Challenges for bathing in rivers in terms of compliance with coliform standards. Case study in a large urbanized basin (das Velhas River, Brazil)

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ABSTRACT

This paper presents a case study on the prospects of bathing in a large water course (das Velhas River, Brazil), which crosses the important metropolitan region of Belo Horizonte (25 municipalities), receiving several point and diffuse discharges. The studies were carried out based on a mathematical simulation of thermotolerant coliforms over 227 km of the river, using an adaptation of the Qual2E model (model Qual-UFMG). Simulations of intervention scenarios were made for the current conditions, with three reference flows for the das Velhas River, tributaries and direct contribution: $Q_{7,10}$ (representative of low-flow conditions), Q_{50} (average conditions) and Q_{10} (rainy season). The intervention scenarios simulated were: (a) current conditions without intervention; (b) scenario with effluent disinfection in the two largest wastewater treatment plants in the basin (around 2.4 million inhabitants); (c) scenario with 95% sewage collection and treatment, with disinfection in all municipalities of the study area; (d) scenario with the calculation of values required for the coverage of sewage treatment and coliform removal efficiencies based on a mathematical optimization process. The monitoring data and results of all simulations indicated improvement in coliform concentration as the river flows downstream. However, results suggested that disinfection *per se* is not enough. Even under hypothetical conditions of excellent sanitary infrastructure for a developing country, coverage of collection and treatment of 95% of the generated sewage, and treatment with disinfection at all wastewater treatment plants, concentrations of thermotolerant coliforms in das Velhas River are likely to be above the maximum allowable of 1,000 MPN/100 mL for bathing purposes. The mathematical optimization indicated the need for very high percentages of sewage treatment coverage (near 100%, i.e. universality of collection and treatment) and implementation of disinfection in most treatment plants in the basin, and highlighted the fact that both items play equally important roles.

Key words | bathing, environmental legislation, mathematical simulation, Qual2E model, Qual-UFMG, thermotolerant coliforms

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INTRODUCTION

The use of water bodies for bathing purposes is highly valued but brings great challenges for its proper implementation. There are several criteria that must be followed in order to have a safe condition of bathing, involving risks associated with physical, chemical and microbiological aspects (MfE/MoH 2003; WHO 2003; NHMRC 2008; USEPA 2009; HEALTH CANADA 2010). Also, the latest policies of the World Health Organization (WHO 2011) set out the main microbial hazards associated with recreational waters, serving as the basis for the outline of the health-based target setting. The estimation of primary etiologic agents is therefore one of the main pillars used to define the quality of recreational waters (Prüss 1998; Craun *et al.* 2005; Pond 2005; Schijven & Husman 2006; Yau *et al.* 2009; Soller *et al.* 2010). Furthermore, the use of modern molecular biology techniques, particularly quantitative polymerase chain reaction (qPCR), enables the detection of faecal pollution indicators within 3 hours (Converse *et al.*

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2009; Wade *et al.* 2010; Mulugeta *et al.* 2012). In addition to the aspects of public health mentioned above, bathing acceptance is influenced by factors such as aesthetics, especially with respect to the transparency of the water (Smith *et al.* 1995; Davies-Colley *et al.* 2003). Other aspects that play an important role in determining the number of swimmers are climate and the day of the week (Songer 2012).

Interpretation of all these aspects requires a multivariate approach. This study assesses only one of these aspects, namely bathing from the important perspective of the thermotolerant (faecal) coliform criterion, made explicit in several regulations worldwide. In Brazil, the legislation on bathing (CONAMA Directives 274/2000 and 357/2005) specifies a maximum allowable value of 1,000 thermotolerant coliforms per 100 mL. This paper presents a case study in the das Velhas River, a very important river in Southeast Brazil, which crosses the metropolitan region of Belo Horizonte (third largest in Brazil), and receives several point and diffuse discharges. The study, based on simple mathematical modelling, brings issues that must be taken into account in other water bodies where bathing is desired.

The main objectives of this study, which can be also applicable to other water bodies, are to: (a) show the difficulties in achieving the bathing standard of 1,000 most probable number (MPN)/100 mL, stated in the legislation in Brazil and in several other countries; (b) show possible ways to comply with the legislation; (c) discuss the relative importance of having both very high percentages of sewage collection/treatment and removal of coliforms in sewage treatment. Therefore, the paper is not structured to go into detail in the mathematical simulation *per se*, but rather to discuss results that bring about issues that influence management decisions in the catchment area.

METHODS

This study looked at the possibility of having bathing conditions in the das Velhas River, in a stretch of approximately 227 km, between the confluences with the Itabirito and Jequitibá creeks, in the metropolitan region of Belo Horizonte, Brazil. The reach involves wastewater discharge from 25 small to large towns, with sewage flows varying from 0.002 to 2.479 m^3/s. From these, only 13 towns have currently some form of sewage treatment. All municipalities have separate sewerage systems (sewage and storm water in separate networks).

