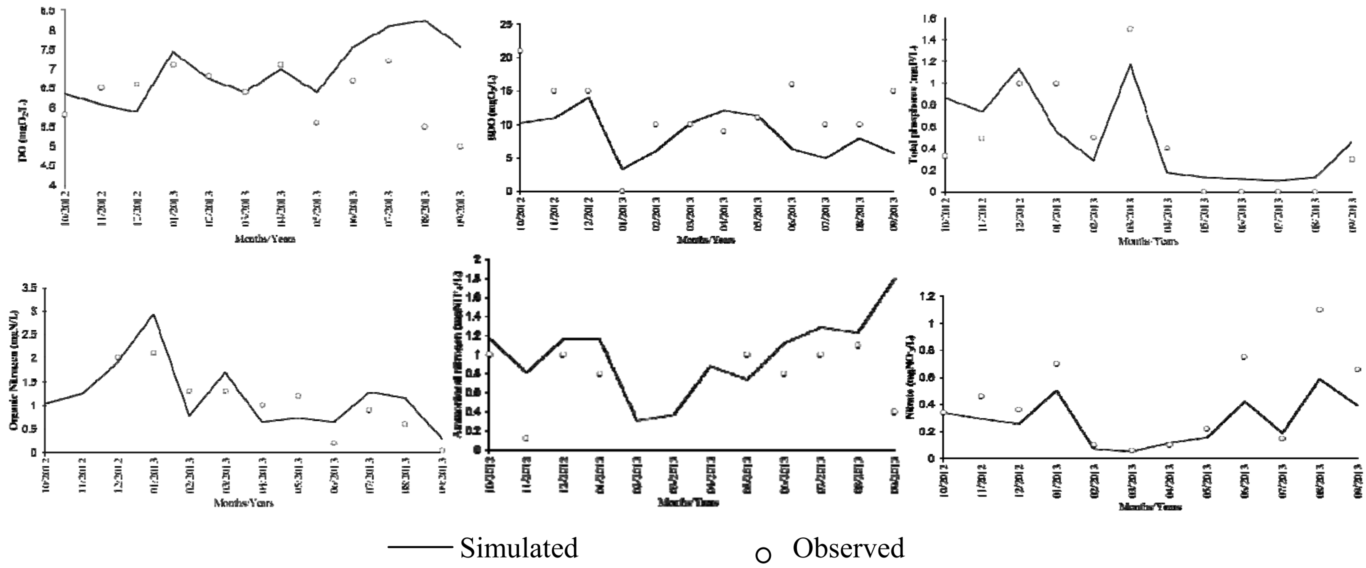
(f) PQ7



(g) PQ8



(h) PQ9



(i) PQ10

Fig. 3 Fits between simulations and data observed at water quality gauging stations PQ2 to PQ10

