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Water quality modeling in the Paraibuna River in Juiz de Fora/MG: diagnosis and prognosis

Modelagem da qualidade da água do Rio Paraibuna em Juiz de Fora/MG: diagnóstico e prognóstico

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ABSTRACT

To support the implementation of instruments of the National Water Resources Policy, as well as the new legal framework for basic sanitation, the environmental assessment of water courses becomes important to guide the planning, monitoring and management of a watershed. Thus, this research aims to contribute to the creation of information structures about the Paraibuna River and its water basin in the central and more urbanized region of Juiz de Fora/MG. The QUAL2K model was used considering two different hydrological periods. The study considered water quality data for the following variables: dissolved oxygen, biochemical oxygen demand, temperature, electrical conductivity and pH. The flow rates in the Paraibuna River and its tributaries were quantified using an Acoustic Doppler Current Profile (ADCP) and a hydrometric windmill. With the calibrated model, future water quality scenarios were simulated for the moment when the new sewage treatment plants are operating at maximum capacity, in accordance with the Juiz de Fora's Municipal Plan for Basic Sanitation Service. The results show that the Paraibuna River, in the central section of Juiz de Fora, provided data with reduced water quality, mainly in the dry season, leading us to conclude that the flow had a direct influence on the water quality. As for the simulated scenarios, we reached the conclusion that the best result obtained for the sewage treatment of the Paraibuna River will be achieved when the treatment conditions of scenario 3 are applied. This scenario includes the Wastewater Treatment Plants of União Indústria, Santa Luzia, and the renovation of the Wastewater Treatment Plant of Barbosa Laje, with an expected reduction of 90% of the polluting load in the streams covered by the present work, and a reduction of 50% of the organic load upstream of the section under study.

Keywords: water pollution; self-purification; QUAL2K.

RESUMO

Para fundamentar a implementação de instrumentos da Política Nacional de Recursos Hídricos, bem como o novo marco legal do saneamento básico, a avaliação ambiental dos cursos d'água torna-se importante para nortear o planejamento, monitoramento e gestão de uma bacia hidrográfica. Assim, esta pesquisa objetivou contribuir para a construção de estruturas de informações sobre o Rio Paraibuna e sua bacia hidrográfica na região central e mais urbanizada de Juiz de Fora, Minas Gerais. Foi utilizado o modelo matemático QUAL2K, considerando-se dois períodos hidrológicos distintos. No estudo foram levados em conta dados de qualidade da água para as variáveis oxigênio dissolvido, demanda bioquímica de oxigênio, temperatura, condutividade elétrica e pH. Foram quantificadas as vazões no Rio Paraibuna e nos seus tributários com o uso do ADCP (Acoustic Doppler Current Profile) e do molinete hidrométrico. Com o modelo calibrado, foram simulados cenários futuros de qualidade de água quando as novas estações de tratamento de esgoto estiverem operando com capacidade máxima, conforme o Plano Municipal de Saneamento Básico de Juiz de Fora. Os resultados mostraram que o Rio Paraibuna, no trecho central de Juiz de Fora, apresentou dados de qualidade de água com qualidade reduzida, principalmente no período seco, e conclui-se que a vazão tem influência direta nessa qualidade. Quanto aos cenários simulados, depreende-se que o melhor resultado obtido, para o tratamento de esgoto do Rio Paraibuna, será alcançado quando aplicadas as condições de tratamento apresentadas no cenário 3. Esse cenário contempla as ETE União Indústria, Santa Luzia e a reforma da ETE Barbosa Laje, com redução esperada de 90% da carga poluidora nos córregos contemplados no presente trabalho e redução de 50% da carga orgânica a montante do trecho estudado.

Palavras-chave: poluição hídrica; autodepuração; QUAL2K.

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Introduction

The disorderly and accelerated growth of cities is one of the most relevant factors when it comes to interference in aspects of water quality and pollution. As a direct consequence, quality limits for different uses are exceeded with negative implications that affect everyone who depends directly or indirectly on the maintenance of this resource. The impacts of this degradation have economic results, such as: the increase in the cost of treating water intended for consumption (Marques et al., 2019), the increase in costs due to the spread and treatment of diseases (Ferreira et al., 2021), the loss of productivity in agriculture and livestock (Okorogbona et al., 2018; Giri et al., 2020), and the reduction of cultural and landscape values (Mulvaney et al., 2020).

In this context, the Basic Sanitation Regulatory Framework Law (Law 14,026) (Brasil, 2020a), establishes deadlines and strategies for the management of water, sewage and disposal of urban solid waste in Brazil. According to the National Sanitation Information System, in 2019, in the national average, the total service rate with water supply network was 83.7%, and the urban water service was 92.9% of the population. Sewage systems reached 54.1% of the population, while the portion of generated wastewater that receives some treatment reached 49.1% of the Brazilian population (Brasil, 2020b). The lack of basic sanitation infrastructure in the water-related health-disease process can be considered relevant (Ferreira et al., 2021). Paiva and Souza (2018) estimated that, in 2015, these diseases corresponded to 2.35% of all hospitalizations in Brazil, totaling 0.7% of the overall expenses of the Unified Health System (SUS) with hospitalizations in that period.

It is also worth mentioning that the National Water Resources Policy (NWRP) (Brasil, 1997) points out a series of management instruments, such as: water resources plans, the use classification of water bodies, the granting rights to use water resources and the water resources information system. Furthermore, the NWRP includes in one of its foundations the management of water resources by hydrographic basin. Thus, it becomes a fundamental condition to advance in the management of water resources by river basin and to make operational the instruments as indicated in the legislation, in order to know the conditions of the river basin in terms of quality and quantity of water resources available there (Antunes et al., 2018; Fu et al., 2020).