The study was based on mathematical modelling of the concentration of thermotolerant coliforms in the river, resulting from raw and treated sewage discharges from municipalities, diffuse contributions and tributaries, besides the decay of coliforms with travel time. The mathematical model was based on steady-state conditions and bacterial decay according to first order kinetics using the Qual2E model (USEPA 1985, 1987), implemented in a spreadsheet (platform Qual-UFMG; von Sperling 2007), which enabled the creation of different scenarios and plots of graphs with the concentration profiles along the das Velhas River. Decay was simply modelled according to Chick's law: $dN/dt = -K_b.t$, where: N = thermotolerant coliforms concentration (MPN/100 mL); K_b = coliform decay coefficient (d^{-1}); t = time (d).

The river was divided into a series of 0.1 km segments (total of 2,270 segments), in which mass balance equations (effluent from previous segment, point sources and diffuse sources) were implemented at the inlet of each segment. Coliform decay was computed according to the previous equation, integrated according to Euler's method. No longitudinal dispersion was taken into account.

Data from the monitoring stations of the Águas de Minas Project (from 1997 to 2009) were used to assess the goodness of fit of the data estimated by the model to the experimental data. The model was calibrated based on the visual fit to these data, resulting in a bacterial decay coefficient K_b of 3.5 d^{-1} (20 °C). The temperature coefficient θ of the Arrhenius equation to convert K_b to other temperatures was assumed to be 1.07 (Thomann & Mueller 1987). Due to the large number of input data used in the studies (hydraulic and hydrologic data, as well as the quantity and quality of the water and sewage from the 25 towns), for reasons of space limitation, they are not presented herein. However, rather than analyse the absolute values resulting from the simulations, this study mainly discusses the conditions for the implementation of control measures of coliforms associated with their relative degree of difficulty.

Simulations of intervention scenarios were made for current conditions (year 2012), with three reference flows for the das Velhas River, tributaries and direct contribution (incremental flow): (i) $Q_{7,10}$ (duration of the minimum equal to 7 d and return period of 10 years, widely used to represent low-flow conditions); (ii) Q_{50} (permanence flow equal to the 50 percentile, thus representing long-term average flow conditions); (iii) Q_{10} (permanence flow equal to the 10 percentile, that is, 90% of the flow values are lower than it, thus representing rainy season). It is difficult to present here all river flow values. However, in order to give an idea of the order of magnitude, Table 1 presents the flow values at the upstream and downstream ends of the

Table 1 | Flow values at the upstream and downstream ends of the studied reach of the das Velhas River (227 km)

Flow conditions	Flow parameter	Flow value at the upstream end (m^3/s)	Flow value at the downstream end (m^3/s)
Dry period	$Q_{7,10}$	5.217	24.086
Average conditions	Q_{50}	9.149	73.753
Rainy period	Q_{90}	16.097	129.805

227 km of the studied reach for the three hydrologic conditions.

Concentrations of thermotolerant coliforms in the wastewater were taken as average monitored values at each existing treatment plant. When data were not available, raw sewage concentrations were assumed to be 5×10^7 MPN/100 mL, effluents from secondary treatment to be 1×10^6 MPN/100 mL and effluents from a disinfection step to be 1×10^2 MPN/100 mL (values based on von Sperling & Chernicharo (2005)). For the coliform concentrations at the tributaries upstream of the discharge points, monitored data were used. When they were not available, values of 10 or 100 MPN/100 mL were used, depending on the urbanization level at the sub-catchment area. Incremental flow (diffuse pollution) values discharged at the das Velhas River were assumed to be 10 MPN/100 mL, representing relatively clean conditions.

Several intervention scenarios have been studied, but this paper presents only the most important ones and those which enable generalization of the discussion to other water courses:

- current conditions without intervention;
- scenario with disinfection of the wastewater treatment plants (WWTP) of Arrudas and Onça (two largest plants in the basin and in the state);
- scenario with a coverage of 95% sewage collection and treatment and the implementation of effluent disinfection in all the municipalities of the study area;
- scenario with the calculation of values required for the percentage of sewage treatment and coliform removal efficiencies based on a mathematical optimization process.

