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Estimation of the water quality of the Rio Grande-Brazil slopes in different scenarios: modelling of the BOD and DO variables using Qual-UFMG

Estimativa da qualidade das águas das vertentes do Rio Grande – Brasil em diferentes cenários: modelagem das variáveis DBO e OD utilizando o Qual-UFMG

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Abstract: This work aimed to evaluate and apply a water quality modeling methodology in the management of water resources, evaluating, among other things, the effectiveness of the obligations foreseen in the legislation, in view of the foreseen uses in the basin. The Brazilian hydrographic basin GD2 was used as a case study, considering the sewage releases from 30 municipalities. Biochemical Oxygen Demand (BOD) and Dissolved Oxygen (DO) were modeled in four scenarios, using the Qual-UFMG model. In the first two scenarios, which portray the current and trending situation (2033), a good condition was verified for most of the basin, with the exception of the headwater stretches, where worrying values for BOD and DO were found. In C-03, the results of complying with legislation were investigated (90% of sewage collected and treated and 70% of BOD removal) for 2033. It was found that, for most headwaters regions, it will not be enough to guarantee the expected uses, requiring higher percentages of attendance and efficiency. In C-04, the minimum BOD removal efficiencies necessary to meet the intended uses were found. Very high and often unattainable efficiencies were found in watercourses with a small dilution ratio, suggesting the need for other control measures.

Keywords: Water quality; modelling; Qual-UFMG.

Resumo: Este trabalho objetivou avaliar e aplicar uma metodologia de modelagem de qualidade das águas, na gestão de recursos hídricos, avaliando dentre outras coisas, a eficácia das obrigações previstas na legislação, frente aos usos previstos na bacia. Utilizou-se como estudo de caso a bacia hidrográfica brasileira GD2, considerando os lançamentos de esgoto de 30 municípios. Foram modelados Demanda Bioquímica de Oxigênio (DBO) e Oxigênio Dissolvido (OD), em quatro cenários, utilizando o modelo Qual-UFMG. Nos dois primeiros cenários, que retratam a situação atual e tendencial (2033), verificou-se uma boa condição para a maior parte da bacia, com exceção dos trechos de cabeceira, onde valores preocupantes para DBO e OD foram encontrados. Em C-03 investigou-se os resultados do atendimento da legislação (90% de esgoto coletado e tratado e 70% de remoção de DBO) para 2033. Constatou-se que, para a maior parte das regiões de cabeceira, não será suficiente para garantir os usos previstos, exigindo maiores percentuais de atendimento e eficiência. Em C-04, foram encontradas as eficiências mínimas de remoção de DBO necessárias para atender aos usos previstos. Foram encontrados, em cursos d'água com pequena razão de diluição, eficiências muito elevadas e muitas vezes inalcançáveis, sugerindo a necessidade de outras medidas de controle.

Palavras-chave: Qualidade das águas; modelagem; Qual-UFMG.

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1. Introduction

Brazil is a country with continental dimensions, with a population of approximately 213.3 million inhabitants (IBGE, 2022). According to the Thematic Diagnosis of Water and Sewage Services (SNIS, 2023), only 60.7% of the sewage generated in Brazil is collected, and the percentage of treatment is even lower, at 49.6%; furthermore, there are uneven sanitation service between large urban centres (higher percentages) and smaller municipalities (low service). The main consequences of insufficient treatment include the depletion of dissolved oxygen (DO), increased turbidity and the release of odours, all of which affect the aquatic community and are related to the discharge of organic matter, represented by the biochemical oxygen demand (BOD) (MATOS et al., 2017; VON SPERLING, 2014a). This is a global problem (SEO et al., 2017), but it is mainly observed in developing countries, with important socioeconomic and environmental consequences (PUJOL-VILA et al., 2016).

Aiming to ensure surface water quality that is compatible with its uses, according to its class of framing, in addition to the release standard (MINAS GERAIS, 2022), the Federal Law No. 14.026 (BRASIL, 2020) was enacted, establishing the *new Legal Framework for Sanitation in Brazil*.

The release standard establishes that all liquid discharges must be properly treated, before being released into the watercourse, with a minimum BOD removal efficiency of 70% (annual average),while the BOD and DO concentrations to be maintained (or achieved) in the watercourse will depend on the Class in which the section was classified. *The new Legal Framework for Sanitation* determining, among other things, those contracts that provide basic public sanitation services must guarantee 90% of sewage collection and water treatment to benefit the population by December 31st, 2033.

Water quality models are important tools for the effective management of water resources, and these models can assist in decision-making by providing water quality simulations for a variety of management actions (KAUFMAN et al., 2021; KOO et al., 2020; WHITE et al., 2021). In addition, these models reduce the need for water collection and analysis, reducing costs and time spent (BUI et al., 2019; VON SPERLING, 2014b).

The modeling can be used to evaluate the effectiveness of the measures proposed and adopted (KAUFMAN et al., 2021; KOO et al., 2020; WHITE et al., 2021), in this case the release standart and the new legal framework for sanitation, in maintaining the quality of surface water within the limits foreseen for its uses. In the specific case of Brazil, the classification of watercourses into classes is used, according to their predominant, current and future uses.

In Brazil, with regard specifically to freshwater, there are 5 classes, and they are fundamentally established according to the predominant uses of water resources (BRASIL, 2005; MINAS GERAIS, 2022). First, there is the Special Class, which cannot receive sewage discharges and serves to preserve the natural balance of aquatic communities; then, there are Classes 1 to 4, where the first has more restrictive parameters of quality and destination for more for a more righteous uses, and the subsequent numbers have an increase in the permittivity of the values of the variables.

In the discharge of wastewater into a receiving body, the minimum efficiencies and maximum concentrations defined in the legislation must be observed, and the class of the watercourse in which the stretch was classified cannot be altered according to the intended uses (Classes 1 to 4). However, due to the inefficiency of sanitation services in many locations, the river is often already in conditions lower than it should be, making it difficult to meet the legal requirements for the release of the treated effluent (TEODORO et al., 2013). This is the case for many river basins, such as the Rio Grande basin, and its planning units, such as GD2 (Grande River Slopes), with a high degree of contamination (in certain stretches), as observed in studies such as Amâncio (2018) and Menezes et al. (2015).