Among the instruments of the NWRP, the classification of water bodies into use classes is only possible when considering National Environmental Council (CONAMA) Resolution N° 357 (Brasil, 2005), which provides for the classification of bodies of water into use classes and environmental conditions guidelines for its classification, as well as establishes the conditions and standards for effluent discharge, while paying attention to the river basin as a management unit. Thus, the present study on the Paraibuna River basin is justified by its importance as a source of water supply and for the management of water resources in the southeastern region of Brazil, the most populous area of the country. Cutting through the Juiz de Fora region, the Paraibuna River directly or indirectly receives untreated and partially treated wastewater from industrial sectors and approximately 570,000 inhabitants. These discharges have caused pollution, contributing to an unfavorable impact on the quality of its waters (Dias et al., 2021; Quadra et al., 2021). In addition to the pollution of waters close to the urban area, water availability in Juiz de Fora has been decreasing over the last few years (Andrade and Ribeiro, 2020), and it is relative, due to the discrepancy of watercourse flows between the rain and drought seasons, which is why the Chapéu D'Uvas Dam was built in the 1990s, upstream from Juiz de Fora, to regulate the flows of the watercourse, and is currently one of the main supply sources of the city (Almeida et al., 2019; Paranaíba et al., 2021).

In order to better understand the relationship between water quantity and quality, the mathematical modeling of water quality is as an important tool for carrying out a diagnosis of the current situation of the watercourse, as well as of its use to present prognosis of wastewater treatment and its impacts on the water quality of the studied basin, being increasingly used by managers as an aid to decision-making, gradually becoming a tool of great relevance, due to the importance of water and sanitation, regarding the treatment of effluents (Antunes et al., 2018; Macedo et al., 2018; Cunha and Ferreira, 2019; Bai et al., 2022).

In 2020, a new domestic wastewater treatment plant (WWTP) was inaugurated in Juiz de Fora, União Indústria WWTP, which is part of a medium and long-term plan to improve the water quality of the Paraibuna River. In this context, the purpose of the work was to evaluate the self-depuration capacity of the Paraibuna River, by means of simulation, through mathematical modeling in different periods and hydrological conditions, considering the current scenario of the hydrographic basin and future scenarios when the new WWTPs are fully operational, as provided for in the Municipal Basic Sanitation Plan of Juiz de Fora (PMJF, 2013).

Material and Methods

Characterization of the place of study and sampling points

This study was carried out in the Paraibuna River basin, which extends, for the most part, through the State of Minas Gerais, also draining a small region of the State of Rio de Janeiro. The Paraibuna River rises in the Mantiqueira mountain range at 1,200 meters above sea level, cuts through different cities, including Juiz de Fora, and after covering 166 km runs on the left bank of the Paraíba do Sul River at 250 meters above sea level. The Paraibuna River basin is formed by three main rivers: Paraibuna, Cágado and Peixe (PMJF, 2013).

According to the Brazilian Institute of Geography and Statistics' data and estimates (IBGE, 2010), Juiz de Fora occupies a total area of approximately 1,436 km², with a population of 573,285 inhabitants, with its headquarters located at -21.76° latitude and -43.34° longitude. The urban perimeter of Juiz de Fora is totally inserted in the middle course of the Paraibuna River. The study stretch is characterized by including the central and most urbanized region of Juiz de Fora, totaling approximately 22 km (Figure 1).