The mathematical optimization (fourth scenario) used the Excel Solver tool, with a non-linear optimization algorithm (generalized reduced gradient). This scenario sought the most cost-effective possible solution. This condition is to have, in the das Velhas River, the largest possible coliforms concentrations, but still complying with the legislation. The Solver algorithm sought to maximize the sum of logarithms (base 10) of coliform concentrations calculated in each of the 2,270 river segments. The $\log_{10}$ of coliform concentrations values in all these segments were added, and each iteration of the convergence process tried to increase the value of the sum, but subject to the constraint of a maximum individual value of 1,000 MPN/100 mL in each segment. At each step of the iteration process, the Solver varied the percentages of treatment and coliform removal efficiencies, for each municipality. However, to prevent the Solver from providing a solution focused on only a few localities (with higher flow rate) or to ensure that the smaller localities had to treat their sewage, minimum and maximum percentage limits were also established for sewage treatment and coliform removal in the treatment (constraints not shown here, due to space limitations).

RESULTS AND DISCUSSION

Model calibration

Figure 1 presents the results of the model calibration, showing the longitudinal profile of thermotolerant coliforms in the studied reach of the das Velhas River. The observed data (monitoring by the Águas de Minas Project, from 1997 to 2009, using 10, 50 and 90% percentiles) and the data simulated are presented. The following points should be highlighted:

- The good fit of the model to the experimental data, increasing the reliability of the model in undertaking prospective intervention scenarios.
- The current, almost systematic, non-compliance with the bathing standard (1,000 MPN/100 mL).
- The decay tendency in the concentrations of coliforms downstream of the major polluting loads in the metropolitan region of Belo Horizonte (especially Arrudas and Onça catchment areas, but stretching to Ribeirão da Mata).
- The step increases at each discharge point, which are due to the instantaneous mixing of the discharge and the river assumed by the model.
- The apparent overestimation of the calculated values, in the stretch between the Arrudas stream and Lagoa Santa. The reason for this is that the data monitored on this reach were almost always reported as '>160,000 MPN/100 mL'. In the statistics, the values were entered as 160,000 ($=1.60 \times 10^5$) MPN/100 mL.

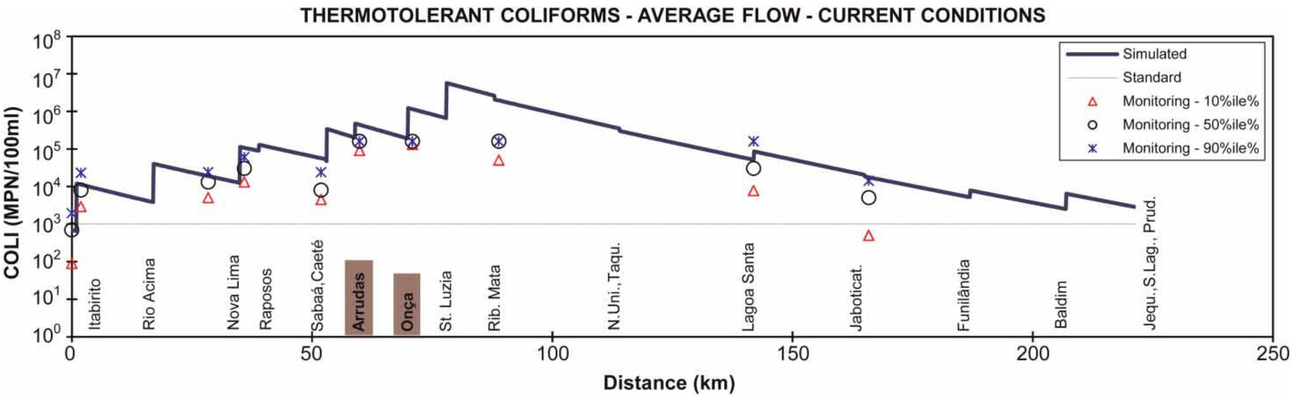

Figure 1 | Simulation of thermotolerant coliforms in the das Velhas River. Comparison between the values simulated by the model (flow Q_{50}, current conditions) and the monitored data.

Thus, the plotted values of the monitored data are in fact lower than the expected real ones. The lack of the actual values of the highest monitored concentrations is the reason why goodness-of-fit coefficients (such as the Coefficient of Determination) could not be calculated, and the model calibration had to rely only on a visual analysis.