The objective of carrying out this work was to adapt, apply and evaluate a methodology for mathematical modeling of surface water quality, aiming, among other things, to verify the effectiveness of the obligations provided for in environmental legislation. As a case study, a Brazilian river basin (GD2) was adopted, considering the current conditions, trends and compliance with legislation.

In this way, the objective, in addition to identifying the current and trending conditions of the basin, is to verify whether the obligations present in the effluent discharge standard and in the new legal framework for sanitation will be sufficient to guarantee compliance with the water classification and, consequently, to the preponderant uses existing in the basin. To this end, the work made it possible to define the minimum BOD removal efficiency required for each municipality, in addition to minimum DO concentrations in the treated effluent in some cases.

2. Method

Brazil has 8 large hydrographic basins, and the São Francisco River basin and Paraná River basin cover much of the most populous region of the country. One of the main subbasins of the Paraná River is the Grande River basin, which is subdivided into 24 Water Resources Planning and Management Units-UPGRH (IGAM, 2013). For the present study, one of these planning units was chosen, called GD2 (Grande River Slopes), which comprises the areas drained by the Mortes River, Jacaré River and Cervo River.

GD2 is located in the South Region of Minas Gerais, with its highest point at 1,200 m and lowest at 780 m above sea level. As the climate is tropical high, with a rainy season and a dry season, there are periods of drought with little or no rainfall. The drainage area of the basin is 10,533 km², and it is divided into 10 subbasins (Figure 01). In its interior, there are 42 municipalities, of which 30 discharge their sanitary effluents into the basin (IGAM, 2013).

Table 01 shows the summary of sewage systems in the basin, in which only 13 municipalities have some form of sewage treatment. Of the total urban population of the basin (541,576 inhabitants), 95% is served with sewage collection; however, only 21.7% of the sewage collected is treated before being released into the receiving bodies, a situation that is worrisome.

In the evaluation, the watercourses that receive discharge from urban areas or have water quality monitoring points were modeled, as shown in Figure 01, and the allocation of municipal headquarters with their respective points of liquid discharge are also shown. The modeled watercourses are represented in the figure as wide colored lines: green (class 1), yellow (class 2) and red (class 3), according to the adopted framework. These are the desired/necessary classes to meet the predicted uses for the basin's surface waters. They were defined by the GD2 Basin Committee (CBH-GD2, 2018).

The pollutant loads considered are those related to the discharge of sanitary sewage from the urban areas of the 30 municipalities located in the interior of the basin. The flows considered are shown in Table 01. As there is no systematic qualitative monitoring of sanitary sewage in the municipalities, the typical values reported in the literature were considered for deterministic modelling, as shown in Table 02.

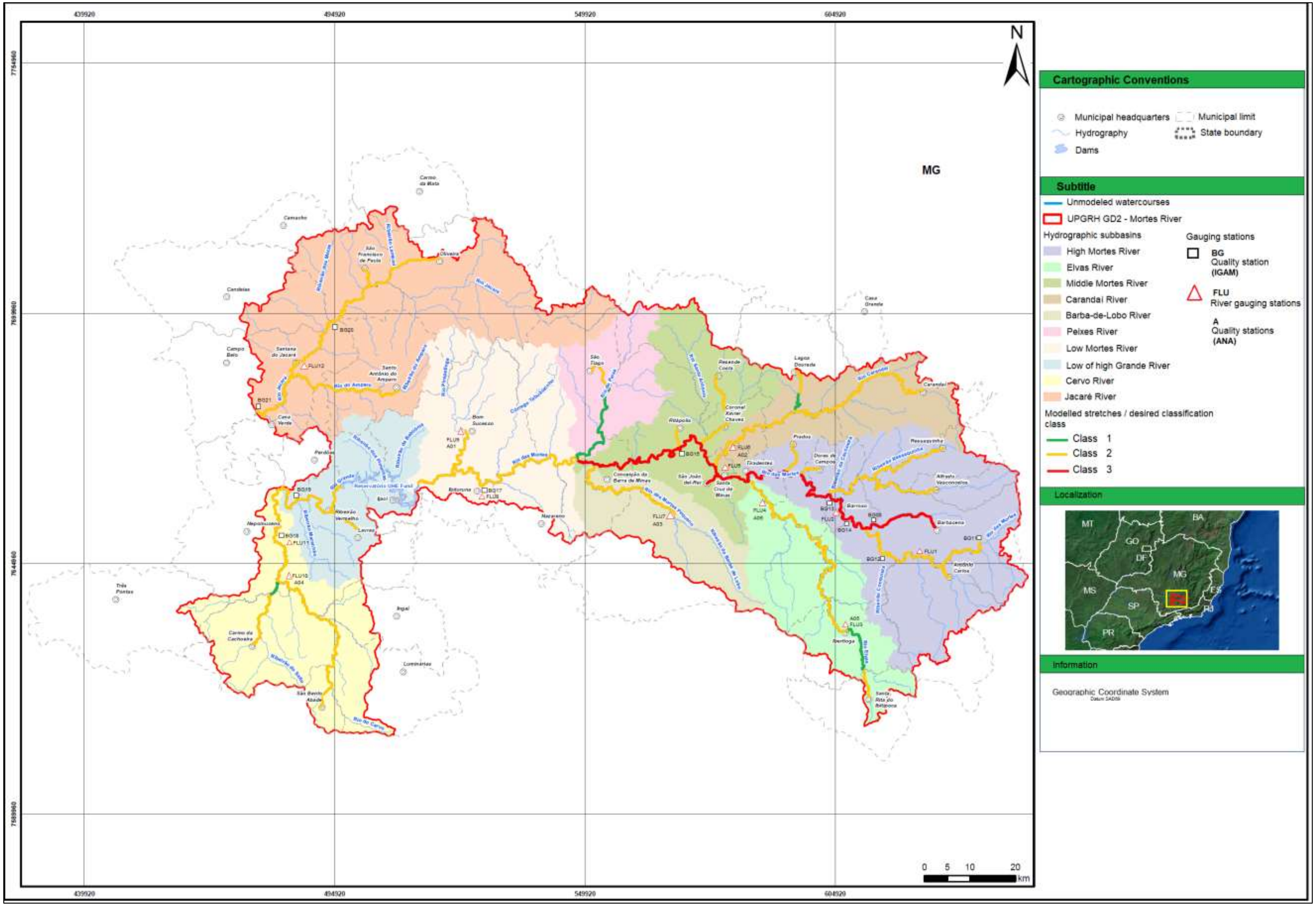


Figure 01 – Hydrographic basin, modelled sections, framework, municipal headquarters, flow and quality river stations
Source: Adapted from IGAM (2013)