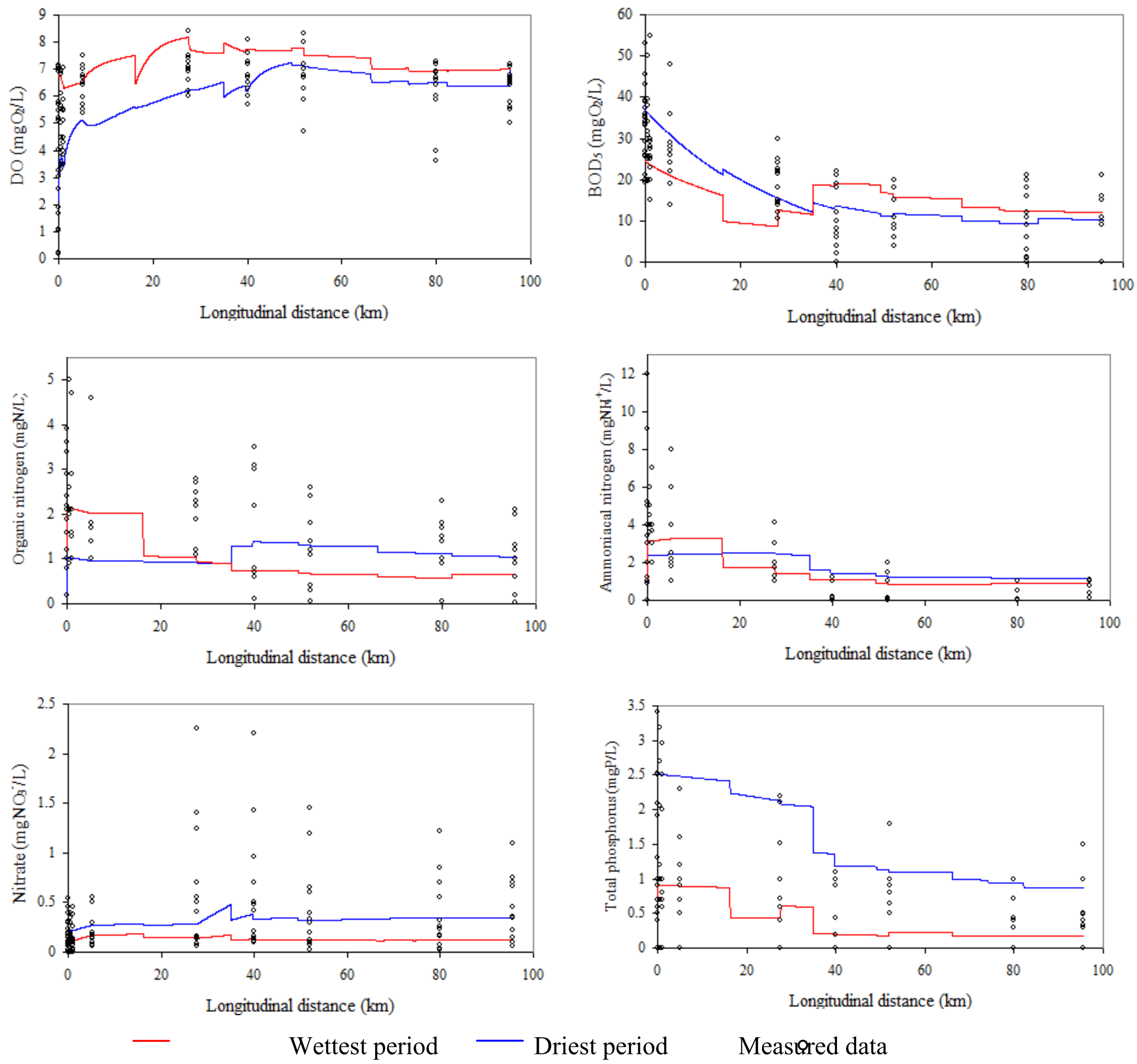


Fig. 4 Longitudinal profiles of the quality parameters simulated for the wettest and driest months, and data measured at the PQ water quality monitoring stations.

Sensitivity analysis

Calibrated constants

The factorial method enabled changes in the concentrations of the quality parameters to be evaluated based on simultaneous variations in K_a, K_d, KN_{oa} and KN_{ai} of +10% and –10% from their calibrated values. Changes in the parameters at all the PQ monitoring stations were consistently higher for DO, BOD_5 and nitrate, with greater amplitudes at stations PQ5 and PQ6. At PQ5, the calibrated value of DO varied by ±4.0% due to the change in K_a. The parameters BOD_5 and DO presented sensitivities, respectively, of ±1.0% and ±3.5% due to the change in K_d. The parameters organic nitrogen, ammonia and nitrate showed sensitivities of ±0.5%, ±0.3% and 0.07%, respectively, due to variations in KN_{oa}. The parameters ammonia and nitrate showed sensitivities of ±0.05% and ±2.6%, respectively, due to variations in KN_{ai}. At PQ6, the calibrated value of DO varied by ±2.5% due to the change in K_a. The parameters BOD_5 and DO showed sensitivities of ±4.0% and ±1.5%, respectively, due to the change in K_d. The variations in KN_{oa} did not cause significant variations. The parameter nitrate showed a sensitivity of ±1.0% due to the variations in KN_{ai}.

Estimated water quality of the intermediary inputs

In the individual variation in each intermediate input, the sensitivity of all the analyzed parameters diminished along the longitudinal length due to dispersion phenomena and biochemical conversions. In contrast, the opposite held true for simultaneous variations, due to the simultaneous inputs of pollutant loads in all the tributaries. In any given segment of Uberaba River, sensitivities based on simultaneous variations were always higher than individual variations.

In segment T20, just upstream of station PQ10, the order of magnitude of the sensitivity was assessed in the simultaneous and individual variations of the intermediate inputs. With regard to the parameter BOD, the simultaneous variations of +10% in the intermediate inputs were found to vary by +7.2% for BOD and by

-0.9% for dissolved oxygen. For the parameter organic nitrogen, the simultaneous variations of +10% in intermediate inputs varied by +8.1%. With respect to individual variations in this parameter, the sensitivity is correlated directly with the area of contribution of each subbasin. Larger areas of contribution provide higher flow rates, and hence, higher pollutant loads flowing into the main river. For the parameter organic nitrogen, the influence of the area of contribution was greater than that of the proximity of intermediate inputs to segment T20 (or PQ10).