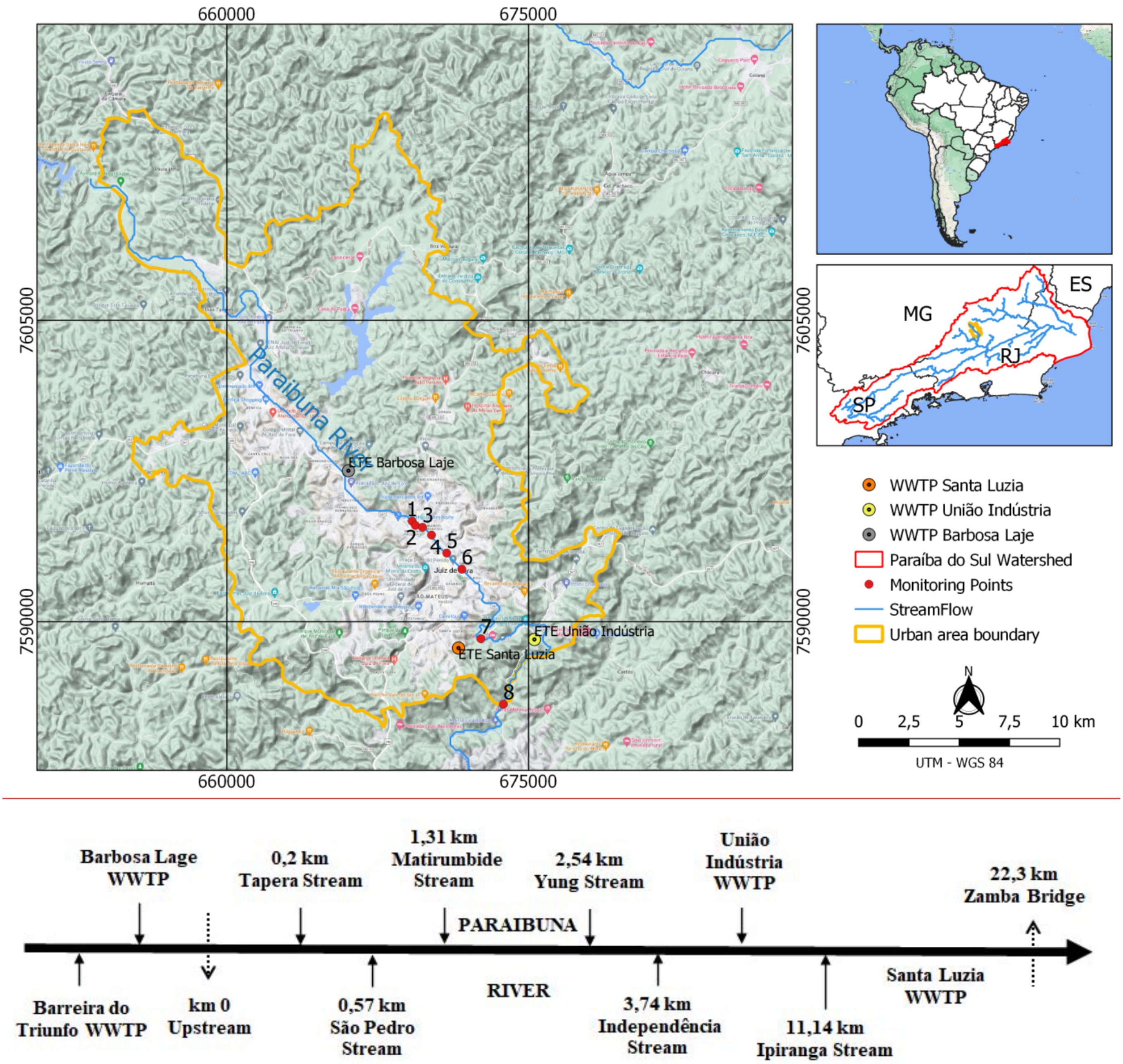

Figure 1 – Georeferenced location of the Paraibuna River basin, spatial distribution of sampling points and wastewater treatment stations, and single-line diagram of the study area.

The sampling campaigns were carried out in the rainy and dry seasons, seeking to describe the purification dynamics of the Paraibuna River, in different situations. Field campaigns took place in September 2019 and March 2020, to obtain representative data in the dry season (September) and in the rainy season (March). For the collection of comparative upstream and downstream of the studied stretch in the Paraibuna River, a point 200 meters upstream of the first tributary (Upstream) was chosen as the initial survey, and the downstream point was chosen as the border of the municipalities of Juiz de Fora and Matias Barbosa Zamba Bridge. The other sampling points were, respectively, upstream the confluence Paraibuna River and each of its tributaries. In order to facilitate the survey and sample representativeness, the bridges over the Paraibuna River were used along the stretch evaluated as support for the collection of samples (Table 1).

Model input and calibration data

For the evaluation of water quality, samples were collected in plastic containers at a depth of 20 to 30 cm. The samples were used to evaluate *in situ* water quality variables regarding: dissolved oxygen (DO), biochemical oxygen demand (BOD), temperature, pH and electrical conductivity (EC). Except for BOD, a HACH multiparametric probe (Model HQ11d) was used to quantify the quality variables. BOD was analyzed in the laboratory using the Winkler method after incubation for five days at 20°C (APHA et al., 2005). The choice of water quality variables is directly related to the parameters measured by the multiparametric probe.

In addition to the mentioned quality variables, the flows in the Paraibuna River were quantified, using the acoustic Doppler current profile (ADCP), and, in the tributaries, using a GURLEY brand vertical axis hydrometric windlass. Except for the Matirumbide and Independência streams, which are channeled, the wet area at the mouth of the stream was surveyed and the method of approximation of the mean-velocity with the use of a float was used. The mean-velocity and depth were obtained during the flow measurement using the ADCP and hydrometric windlass in the tributaries and in the headwater section of the study stretch. For the other points of the Paraibuna River, the Manning equation was used (Zhang et al., 2021). In order to compare the used methods, the linimetric rules of National Water and Sanitation Agency were also used, on the day of the campaigns, installed on the Paraibuna River between the Independência and Ipiranga streams. Environmental data on air temperature, relative air humidity and daily rainfall were obtained at the climatological station of the Climatology and Environmental Analysis Laboratory of the Universidade Federal de Juiz de Fora.

To assess the self-depuration capacity of the Paraibuna River, the QUAL2K model version 2.12, developed by Chapra et al. (2012), was used. The choice of this model, over others, such as QUAL2E, is justified because it is an updated version, distributed worldwide, freely available on the internet and, above all, more complete. With the input data, it was possible to parameterize the model with the necessary information for performance thereof. The model was applied in order to calibrate it, comparing the curve simulated by the software with the data collected in the field. The "INTERNAL" option was used, with the equations of the O'Connor and Dobbins model to adjust the reaeration coefficient (K_2), obtaining the coefficients K_1 and K_2, used for calibration. As no evaluation was performed regarding the presence of solids and nitrogen in the waters, not even an evaluation of the bed of the watercourse, regarding the presence of sediments, the sedimentation coefficient and the oxygen consumption value by the benthic oxygen demand were adopted as the Qual2K default, being respectively 0.008 m d^{-1} and 2 g m^2 d^{-1} of O_2.

Table 1 – Identification and geographic coordinates of sampling points along the Paraibuna River in Juiz de Fora-MG.

Sampling point	Geographic Coordinates
1 - Upstream	S 21°44'37.51"
2 - Tapera Stream	S 21°44'38.27"
3 - São Pedro Stream	S 21°44'40.32"
4 - Matirumbide Stream	S 21°44'42.91"
5 - Yung Stream	S 21°45'13.50"
6 - Independence Stream	S 21°45'41.09"
7 - Ipiranga Stream	S 21°47'39.81"
8 - Zamba Bridge	S 21°49'20.34"

Simulation of future scenarios

The city of Juiz de Fora has three wastewater treatment plants (WWTP) that directly influence the place of study of this research. Barbosa Laje WWTP is located upstream of the study stretch, União Indústria WWTP will receive the effluents currently released into the Tapera, São Pedro, Matirumbide, Yung and Independência watercourses, and finally Santa Luzia WWTP, still in the field project, will receive the effluents currently destined for the Ipiranga tributary. To envision the possible future scenario for the year 2025, as described in the Municipal Plan for Basic Sanitation of Juiz de Fora (PMJF, 2013), three different scenarios were simulated, keeping the kinetic parameters previously determined in the model calibration. The simulated scenarios drain the catchments where the effluent treatment plants are installed (Table 2). The organic matter removal efficiencies in União Indústria and Santa Luzia WWTPs, by the operating process, were confirmed by Waqas et al. (2020). Barbosa Laje WWTP was proposed to increase efficiency by 50% in the treatment of effluents discharged into the Paraibuna River upstream of the studied stretch, according to the expansion that is contemplated in the Municipal Plan for Basic Sanitation of Juiz de Fora (PMJF, 2013).