Table 01 – Current status of sewage systems in the basin

Municipality / Subbasin	Urban population 2020	Sewage collection service (%)	Q med - sewage (L s^{-1})		Treatment coverage (%) *
			Generated	Collected	
Upper Mortes River Basin					
Alfredo Vasconcelos	4,632	100.0	6.29	6.29	0.0
Antônio Carlos	8,069	95.0	9.68	9.20	0.0
Barbacena	126,477	91.1	122.37	111.48	31.3
Barroso	20,236	91.8	39.77	36.51	6.4
Dores de Campos	9,297	100.0	17.36	17.36	0.0
Ressaquinha	3,091	99.6	3.18	3.17	0.0
Tiradentes	6,234	62.8	12.85	8.07	0.0
Prados	6,423	97.4	6.01	5.86	100.0
Barba-de-lobo River Basin					
Conceição da B. de Minas	2,787	61	2.96	1.80	71.8
Middle Mortes River Basin					
Coronel Xavier Chaves	1,876	100.0	3.52	3.52	0.0
Resende Costa	9,280	39.4	11.80	4.65	100.0
Ritápolis	3,156	20.0	3.64	0.73	0.0
Santa Cruz de Minas	8,664	100.0	28.67	28.67	0.0
São João Del-Rei	85,556	99.5	427.98	425.84	3.2
Elvas River Basin					
Ibertioga	3,439	100.0	6.25	6.25	100
Santa Rita do Ibitipoca	2,120	90.0	2.48	2.23	0
Low of High Grande River Basin					
Ijaci	6,323	100.0	11.10	11.10	85.7
Lavras	99,846	90.6	132.32	119.88	100.0
Ribeirão Vermelho	3,748	100.0	3.59	3.59	0.0
Jacaré River Basin					
Oliveira	37,301	100.0	50.77	50.77	10.0
Santana do Jacaré	4,623	100.0	12.72	12.72	0.0
Santo Antônio do Amparo	16,297	100.0	18.18	18.18	33.0
São Francisco de Paula	4,678	100.0	26.96	26.96	0.0
Peixe River Basin					
São Tiago	8,791	63	11.00	6.96	62.5
Low Mortes River Basin					
Bom Sucesso	14,494	99.8	21.14	21.09	100.0
Ibituruna	2,598	100.0	3.01	3.01	0.0
Carandaí River Basin					
Carandaí	20,016	100.0	41.21	41.21	0.0
Lagoa Dourada	7,343	90.0	27.75	24.97	0.0
Cervo River Basin					
Carmo da Cachoeira	9,228	84.5	11.23	9.49	0.0
São Bento do Abade	4,953	100.0	6.98	6.98	0.0

Source: SNIS (2021)

** Regarding the volume of sewage collected Q med = average sewage flow*

Table 02 – Average qualitative characterization of raw sewage

Variable	Value considered (mg L^{-1})
Biochemical Oxygen Demand - BOD	350
Organic Nitrogen	20
Ammoniacal nitrogen	30
Dissolved Oxygen – DO	0

Source: Matos et al., (2017); Von Sperling (2014a)

The QUAL-UFMG model was chosen, and this model is widely used in Brazil because of its versatility and ease of use, allowing greater applicability and good reliability (SRIKRISHNAN; KELLER, 2021). The model consists of an Excel platform developed by von Sperling (VON SPERLING, 2014b) and was developed from simplifications of the QUAL2E model (BROWN; BARNWELL, 1987) and the adaptation of their equations to spreadsheets (DE OLIVEIRA FILHO; LIMA NETO, 2018; LIMA; MAMEDE; LIMA NETO, 2018). For technical simplification, the algae component of the modelling and the longitudinal dispersion were excluded from the model since advection is the main transport phenomenon in rivers. The calculations were made considering the numerical integration by the Euler method (TEODORO et al., 2013).

In Qual-UFMG, the dynamics of some variables can be evaluated; however, this study was restricted to only two, the biochemical oxygen demand (BOD) and the dissolved oxygen (DO). BOD is one of the most commonly used variables for assessing water quality and the impacts caused by the release of discharges, mainly due to its direct relationship with the decrease in DO. Conversely, DO is of fundamental importance for the maintenance of balance in the aquatic environment and is indispensable for the maintenance of all aerobic life forms (MATOS et al., 2017).

In the legislation of the state of Minas Gerais (MINAS GERAIS, 2022), the average annual BOD removal efficiency should be at least 70%, while the BOD and DO concentrations to be maintained (or achieved) in the watercourse will depend on the class in which the stretch was classified.

The decomposition process of organic matter in water follows a first-order kinetic reaction, where the organic matter reduction rate (BOD) is proportional to the concentration of the substrate present in the medium (VON SPERLING, 2014a). According to Streeter and Phelps (1925), the process can be represented by two equations related to the dynamics of the BOD and DO concentrations, which, in turn, involve the physical, chemical and biological processes in the water body, such as deoxygenation and reoxygenation. In Qual-UFMG, also considers the consumption of DO due to the conversion of ammonia to nitrite and from nitrite to nitrate in the nitrification process, which consists of the nitrogen demand.

The flow rate considered for the dilution of waste in receiving bodies was the minimum, mean of 7 consecutive days, with a recurrence time of 10 years ($Q_{7,10}$), according to the legislation of the State of Minas Gerais (MINAS GERAIS, 20022).