For ammonia, nitrate and total phosphorus, the simultaneous variations of +10% in intermediate inputs caused the highest variations of +5.3%, +6.8% and +5.9%, respectively. The parameter dissolved oxygen varied by –2% in segment T20 due to simultaneous changes of –10% in the intermediate inputs. As for the individual variations in ammonia, nitrate, total phosphorus and dissolved oxygen, the proximity of intermediate inputs to segment T20 showed a greater influence than the area of contribution of the subbasins.

Scenarios

An analysis was made of the minimum water quality required for all the intermediate inputs to comply with Minas Gerais (2008) and Brazil (2005) for Class 2 of the Uberaba River. The critical flow $Q_{7,10}$ was adopted for all the intermediate inputs, whose values are listed in **Table 1**.

For Scenario 1, in which the water quality of all the intermediate inputs was kept equal to the values considered for October 2012 (the driest month), the quality parameters of DO, BOD_5 and P_{total} were found not to meet the specifications of the government environmental agencies (see **Fig. 4**). The parameters BOD_5 and P_{total} were noncompliant throughout the longitudinal length, with values of 9.4 to 38.8 mgO_2/L and 0.9 to 2.5 mgP/L, respectively. However, the parameter DO was noncompliant only in the first 5 segments (*T1* to *T5*), showing a minimum value of 2.1 mgO_2/L.

Based on the results obtained in Scenario 1, Scenario 2 evaluated what variations in intermediate inputs would be needed, upstream to downstream, so that all the parameters along this stretch of the Uberaba River would meet the limit valuesestablished by Minas Gerais (2008) and Brazil (2005). Scenario 2 evaluated only variations in the intermediate input PQ1, in which the changes in DO, BOD and P_{total} sufficed for the values of the parameter in segment T1 to meet the specifications of the environmental agencies. As for the parameter DO, it was found that the increase of 156% in October 2012 caused the entire longitudinal profile of DO to exceed the minimum value of 5.0 mgO_2/L. Due to the shorter length of segment T1 in comparison to that of the total studied stretch, viewing the profile in this sub-segment was impaired.

In Scenario 3, maintaining the changes in PQ1, the focus was on the variation of BOD and P_{total} in the STP. In Scenario 4, the changes in PQ1 and STP were maintained while the focus fell on the variation of BOD in Santa Gertrudes Stream and Verissimo River, and on P_{total} in São Félix Stream to Bernardes Stream.

Lastly, in Scenario 5, the concentration profile of the parameters was adjusted to the specifications set forth by the environmental agencies. In general, it was found that, considering the critical flow $Q_{7,10}$, the parameters of organic nitrogen, ammonia and nitrate would comply with the legally established limits. The concentration of the parameter DO would have to increase by 156% when compared to the value of the driest month, albeit only at the intermediate input PQ1. However, the parameters BOD_5 and P_{total} were the most problematic, presenting high values in almost all the intermediate inputs, except for the with Jataí and Preguiça streams, whose subbasins have small areas of contribution (see **Fig. 1**). This indicates that, in addition to the pollutant loads from the urban area of Uberaba, the use of 77% of the total area of the Uberaba River subbasin for agricultural purposes contributes to the high concentrations of BOD and P_{total}.

The sensitivity analysis of the initially calibrated constants K_a, K_d, KN_{oa} and KN_{ai} and the quality parameters of the initially estimated intermediate inputs generally showed low variations (lower than 9% for the parameters DO, BOD and nitrate).

In the prognostic analysis, Scenario 1 demonstrated that the pollution caused by the discharge of raw sewage upstream of PQ1 is responsible for the noncompliance of the parameters DO, BOD_5 and P_{total} with the limits established by Minas Gerais (2008) and Brazil (2005) for Class 2 of the river.

Upon altering the concentrations of parameters DO, BOD and P_{total} at station PQ1 in Scenario 2, it was found that the river presented characteristics that allowed it to be classified as Class 2, based on the analyzed parameters, corroborating the information that the current situation of the Uberaba River largely originates from the land use and occupation in the city of Uberaba (Minas Gerais).