For the statistical analysis of the data, in addition to the descriptive statistics, the Shapiro-Wilk test was applied to the water quality data collected along the Paraibuna River to assess the normality of the data, and then the Spearman's Correlation analysis was performed, for data that do not follow the normal distribution. Subsequently, the Principal Component Analysis was performed on the data. For data analysis, the PAST software was used.

Table 2 – Summary of scenarios simulated in the QUAL2K model with the WWTPs in operation in each scenario and their respective efficiency of organic matter removal.

Scenarios	WWTPs in operation	Efficiency considered (%)
1	União Indústria	90
2	União Indústria	90
	Santa Luzia	90
3	União Indústria	90
	Santa Luzia	90
	Barbosa Laje	50

At the end of the simulations with QUAL2K, the statistical index of REMQ (Root-Mean Square Error) was used to indicate how significant the relationship between simulated and measured values is (Soares and Calijuri, 2021).

Results and Discussion

Results diagnosis and modeling of water quality

It can be seen in Table 3 that the variation of flows in the Paraibuna River along the measured stretch and on the days studied is relatively large. The maximum measured flow was 66.44 $m^3 s^{-1}$ and the minimum flow was 3.92 $m^3 s^{-1}$. The lower flow was due to the dry season and the maximum was due to the intense rains in Juiz de Fora. According to National Institute of Meteorology (INMET) data, there were monthly mean values accumulated in the months of January and February of 371.4 mm and 347.6 mm, respectively, values above the historical mean for those months in the region, which are 287 and 181 mm.

When comparing the flow measured in the Paraibuna upstream Ipiranga stretch with the readings from the limnimetric scale ruler of the Juiz de Fora Downstream Station (Code 58480500) operated by ANA and installed in the same location, an accuracy of approximately 95% in the dry season and 99% in the rainy season is found, evidencing that the method used is precise in the quantification of the flow, and the measured flows reflect the local reality.

The simulations with the QUAL2K model (Figure 2A), as well as the values measured in the field, indicate a large variation in flow during the two sampling campaigns. The flow rate of water bodies effectively influences the concentrations of dissolved compounds, and, of course, there will be an intervention in the environmental quality of the compounds studied herein, dissolved oxygen and biochemical oxygen demand. Patil et al. (2022), when studying the characteristics of the flow and the variables of water quality, observed a direct relationship between the flow rate and the environmental quality of the water, and indicated that the most efficient alternative to reduce the impacts on water quality would be to adjust the load of pollutants or increase discharges upstream of the river. From this point of view, the flows of the studied tributaries are very low when compared to the Paraibuna River (Table 3), contributing little to wastewater dilution.

The water temperature in the Paraibuna River and tributaries studied herein suffered little variation in the two field campaigns, being slightly higher during the rainy season (Table 3). It is noted that, between the two campaigns, the variation in water temperature in the tributaries was greater, as they are shallower and are more influenced by ambient temperature, as verified by Fia et al. (2015). Exception is made here to the Independência Stream for having a long channeled stretch and suffering less influence of the external temperature and solar radiation. Due to the small variations occurred and the influence of the tributaries on the water temperature of the Paraibuna River, the values adjusted by the QUAL2K Model should not have an adequate efficiency, so the release of its treated effluents seems to alter the quality of the receiving body, which is in disagreement with current environmental legislation (Figure 2B).

Table 3 – Values of the variables monitored along the Paraibuna River and tributaries of the study area during the dry and rainy seasons.

Stretches samples	Dry season						Rainy season					
	Q	T	EC	pH	DO	BOD	Q	T	EC	pH	DO	BOD
Upstream - 1	3.92	21.7	98.9	7.0	4.1	22.8	60.25	22.8	61.9	7.0	6.4	1.6
1	0.20	21.5	95.6	7.5	2.9	49.5	0.32	23.5	133.0	7.3	5.8	1.0
1 – 2	4.12	21.3	103.4	7.0	2.3	26.9	60.58	22.9	61.9	7.3	6.6	1.7
2	0.68	20.6	111.6	7.4	1.6	*	1.19	23.2	121.4	7.5	5.8	2.2
2 – 3	4.80	21.2	100.2	7.1	0.7	26.1	61.76	23.1	62.4	7.2	6.4	0.9
3	0.45	21.4	168.6	7.7	1.5	138.5	0.55	23.9	241.0	7.6	4.3	18.5
3 – 4	5.25	21.2	100.6	7.1	1.8	38.1	62.31	22.8	72.5	7.2	6.0	2.3
4	0.55	21.0	103.1	7.6	2.1	65.5	1.38	23.4	125.2	7.3	5.3	6.2
4 – 5	5.80	21.3	102.5	7.1	1.3	41.5	63.69	22.8	78.3	7.2	6.0	4.4
5	0.60	22.7	146.4	7.7	1.5	*	1.81	23.7	219.7	7.5	5.0	49.4
ANA**	**6.73**	-	-	-	-	-	**64.90**	-	-	-	-	-
5 - 6	**6.40**	21.8	106.0	7.2	2.1	42.9	**65.50**	22.9	65.9	7.1	6.1	11.3
6	0.62	22.1	106.4	7.6	3.2	53.6	0.93	23.3	112.5	7.3	6.0	18.5
6 - Downstream	7.02	22.9	103.6	7.6	7.1	24.1	66.44	22.1	45.2	7.0	7.1	3.8

*Value not obtained; **flow obtained from the reading of the limnimetric scale ruler operated by ANA; T: temperature (°C); EC: electrical conductivity ($\mu S\ cm^{-1}$); Q: flow rate ($m^3 s^{-1}$); DO: dissolved oxygen ($mg\ L^{-1}$); BOD: biochemical oxygen demand ($mg\ L^{-1}$).