To obtain $Q_{7,10}$, at each point of the watercourses of the basin, Equation 1 was used, which relates the referred flow to the upstream drainage area. This equation was obtained by the Hydrotec tool (UFV, 2009), made available by the Federal University of Viçosa (UFV), which performed the hydrological studies for the 12 existing river stations within the basin (Figure 01).

$$Q_{7,10} = 0{,}00686 * A^{0{,}9495} \qquad (1)$$

Where:

$Q_{7,10}$ = Minimum flow rate, mean of 7 consecutive days, with a recurrence time of 10 years ($m^3\ s^{-1}$);

A = Upstream drainage area (km^2);

It should be noted that, for future studies, it would be interesting to use more recent historical flow series and obtain new equations for $Q_{7,10}$, which would increase the safety and reliability of the results.

For the definition of the velocities and depths to be adopted in the study, variables that would condition the values of the coefficients of reaeration (K_2), regression analysis was performed for the historical series of the 12 existing river gauging station within the river basin. Data from the last 10 years of monitoring were considered for the drought period (April to September).

Regarding the water quality data, we used data from 11 surface water quality monitoring stations (Figure 01) operated by the Minas Gerais Water Management Institute (IGAM, 2022) and 6 stations operated by the National Water Agency (ANA) (ANA, 2022). The mean values of the last five years in the dry season (April to October) are shown in Table 03.

Table 03 – Average values for model-related variables at monitoring stations

Station	Variables (mg L^{-1})						
	BOD	DO	N org	N amm	Nitrite	Nitrate	Temperature (ºC)
BG – 08	10,2	6,0	0,87	9,04	0,077	1,87	17,1
BG – 11	2,0	8,1	0,23	0,19	0,008	0,74	16,4
BG – 12	2,0	8,3	0,30	0,25	0,022	1,22	17,1
BG – 13	2,7	7,6	0,45	0,68	0,077	1,81	18,3
BG – 14	2,4	8,4	0,46	0,69	0,086	1,59	17,8
BG – 15	2,1	7,6	0,32	0,38	0,036	0,70	18,9
BG – 17	2,2	8,2	0,24	0,18	0,006	1,10	17,7
BG – 18	2,0	8,8	0,11	0,12	0,002	0,48	17,4
BG – 19	2,0	7,4	0,28	0,20	0,003	0,51	20,7
BG – 20	2,0	7,4	0,31	0,32	0,011	1,02	20,5
BG – 21	2,0	7,9	0,25	0,15	0,002	0,77	20,0
A – 01	-	9,5	-	-	-	-	21,2
A – 02	-	9,9	-	-	-	-	18,9
A – 03	-	9,9	-	-	-	-	18,4
A – 04	-	8,3	-	-	-	-	17,9
A – 05	-	8,5	-	-	-	-	16,3
A – 06	-	9,3	-	-	-	-	18,1

Source: Authors (2024)

BG = IGAM stations
A = ANA stations
N org = Organic Nitrogen
N amm = Ammoniacal nitrogen

The data presented in Table 03 were used in the calibration of the model for $Q_{7,10}$.

Of the monitoring stations, only BG - 11 is upstream of the urban sites, and therefore, it has little or no release of discharge. For this reason, their average monitoring results were used as headwater data, which were assumed to be the initial values for the modelled variables in the initial stretches of the watercourses. The only exception was for the variable DO, where 90% of the saturation concentration (Sc) was considered (VON SPERLING, 2014b).

To calibrate the model, the coefficient of determination (CD) was used, which consists of the relationship between the sum of the square residuals by the total variance of the observed data, according to Equation 2

$$CD = 1 - \frac{\sum (Y_{obs} - Y_{est})^2}{\sum (Y_{obs} - Y_{obsméd})^2} \qquad (2)$$

Where:
Y_{obs} = average value observed at the monitoring station
Y_{est} = value estimated by the model
$Y_{obsméd}$ = average of observed values

Calibration was performed using the Excel Solver tool, seeking to maximize the CD, varying the model coefficients within the ranges reported in the literature. For the BOD variable, a CD = 0.98 (with a relative error of 0.0691) was obtained. For DO, the CD was 0.77 (with a relative error of 0.0087). In both cases, the performance of the model was considered adequate.

After its calibration, the model was used to perform deterministic and probabilistic simulations for the four scenarios proposed below, always considering the Q 7.10 of the receiving body. In the first scenario (C-01), the current populations, current flows and levels of sewage collection and treatment were considered, as shown in Table 01 (SNIS, 2021). In the future scenario (C-02), the urban populations of the municipalities were projected for 2033, and the current rates of sewage collection and treatment were maintained (Table 01). In the population projection calculations, data from the last two Brazilian demographic censuses, 2000 and 2020, were considered (IBGE, 2022), and a geometric progression was applied to obtain the population in 2033.

The third scenario (C-03) consisted of considering the urban populations projected for the year 2033 and a minimum value of 90% for sewage collection and treatment, as determined by the Sanitation Legal Framework (BRASIL, 2020). A BOD removal efficiency of 70% was considered to meet the release standard (MINAS GERAIS, 2022). For nitrogen, as there are no limits for sanitary sewage, a removal of 30% was considered, compatible with the level of secondary treatment. The DO in the treated effluent was considered to be zero (VON SPERLING, 2014b).

Finally, the fourth scenario (C-04) referred to the deterministic model to find the necessary efficiencies for the removal of organic matter so that the proposed framework for the basin (CBH-GD2, 2018), illustrated in Figure 02, could be achieved considering the population in 2033. The maximum values for BOD and the minimum values for DO for the watercourse to be in each class are shown in Table 04.

Table 04 – Limits for DO and BOD in each framing class

Parameter	Framing class			
	1	2	3	4
DO (mg/L)	≥ 6.0	≥ 5.0	≥ 4.0	≥ 2.0
BOD (mg/L)	≤ 3.0	≤ 5.0	≤ 10.0	-

Source: Brasil (2005); Minas Gerais (2022)

3. Results and discussion

The deterministic results of the model are presented below, which proved to be suitable for the framework analysis. A probabilistic approach, with uncertainty and sensitivity analysis can be consulted in Gomides et al. (2023).