Although Scenario 3 proposes significant changes to improve the quality of the effluent treated by the STP, the pollutant loads from some tributaries in the lower course of the river Uberaba impair the water quality. Scenario 4 showed that the larger subbasin of the middle and lower courses of Uberaba River favor a slight decline in the BOD concentration. However, the data for these subbasins were estimated; hence, they may not reflect the individual characteristics of each subbasin. Scenario 5 showed how the entire stretch under study could fit Class 2, which would require an improvement in the water quality of all the tributaries.

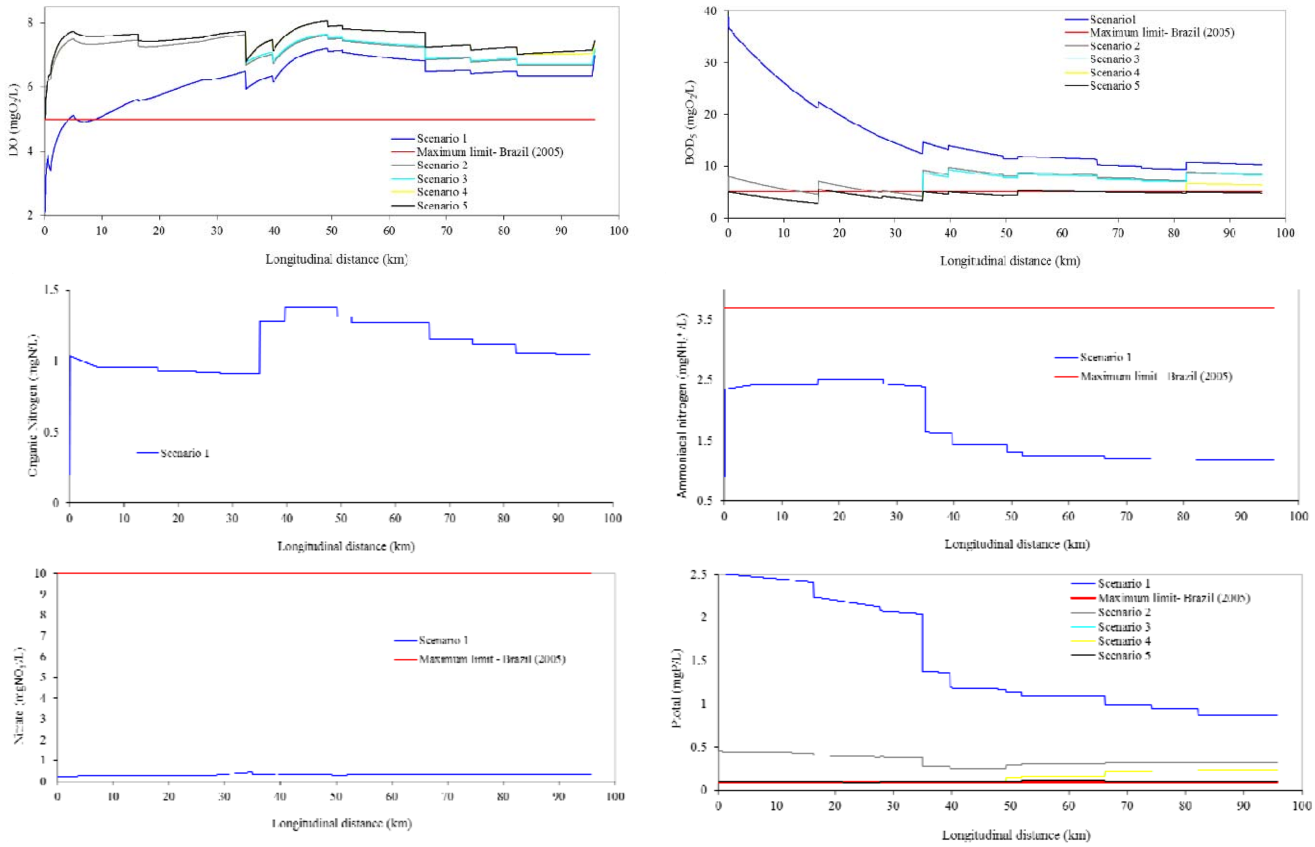


Fig. 5 Scenarios of the self-cleaning ability of the middle and lower courses of the Uberaba River.

The scenarios demonstrated the need for management on a river basin scale, since they characterize the need for a management system that ensures the diversity of use, which today is restricted due to the quality of the water.

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