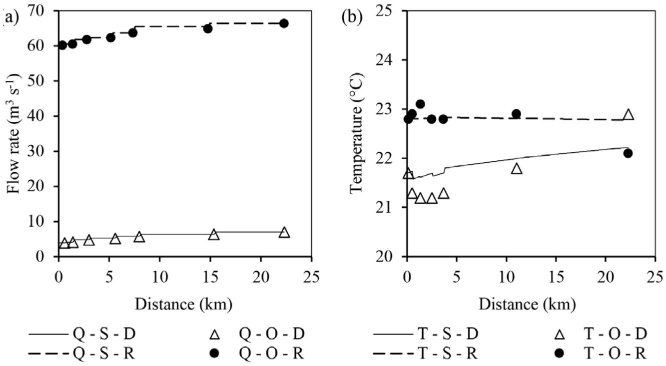

Figure 2 – Flow rate (Q) and temperature (T) values observed (O) in the Paraibuna River and simulated (S) by QUAL2K during the first and second sampling campaigns in dry (D) (May 09, 2019) and rainy (R) (March 03, 2020) seasons.

The measured pH values ranged between 7.0 and 7.7 during the campaigns, which shows that they are slightly basic (Table 3). As watercourses receive untreated domestic wastewater, lower pH values were expected due to the anaerobic degradation of organic matter (Che et al., 2020). Thus, as the pH values ranged from neutral to slightly basic, it may be indicative of the contribution of industrial wastewater in the region (Bisimwa et al., 2022). It is difficult to establish an immediate explanation for the pH behavior, as it is influenced by numerous factors, such as solids, dissolved gases, hardness, alkalinity, temperature, biotic factors, among others (Fritzsons et al., 2003). CONAMA Resolution N° 357/2005 establishes the pH range between 6 and 9 for all use classes, which shows that the studied stretch is within the norms regarding this quality variable.

For electrical conductivity in the dry season, analyzing the Paraibuna River (Table 3), higher values were obtained with a mean of 102 µS cm^{-1}, against a mean of 64 µS cm^{-1} for the rainy season. As the conductivity indicates the concentration of ions in the water, the dilution factor is extremely relevant. The electrical conductivity of streams was high for both campaigns, and greater than 100 µS cm^{-1} in all analyzes of the dry season campaign. This is indicative of a higher concentration of domestic wastewater in the streams, since all sewage in the region is released *in natura* directly into the streams. In this case, the contribution of the industrial effluent in watercourses is also noteworthy.

Regarding the water quality data referring to the DO and BOD (Table 3), there is a water-environmental picture of the monitored streams that were extremely impacted, especially during the dry season. Analyzing this period and excluding the most downstream stretch — Zamba Bridge — the other stretches have a DO below 5 mg L^{-1} — a lower limit for a class 2 river, according to Brasil (2005), a result of the discharge of untreated effluents into watercourses, aggravated by the lower flow in dry season with lower dilution potential. This fact provided BOD values greater than 5 mg L^{-1}, the upper limit for the proposed objectives for a class 2 river, according to Brasil (2005). The BOD value measured for the Matirumbide Stream, which presented a concentration of 139 mg L^{-1}, stands out. This value corresponds to about half of the value observed in raw sewage. It is noteworthy that in the São Pedro and Independência Streams it was not possible to analyze the BOD, but because they are in the central region of the city and, due to the visual aspect, they present aspects of water with a high organic load.

It is evident here that in the stretch – Paraibuna upstream Matirumbide with a DO of 0.7 mg L^{-1}, we have an anoxic environment located in the most central region of Juiz de Fora. However, the Paraibuna River at Zamba Bridge presented a relatively high DO value, justified by the higher speed and turbulence of the water in the stretch. Despite the load of organic matter, there is a high capacity for self-purification, associated with high rates of degradation of organic matter and favorable physical conditions of turbulence that promote the process of more efficient atmospheric reaeration in the water body (Abreu and Cunha, 2017).

Analyzing the rainy season, higher DO values were obtained when compared to the dry season. All stretches of the Paraibuna River studied in this period have a DO greater than 5 mg L^{-1}. The worst stretch in the river is — Paraibuna Upstream Yung — where a value of 5.98 mg L^{-1} was found, a number considered acceptable by CONAMA Resolution Nº 357, for class 2 (Brasil, 2005). In the work by Fraga et al. (2020) modeling the seasonality of the water quality of the Piracicaba River, it was observed that in the rainy season, in all sections, the DO concentrations were higher than the minimum recommended by the legislation and were always close to saturation values.

The DO concentration values at the mouth of the six tributaries are lower than those measured in the main body of the Paraibuna River, probably due to the higher proportion between the wastewater dumped and the watercourse flow. This fact was mainly observed for the dry season, aggravated by the lower flows in the dry season, culminating in DO values in some tributaries lower than 2 mg L^{-1}. Corroborating the results, Alvarenga et al. (2012) observed that in the dry season there are lower temperatures in the water and low flow of precipitate to the river, causing lower dilution of the compounds dissolved there and reduction in DO levels.

The tributaries during the rainy season have acceptable DO values, with an average of 5 mg L^{-1}, due to the higher flow rate in the streams resulting in greater turbulence and dilution of the organic matter present in the midst, reflecting in lower values of BOD. Analyzing only the Paraibuna River, all the stretch was in compliance with CONAMA resolution Nº 357/2005, with the exception of the Paraibuna stretch upstream Ipiranga, which presented a concentration of 11 mg L^{-1} of BOD. In this stretch there is a slaughterhouse, which, despite having an effluent treatment plant, does not seem to maintain the quality of the watercourse. The Matirumbide, Independência and Ipiranga tributaries also showed high values for this campaign, respectively, 18, 49 and 18 mg L^{-1}.

In general, the results obtained from BOD for the dry season — tributaries and Rio Paraibuna — are inconsistent with the demands for water sustainability required by a more developed society. The analysis of this information allows us to conclude that there is effectively an immense load of organic matter contributed to the Paraibuna River by the six sub-basins analyzed herein (Tapera, São Pedro, Matirumbide, Yung, Independência and Ipiranga). In Brazil, watercourses that cross larger cities usually have poor water quality due to the discharge of domestic effluents and industrial wastewater, partially treated or untreated (Morais et al., 2021; Tonhá et al., 2021).

In the watersheds studied in the present work, there are several industrial enterprises of small and medium size, of the textile and animal slaughtering types, which are known to contribute with high organic loads in their effluents. Thus, the picture outlined herein is not limited to the release of *in natura* domestic effluents into the river, but also industrial wastewater, as verified by Piratoba et al. (2017) in Barcarena (PA), and Bisimwa et al. (2022) in the Republic of Congo.