3.1 BOD

Figure 03 shows the expected conditions for the basin, for each of the four scenarios studied, for the BOD variable, and according to the 4 framing classes.

In C-01, we see that most of the main bed of the Mortes River, even with the current precarious conditions of sanitary sewage, presented excellent water quality, with 91.3% of its extension within the limits of Class 1. This fact was verified in part of the basin by Amâncio et al. (2018). This result is justified by its large drainage area and, consequently, large dilution flow rate. The same occurred with the Barba-de-lobo River, Elvas River, Pirapetinga River and most of the main bed of the Cervo and Jacaré Rivers.

In C-02, with the increase in population and the maintenance of the current levels of sewage collection and treatment, we observed a reduction of Class 1 area and an increase of Classes 2 and 3 areas; however, the values were still within the proposed framework for the basin (Figure 01) since most of the main bed of the Mortes River is classified as Class 3. When analysing Scenarios 3 and 4, we found that the entire extension of the main bed would be within the limits of Class 1. Figure 02 presents the longitudinal profiles for the four scenarios studied.

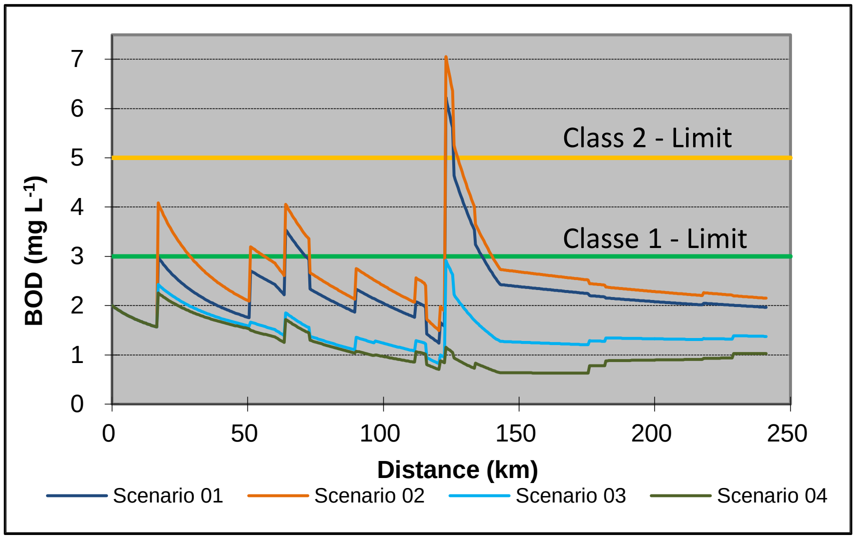


Figure 02 – Longitudinal profiles (BOD) Mortes River
Source: Authors (2024)

For the other modelled stretches, which did not have such a high dilution flow rate, due to their headwater positioning and small drainage area, the situation was less desirable, presenting stretches within Classes 4 and 3 (Scenarios 01, 02 and 03). Even with the framework (CBH-GD2, 2018), most stretches were determined as Class 2 (Figure 01). Table 05 shows the stretches with a situation at odds with the proposed framework, according to the scenarios studied.

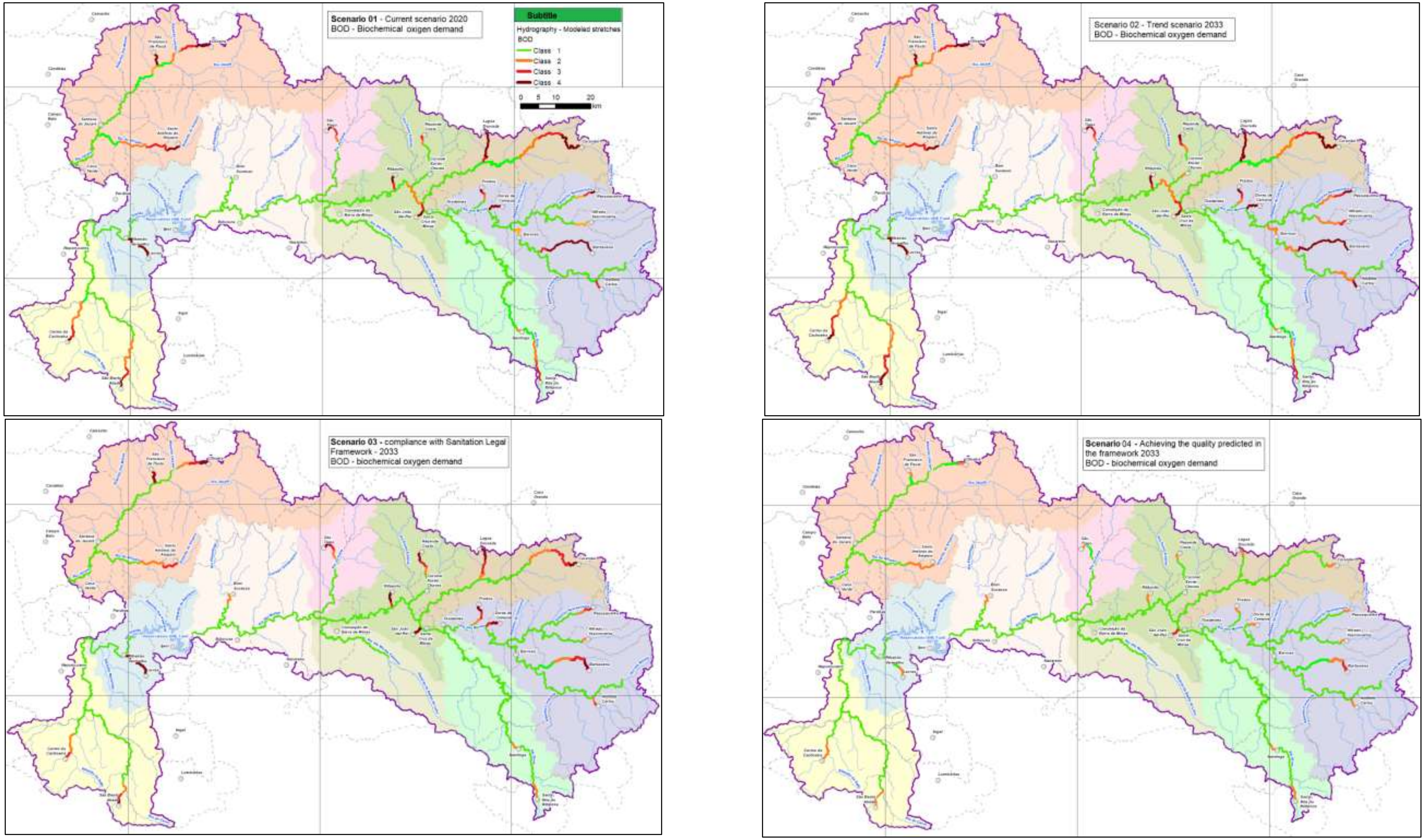


Figure 03 – Expected Basin Conditions (BOD)
Source: adapted from IGAM (2013)

Table 05 – The stretches with a situation at odds with the proposed framework

Municipality	Watercourse	Sub basin	framework	Quality condition by Scenario			
				C-01	C-02	C-03	C-04
Antônio Carlos	Bandeirinha	ARM	2	3	3,4*	3,2	2
Barbacena	Caieiros	ARM	3	4,3	4,3	4,3,2,1	3,2,1
Ressaquinha	Ressaquinha	ARM	2	4,3,2,1	4,3,2,1	3,2,1	2,1
Dores de Campos	Patusca	ARM	2	4	4	4,3	2,1
Prados	Pinhão	ARM	2	4,3,2,1	4,3,2,1	4,3,2,1	2,1
Carandaí	Carandaí	CAR	2	4,3,2,1	4,3,2,1	4,3,2,1	2,1
Lagoa Dourada	Tanque Grande	CAR	2	4,3	4	4,3,2	2,1
São João Del Rei	Água Limpa	MRM	3	4	4	4	3
Resende Costa	Quilombo	MRM	2	3,2,1	4,3,2,1	4,3,2,1	2,1
Ritápolis	Paiol	MRM	2	4,3	4,3	4,3	2,1
Lavras	Ribeirão Vermelho	ABRG	2	4	4	4	2,1
São Bento Abade	Algodão / Cervo	CER	2	4,3,2,1	4,3,2,1	4,3,2,1	2,1
Carmo Cachoeira	Carmo / Salto	CER	2	4,3,2,1	4,3,2,1	3,2,1	2,1
Oliveira	Maracanã/Lambari	JAR	2	4,3,2	4,3,2	4,3,2,1	2,1
S. F. de Paula	Machadinha	JAR	2	4	4	4	2,1
S. A. do Amparo	Amparo	JAR	2	4,3,2,1	4,3,2,1	3,2,1	2,1

Source: Authors (2024)

** The same watercourse can be in different classes along its length*

ARM = High Mortes River CAR = Carandaí River MRM = Middle Mortes River

BARG = Low of the High Grande River CER = Cervo River JAR = Jacaré River

It is verified that, even for C-03, which considers the Sanitation Legal Framework, the framework proposed by the legislation (CBH-GD2, 2018) is not fully met, indicating that the proposed measures are not sufficient.

In terms of meeting the proposed framework, the minimum BOD removal efficiency of 70%, provided for in the legislation, was not always sufficient. According to the results of the modelling, for C-04 (compliance with the framework), the efficiencies shown in Table 06 would be necessary.

Table 06 – Minimum BOD Removal Efficiency to meet the framework

Municipality	Minimum BOD Removal Efficiency (%)	Municipality	Minimum BOD Removal Efficiency (%)
Alfredo Vasconcelos	70	Oliveira	94
Antônio Carlos	75	Prados	94
Barbacena	97 *	Resende Costa	96
Barroso	70	Ressaquinha	81
Bom Sucesso	70	Ribeirão Vermelho	70
Carandaí	90	Ritápolis	96
Carmo da Cachoeira	77	Santa Cruz de Minas	70
Conceição da Barra de Minas	70	Santa Rita do Ibitipoca	70
Coronel Xavier Chaves	70	Santana do Jacaré	75
Dores de Campos	96	Santo Antônio do Amparo	84
Ibertioga	70	São Bento do Abade	89
Ibituruna	70	São Francisco de Paula	98 **
Ijaci	70	São João Del-Rei	94 **
Lagoa Dourada	98	São Tiago	97
Lavras	98	Tiradentes	70

Source: Authors (2024)

* *Treated sewage must have OD ≥ 1 mg* L^{-1}
** *Treated sewage must have OD ≥ 3 mg* L^{-1}

It was verified that in municipalities where the drainage area of the discharge point of the treated effluents is large, and consequently the dilution flow rate of the receiving body is also large, the efficiency required for the treatment is small (LIANG; YANG, 2019; SEO et al., 2017; TEODORO et al., 2013). Municipalities such as Barroso and Santa Cruz de Minas, which are on the banks of the Mortes River, may have a minimal treatment efficiency (70 %), but it still meets the framework. Conversely, municipalities such as Oliveira and Prados, which are close to the headwaters, require high treatment efficiencies.

As previously mentioned, the four largest municipalities of the basin together generate 67.7% of the sewage. Due to the location of these municipalities and the fact that the receiving bodies have reduced drainage areas, they will have difficulties in meeting the framework requirements. The municipality of Barbacena releases 111 L s^{-1} of sewage into the Caieiros stream, which is immediately downstream from the urban area of the city and has a minimum reference flow ($Q_{7.10}$) of only 6.2 L s^{-1}, producing a dilution ratio of 0.056. Thus, even when treating 100% of the collected sewage, the minimum BOD removal efficiency should be 97%.