Table 4 demonstrates that all variables present a correlation greater than 0.5, with at least two other water quality variables, except for pH in the rainy season. Correlation coefficients greater than 0.5 express a strong relationship between water quality variables, as observed by Helena et al. (2000). The K_2 values obtained in relation to the DO values, in the dry season, were significantly correlated, considering that the K_2 values were obtained from the monitored DO values. Also, the pH showed a significant correlation in relation to the flow rate values, while EC and K_1 presented a strong correlation regarding the flow rate (r > 0.75), due to the increase in the concentration of salts and organic matter by the flow rate reduction.

In the rainy season, there was a significant and positive correlation between flow and BOD (Table 4), because along the river, with the increase in the flow rate due to the contribution of tributaries, there was also an increase in BOD from them. There was a significant correlation between the flow rate and the K_1 values, probably due to the contribution of organic matter along the length of the studied stretch, considering that BOD and K_1 were also significantly correlated. As for K_2, there is a strong correlation with pH, EC, DO and flow rate, although not significant. That is, the flow rate variation strongly influenced the K_2 values in the rainy season, which did not occur in the dry season.

The behavior of the water quality variables monitored in the Paraibuna River in the study region was composed of two principal components (Table 5). The selection of the number of principal components was the one in which the accumulated percentage of the total variance was greater than 85%, being more conservative in relation to that adopted by Guedes et al. (2012), and offering a good idea of the representation of the original discrepancy of the variables.

Table 4 – Correlation matrix of water quality variables in the Paraibuna River.

Dry season								Rainy season							
	pH	EC	DO	BOD	Q	K_1	K_2		pH	EC	DO	BOD	Q	K_1	K_2
pH								pH							
EC	**0.64**							EC	0.41						
DO	0.06	0.29						DO	-0.24	**-0.96***					
BOD	0.28	**0.54**	**-0.50**					BOD	-0.17	0.38	-0.35				
Q	**0.95***	**0.75**	0.07	0.43				Q	-0.30	0.13	-0.05	**0.79***			
K_1	**-0.69**	**-0.50**	-0.43	-0.18	**-0.75**			K_1	0.46	-0.02	0.03	**-0.88***	**-0.88***		
K_2	0.27	0.20	**0.79***	**-0.59**	0.13	-0.23		K_2	**-0.50**	**-0.56**	**0.57**	0.11	**0.52**	-0.37	

* Significant at 5%.

Table 5 – Factor weight matrix of water quality variables observed in the Paraibuna River in the three principal components selected (PC).

Variables	Dry season		Rainy season	
	PC 1	PC 2	PC 1	PC 2
pH	0.49	-0.08	0.01	-0.01
EC	0.29	0.37	**0.99**	0.01
DO	0.41	-0.36	-0.04	-0.01
BOD	0.00	**0.65**	0.04	**0.85**
Q	**0.55**	0.27	-0.07	0.48
K_1	-0.37	-0.31	0.02	-0.18
K_2	0.41	-0.38	-0.04	0.04
Eigenvalue	3.73	2.33	108.48	16.59
Variance (%)	53.32	33.33	85.34	13.05
Accumulated variance (%)	53.32	86.65	85.34	98.39

Table 5 shows the loads for each monitored variable. These loadings reflect the relative importance of each variable responsible for a specific principal component: the greater the loading of a variable, the greater the contribution representing the principal components.

The first principal component represented 53.3 and 85.3% of the variability of the data accumulated in the dry and rainy season, the flow rate in the dry season and the electrical conductivity in the rainy season. On the other hand, the reduction of eigenvalues in the second principal component was responsible for the lower data variability.

Model calibration results

The analysis of the data in Table 6 allows us to conclude that the K_1 values, referring to the calibration of the water quality data — DO and BOD, are higher compared to the literature (Von Sperling, 2014), especially for the first three stretches. The Matirumbide Stream had the highest BOD value in the dry season, which probably reduced the DO concentration in the Paraibuna River in the Matirumbide — Yung stretch, leading to a reduction in aerobic degradation and, consequently, to a reduced K_1 value (0.05 d^{-1}). Another relevant factor may be some industrial activity present along the Matirumbide Stream catchments, which may have contributed to an organic matter that is more difficult to biodegrade, causing the reduction of the values of K_1, in this section. In general, the values obtained for K_1 denote the presence of large organic loads in the analyzed stretches with good biodegradability in the first analyzed stretches of the river, with a tendency to reduce K_1 as the runoff advances downstream, mainly after the stream Yung (the most central and urbanized region of the city). In the work by Menezes et al. (2015), the analysis of the effect on seasonality in the self-depuration of Ribeirão Vermelho, found values of K_1 ranging between 0.07 and 0.15 d^{-1}. Barros et al. (2011), evaluating the oxygen balance in the Turvo River, at different seasons, observed this pattern, with lower K_1 values and a slower stabilization rate of organic matter, resulting in a high BOD. In contrast, samples with higher K_1 values degraded organic matter faster.

Table 6 shows high values of K_2 when compared to typical values observed in the literature (Von Sperling, 2014), mainly for the dry season, whose mean along the entire stretch of the river was 2.07 d^{-1}, with a variation between 1.52 and 3.15 d^{-1}. These values are atypical for the characteristics of the Paraibuna River, and characteristic of runoff with high slope, especially upstream of the Independência Stream, where the slopes of the Paraibuna River are reduced. It is believed that the greatest interference of the river's hydraulic characteristics influencing the K_2 values is found in the lower water depth resulting from the low flow, which may have favored gas exchange between the atmospheric environment and the river. Menezes et al. (2015), studying Ribeirão Vermelho, found high K_2 values during the winter season, with low flow rate, small water depths and a tendency to have a higher reaeration coefficient, due to the ease of mixing in the depth profile and greater surface turbulence. Haider and Al (2013), in a river in Pakistan, observed the same conditions as K_2 based on the hydrodynamic conditions of the river and the applied model.