A similar situation occurs in the municipalities of São João del Rei, Lavras e Oliveira. The emergence and growth of cities in Brazil is a spontaneous process, in most cases without planning, so the location within the watershed and consequently the dilution ratio for the liquid discharges are not considered, causing problems such as those reported above (MOTA, 2003). Other municipalities, which are also located at the headwaters and have a receiving body with a reduced drainage area, could reduce the BOD removal efficiencies required for WWTPs with the construction of treated sewage outfalls, e.g., Dores de Campos, Prados, Resende Costa, Ritápolis, São Francisco de Paula, São Tiago and Lagoa Dourada.

3.2 DO

Figure 05 shows the expected conditions for the basin under each of the four scenarios studied for the variable OD. We can verify that, even for Scenarios 01 and 02, without interventions in the basin, there is an absolute predominance of Class 1 in the modelled stretches, evidencing, in general, the good water quality. According to Teodoro et al. (2013) and von Sperling (2014b), high flow rates favour the greater dilution of discharge and greater conditions for reoxygenation, resulting in higher DO values.

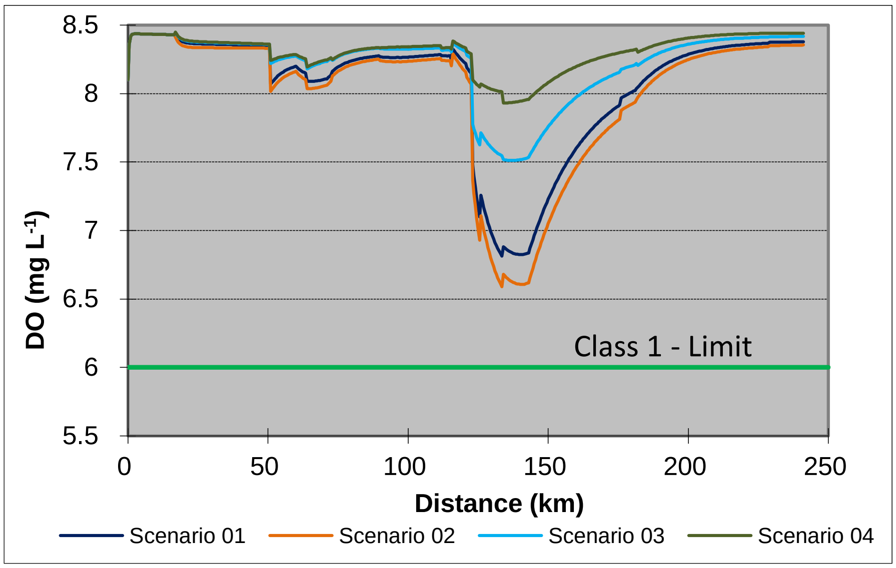
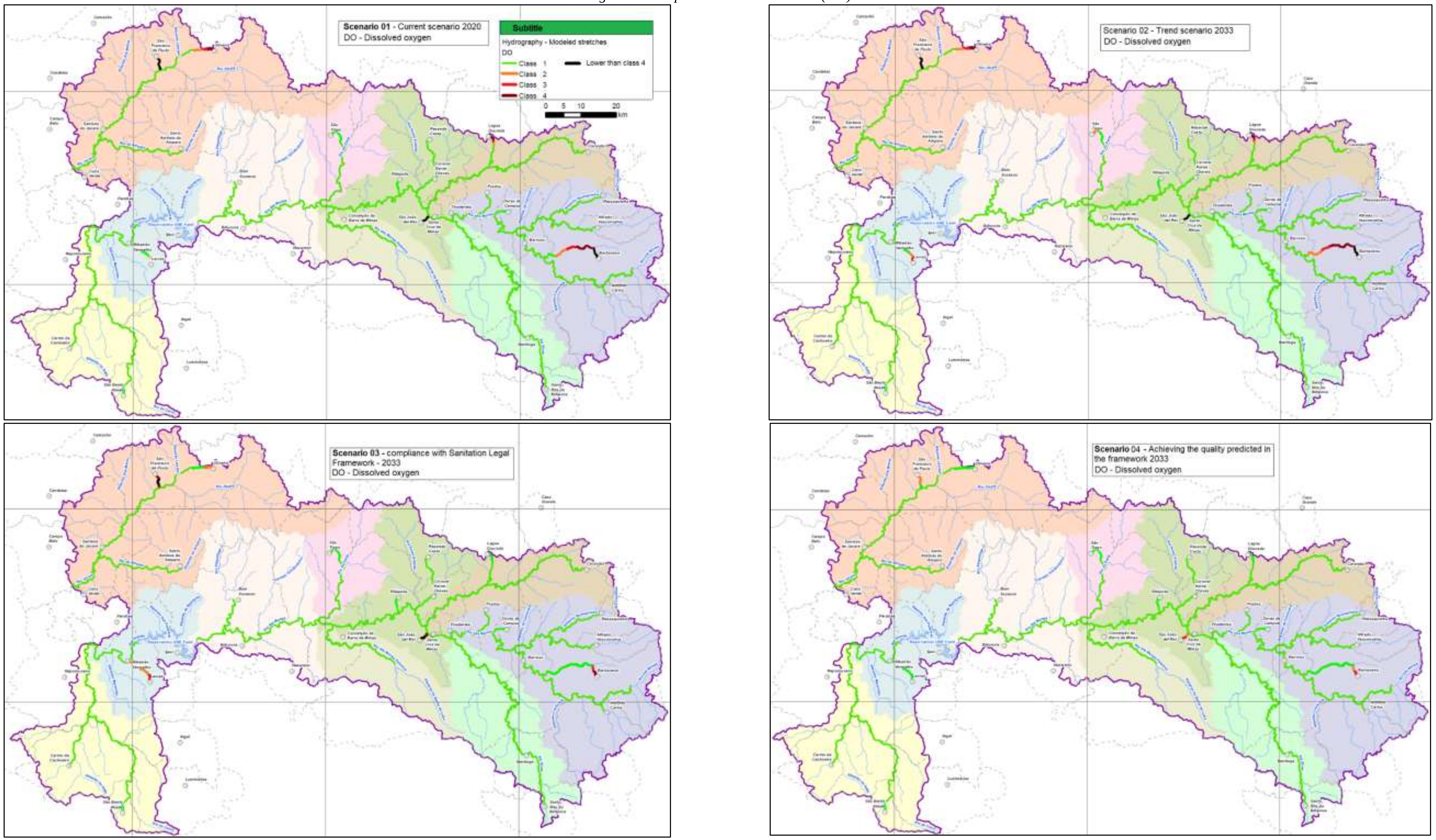


Figure 04 – Longitudinal profiles (DO) Mortes River
Source: Authors (2024)

Figure 05 – Expected Basin Conditions (DO)



Source: Adapted from IGAM (2013)

In the longitudinal profiles for the Mortes River (Figure 04), we can see that the DO is always above 6.5 mg L^{-1}, even downstream of the municipality of São João Del Rei, where the critical DO level occurs. The exceptions to the excellent values for DO occur in 6 specific stretches located in the headwaters and in areas with significant sewage discharge, as described in Table 07.

Table 07 – Stretch with adverse conditions of the proposed framework

Municipality	Watercourse	Sub basin	framework	Quality condition by Scenario			
				C-01	C-02	C-03	C-04
Barbacena	Caieiros	ARM	3	(a)	(a)	4,3,1	3,2,1
Lagoa Dourada	Tanque Grande	CAR	2	(b)	(b)	1	1
São João Del Rei	Água Limpa	MRM	3	(c)	(c)	(d)	4,3
Lavras	Ribeirão Vermelho	ABRG	2	2,1	3,2,1	3,2	1
Oliveira	Maracanã/Lambari	JAR	2	4,3,2,1	4,3,2,1	2,1	1
S. F. de Paula	Machadinha	JAR	2	(e)	(e)	(d)	2,1

Source: Authors (2024)

ARM = High Mortes River CAR = Carandaí River MRM = Middle Mortes River
BARG = Low of the High Grande River JAR = Jacaré River
(a) Presents the 4 classes, a stretch below class 4 and anaerobiosis
(b) Presents the 4 classes and a stretch below class 4
(c) Part of the stretch below class 4 and anaerobiosis
(d) Part of the stretch in class 4 and part below it
(e) Anaerobiosis

The watercourses listed in Table 07, which do not conform to the framework for the DO variable, consist of problematic stretches of the basin for the environmental licensing of projects that generate liquid effluents, and the release of new discharges is not authorized until compliance with the framework is established.

The Caieiros stream, for the first two scenarios, has sections below Class 4 and even anaerobic stretches. The interventions proposed in C-3 were not sufficient, and there was still a stretch in Class 4 (Figure 05). To reach Class 3, maintaining the release point just downstream of the urban area of the municipality, in addition to a BOD removal efficiency of 97%, the DO of the treated sewage should be above 1.0 mg L-1 (Table 06).

A similar situation occurs in the Água Limpa stream (São João Del Rei) and Machadinha stream (São Francisco de Paula), where BOD removal efficiencies greater than 93% and sewage treated with DO ≥ 3.0 mg L-1 are necessary for meeting the framework. In the Vermelho stream (Lavras), from 2033 onwards, efficiencies greater than 97% would be necessary. Of the six stretches, the requirements set out in the Sanitation Legal Framework (BRASIL, 2020) would be sufficient to keep DO within the limits of the framework only for Tanque Grande Stream (Lagoa Dourada) and Maracanã/Buriti Stream (Oliveira).

In general, it was found that the obligations provided in the Sanitation Legal Framework will not be sufficient to maintain the watercourses within the proposed framework criteria. The implementation of WWTPs with high BOD removal efficiency and/or the implementation of treated sewage outfalls, especially for headwater municipalities, will be necessary.

3.3 Discussion

Considering the modeled variables (BOD and DO), for the current condition (C-01) and trend condition (C-03), the results showed excellent values for the downstream stretches of the watercourses, and values that are often worrying for the upstream stretches, where the flow of watercourses is reduced. Amâncio et al. (2018) had also found this for part of the Mortes river basin, as well as Menezes et al. (2015) for Vermelho river.

The dilution ratio is an important factor to be considered when allocating resources and defining the treatment modalities to be implemented in the basin. The headwater municipalities, for the most part, will need WWTPs with high efficiency, often prohibitive or the implementation of long outfalls. A similar conclusion has also been reported by Liang and Yang (2019), Seo et al. (2017) and Teodoro et al. (2013). Therefore, for these municipalities, the study of treated sewage outfalls, with a view to launching them in hotter stretches, could be an interesting alternative.

The obligations foreseen in the legislation, according to C-03, will not be enough to guarantee, in the headwater sections, quality compatible with the uses foreseen in the framework. On the other hand, in downstream stretches, with considerable flow, some of the obligations may even be unnecessary. Hence the importance of studying and discussing point by point. Gomides et al. (2023) reached a similar conclusion, for the variable thermotolerant coliforms, with the modeling of the same basin.

To fully achieve the quality envisaged in the basin framework, which for the most part is class 2 (Figure 01), the universalization of sewage collection and treatment is necessary in almost all municipalities, with very high efficiency in the headwater municipalities.

The framework is made according to the predominant uses found or foreseen in the basin, reflecting the necessary and, mainly, desired water quality. However, it must be done judiciously, taking into account technical and mainly economic criteria related to the treatment of sanitary sewage, under penalty of imposing heavy burdens on municipalities (mainly smaller ones) and sanitation companies. One example is the small municipality of Lagoa Dourada (7,343 inhabitants), which would need 98% efficiency in terms of BOD removal, in addition to universal sewage collection and treatment, to comply with the framework. It should be evaluated on a case-by-case basis, bearing in mind the real and necessary uses of each section, as well as the existing releases of evictions and the economic capacities of each municipality. If necessary, the allowed uses can be reviewed or even intermediate goals created. This is of fundamental importance in Brazil and other developing countries, where investments in sanitation are very limited.

4. Final considerations

The adopted modeling methodology proved to be an interesting water resource management tool. Its relative simplicity of use, with few input parameters, in addition to being free to use, make it a good alternative for developing countries, where monitoring data and financial resources are scarce;

It is important that, in future studies, these stretches are the object of specific and more detailed studies, made with real and current field monitoring data

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