Regarding the rainy season, the mean value of K_2 was 0.92 d^{-1}, with a variation between 0.70 and 1.95 d^{-1}, which are typical values of fast rivers. During this campaign, the high flow of the Paraibuna River provided greater turbulence in the water body, but not enough to influence K_2 as verified by the reduced water depths of the dry season. In both seasons, the last stretch, upstream of the Ipiranga Stream, found high values for K_2, justified by the increase in water velocity due to the greater slope and turbulence in the stretch. Fraga et al. (2020), modeling the seasonality of the Piracicaba River, found higher K_2 values for the dry season, with a range of values from 2.10 to 6.35 and 1.75 to 3.28, respectively, for the dry and rainy seasons.

Regarding the simulations with the model, it is observed in Figure 3A that the adjustment between the measured and simulated DO values are quite similar, indicating that the values of parameter K_2, presented in Table 6, represent well the hydrodynamics of water transfer of atmospheric oxygen to the water body, although there is a certain discrepancy between the simulated periods. The same reasoning applies to the values of parameter K_1, which well represented the char-

Table 6 – Flow rate (Q), water velocity (V) and watercourse depth (H) values obtained in the field, and values of organic matter degradation coefficient (K_1) and reaeration coefficient of watercourse (K_2) (20°C) obtained in the model calibration.

Stretches	Dry season					Rainy season				
	Q	V	H	K_1	K_2	Q	V	H	K_1	K_2
1	3.92	0.20	0.85	1.65	2.24	60.25	0.35	2.75	1.65	0.71
2	4.12	0.20	0.95	1.85	1.90	60.58	0.35	2.75	1.65	0.71
3	4.80	0.20	0.95	2.95	1.90	61.76	0.35	2.60	2.45	0.75
4	5.25	0.20	1.00	0.05	1.76	62.31	0.33	2.70	1.50	0.71
5	5.80	0.20	1.10	0.70	1.52	63.69	0.40	2.80	0.60	0.70
6	6.40	0.40	1.14	0.22	2.04	65.50	0.50	3.00	0.19	0.95
7	7.02	0.55	0.95	0.01	3.15	66.44	0.65	2.50	0.01	1.95

Q: $m^3 s^{-1}$; V: $m s^{-1}$; H: m; K_1:day^{-1}; K_2: day^{-1}; Stretches: 1. Upstream – Tapera Stream; 2. Tapera Stream – São Pedro Stream; 3. São Pedro Stream – Matirumbide Stream; 4. Matirumbide Stream –Yung Stream; 5. Yung Stream –Independência Stream; 6. Independência Stream –Ipiranga Stream; 7. Ipiranga Stream – Zamba Bridge.

acteristics of the organic matter present in the watercourse, with good adjustments between the values measured in the field and the values simulated with the model (Figure 3B). Bottino et al. (2010) also observed a discrepancy in the results for the calibration of the QUAL2K model with the sampling data from the Canha River, however, many parameters and applications presented in the model are attributed to temperate environments, which may compromise the calibration of some variables. On the other hand, in studies on the quality of water in a river in Malaysia, Hossain et al. (2014) observed that the result of the calibration of the QUAL2Kw model agreed with the observed values.

In general, the values of K_1 and K_2 adequately reproduced the values of BOD measured in the stretch of river studied for the QUAL2K model. As mentioned earlier, the BOD values found for the Matirumbide and Independência streams differ from the others. These are high values (see Table 3), perhaps due to the channeling of the streams, which makes their self-depuration very difficult, as the reaeration process does not occur efficiently, since the concentration of DO in the air is low and there is little turbulence, due to low roughness of the riverbed.

By statistically analyzing the REMQ, it was possible to establish how significant the QUAL2K simulation was with the data observed in the field. Regarding the DO for the dry season, a REMQ of 0.70% was found, and, for the rainy season, it was 0.19%. These results show that there was a better fit of the data during model calibration in the rainy season. Similarly, Abdeveis et al. (2020) found an adjustment between observed and simulated data based on REMQ for DO (14%) when using QUAL2K to model water quality in the Dez River in Iran. The same was observed by Hossain et al. (2014) when modeling water quality in the Tunggak River in Malaysia, where the REMQ was 1.6% for the OD. These rivers have in common with the Paraibuna River the fact that they are in regions with a tropical climate, with two well-defined seasons, hot and rainy summers, and cold and dry winters.

Regarding the BOD data, the REMQ index for the dry season was 10.97%, and for the rainy season it was 3.22%. These results show that there was a better adjustment of the simulated data during the rainy season. However, Camargo et al. (2010) report that a REMQ value lower than 20% can be considered a good adjustment between the observed and predicted values by the model.

Future scenarios

In Figure 4A, it is noted that the simulated BOD values for scenarios 1 and 2 are coincident up to approximately 12 km from the beginning of the studied stretch, a point from which the Santa Luzia WWTP will start operating (scenario 2), reducing the BOD value from this point onwards. And, in Figure 4B, the simulated BOD values for scenarios 1 and 2 are coincident throughout the studied stretch, these being influenced more by the increased flow than by the insertion of a new WWTP (Santa Luzia) in the study region (scenario 2).

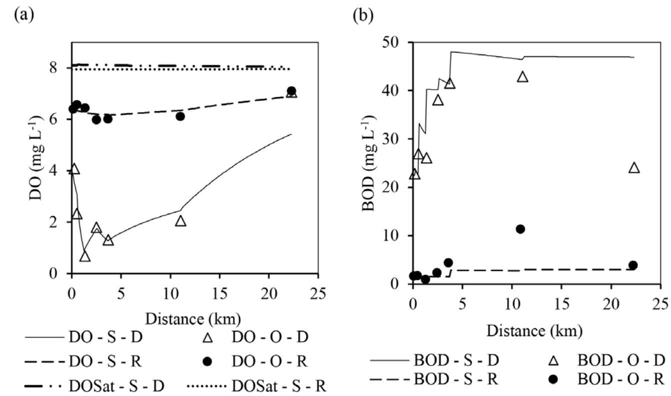

Figure 3 – Values of dissolved oxygen (DO), oxygen saturation concentration (DOSat) and biochemical oxygen demand (BOD) observed (O) in the Paraibuna River and simulated (S) by QUAL2K during the first and second sampling campaigns in the dry (D) (09/05/2019) and rainy (R) (03/03/2020) seasons.

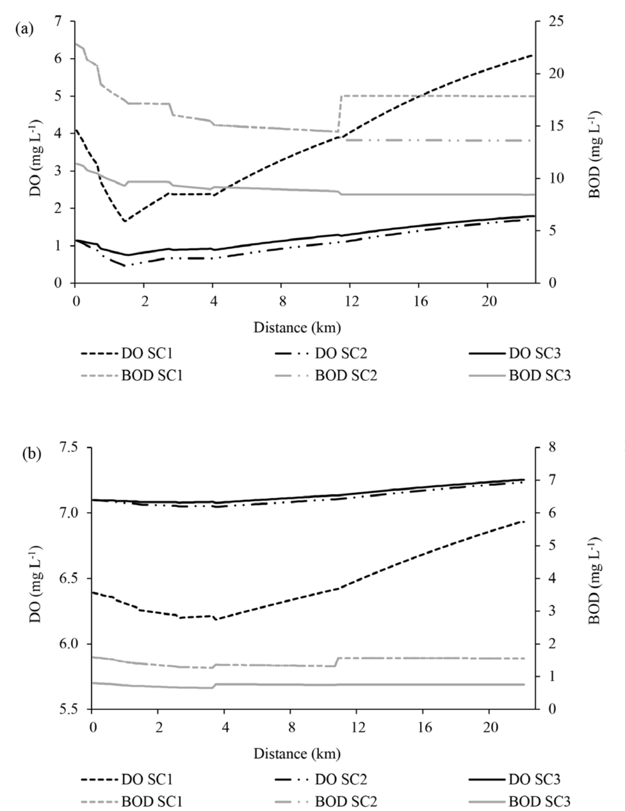

Figure 4 – Simulated values of dissolved oxygen (DO) and biochemical oxygen demand (BOD) for the three different scenarios (SC) in the (A) dry and (B) rainy seasons.

When observing the results referring to the simulation of future scenarios for the DO and BOD variables (Figure 4) it is verified that, due to the total functioning of the new planned WWTPs (União Indústria and Santa Luzia), plus a reform and expansion of Barbosa Laje WWTP, scenario 3 is the one that presents the best qualitative result of the quality variables. In this scenario, analyzing the dry season, a recovery of DO levels is observed in the studied stretch closer to the headwaters, compared to the other scenarios. The headwater DO concentration did not change, but it is believed that, with the improvement in the upstream wastewater treatment system, this concentration tends to increase. Even in this analysis, there was a recovery of DO from 4 to 6.5 mg L^{-1} in a region with high organic matter input, which is the most central and urbanized region of the city. BOD concentrations varied along the river from 11.4 mg L^{-1} to just over 8 mg L^{-1}, but still above 5.0 mg L^{-1}, as suggested by quality class 2.

It is noteworthy that, in the dry season, the worst quality scenario of the Paraibuna River is visualized throughout the year, as the flows remain extremely low in this period. Regarding the rainy season, the results are compared to a class 1 river. At the last point analyzed, on the border between the city of Juiz de Fora and Matias Barbosa, the DO concentration is approximately 7 mg L^{-1}, a value compared to clean water rivers with a high diversity of aquatic life. BOD concentrations are always below 1 mg L^{-1}, representing small concentrations of organic matter.

Scenario 3 becomes the one expected from the standards established by CONAMA Resolution No. 357/2005. The forecast to achieve this scenario is in 2025. This reinforces the need for a better monitoring of environmental agencies in relation to the efficiencies of domestic and industrial wastewater treatment stations, because, although the environmental agency allows the establishment of minimum efficiencies for the removal of organic matter in treatment stations when it is not possible to reach the standards of release of BOD and COD, it is also established that the release of treated effluents cannot change the quality of the water, which has been constantly observed, especially in the Paraibuna River in the studied stretch during the dry season.

Finally, it is worth noting the contribution of this work in the evaluation of the capacity to support the polluting load of the receiving body, in this case the Paraibuna River, established in the State of Minas Gerais, by the Joint Normative Deliberation COPAM/CERH No. 1 (Minas Gerais, 2008). This study with the respective benefits of controlling the polluting load released into the watercourse will allow the improvement of water quality, especially in the dry season.

Conclusions

It was possible to verify in this study that the water quality of the Paraibuna River is below satisfactory levels for quality class 2, according to CONAMA Resolution No. 357/2005, since all domestic and industrial wastewater produced in the central region of Juiz de Fora is released *in natura* causing degradation of water quality. The water quality of the Paraibuna River is altered due to seasonality, as there were differences in the concentrations of qualitative variables in the periods evaluated.

When calibrating the QUAL2K mathematical model for the Paraibuna River stretch, the conclusion was that the values that best fit the deoxygenation coefficient (K_1) ranged from 0.01 to 2.95 d^{-1}, its highest values being found in regions with the highest organic matter input, as is the case of Matirumbide Stream, and the lowest values downstream of Ipiranga Stream. The reaeration coefficient (K_2) varied from 0.70 to 3.15 d^{-1}, being adjusted according to the hydraulic characteristics of each stretch.

Regarding the simulated scenarios, the conclusion is that the best result obtained for the wastewater treatment from the Paraibuna River will be achieved when the conditions of scenario 3 are applied. This scenario includes União Indústria and Santa Luzia WWTPs and the renovation of Barbosa Laje WWTP. The suggested treatment systems were the UASB, followed by activated sludge, with an expected reduction of 90% of the polluting load in the streams contemplated in the present work, and a 50% reduction of the organic load upstream of the studied stretch.

Contribution of authors:

DUTRA, W. C. P.: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Writing — original draft; FIA, R.: Conceptualization; Methodology; Formal analysis, Supervision; Project Administration; Writing – revision and editing; RIBEIRO, C. B. de M.: Conceptualization; Methodology; Formal analysis, Supervision; Writing – revision and editing.

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