Scenario 1. Current conditions and disinfection in the large Arrudas and Onça WWTPs

Figure 2 shows the profile of thermotolerant coliforms in the reach of the das Velhas River under study, comparing two situations: (a) current situation and (b) current conditions, but assuming disinfection of the effluents from Arrudas and Onça WWTPs. These are the most important WWTPs in the state of Minas Gerais and account for 92% of the treated sewage in the study area (treated flows: Arrudas WWTP = 1.750 m^3/s; Onça WWTP = 0.965 m^3/s). The total sewage flow (treated and untreated) in these two catchment areas is 4.373 m^3/s (Arrudas basin = 2.479 m^3/s; Onça basin = 1.894 m^3/s) and the $Q_{7,10}$ river flow immediately upstream of these two discharges is only 11.980 m^3/s, which gives a very small dilution ratio. Before this study, the environmental agency and water utility had high expectations that the disinfection in these two wastewater treatment plants would give a large contribution to the compliance with the coliform bathing standard. Both simulations were carried out for the $Q_{7,10}$ reference flow. It can be observed that the curves practically overlap, i.e. effluent disinfection at the two main WWTPs is not enough to change the profile of coliforms in the das Velhas River. This can be explained by the fact that the percentage of untreated sewage in both basins, with a discharge flow containing very high concentrations of coliforms (between 10^7 and 10^8 MPN/100 mL) implies a load that, even with a component of treated and disinfected sewage, results in a high concentration of coliforms.

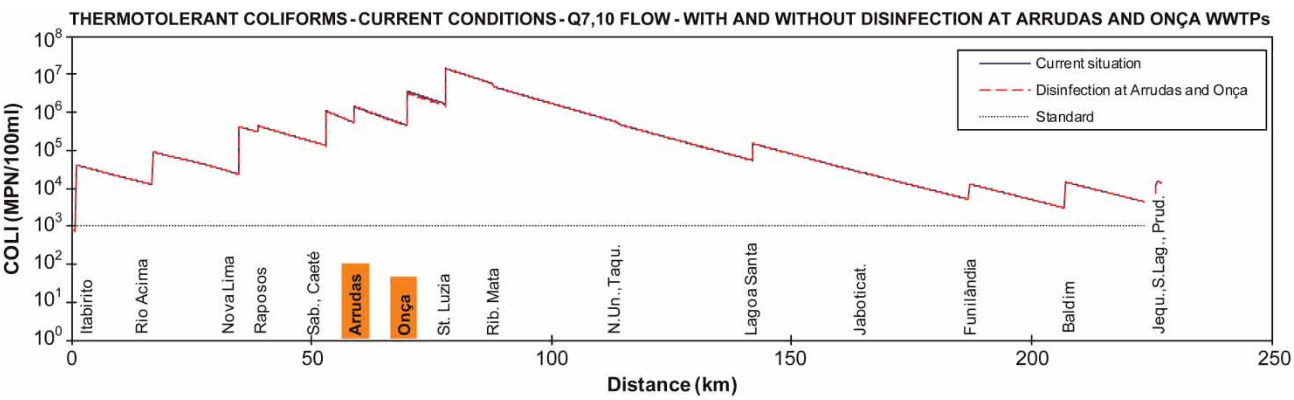

Figure 2 | Simulation of thermotolerant coliforms in the das Velhas River. Current conditions. Flow $Q_{7,10}$. Scenario with and without disinfection of the effluents from the WWTPs of Arrudas and Onça.

This is a very important point, not only in the context of the present study, but also for the water management at other catchment areas in the world: in the present case, sewage was planned to be disinfected at large WWTPs that account for 92% of the flow in the basin and still no positive effects could be clearly seen. In order to understand this, a side analysis is presented now, using a hypothetical and didactic simple calculation example, which can apply to any catchment area. In this example, a thermotolerant coliform concentration in the raw sewage of 1.00×10^8 MPN/100 mL is used. For instance, if a particular basin has excellent treatment coverage, with 99% of its sewage being collected and treated, and if, in the sewage treatment with disinfection there is a coliform removal efficiency of 99.9999% (6 logarithmic units), the resulting coliform concentration in the mixture of raw and treated sewage to be discharged in the receiving water body is given by the following weighted average:

$$\begin{aligned}\text{Coli mixture} &= \frac{\text{Flow untreated sewage} \times \text{Coli untreated sewage} + \text{Flow treated sewage} \times \text{Coli treated sewage}}{\text{Flow untreated sewage} + \text{Flow treated sewage}} \\ &= \frac{0.01 \times 1 \times 10^8 + 0.99 \times (1 - 0.999999) \times 1 \times 10^8}{0.01 + 0.99} \\ &= \frac{1,000,000 + 100}{1} = 1,000,100 \\ &= 1.0001 \times 10^6 \text{ MPN/100 mL}\end{aligned}$$

On the other hand, if the WWTP had no disinfection, achieving only a typical 99% coliform removal efficiency on the secondary treatment (von Sperling & Chernicharo 2005), the resulting concentration in the mixture would be:

$$\begin{aligned}\text{Coli mixture} &= \frac{\text{Flow untreated sewage} \times \text{Coli untreated sewage} + \text{Flow treated sewage} \times \text{Coli treated sewage}}{\text{Flow untreated sewage} + \text{Flow treated sewage}} \\ &= \frac{0.01 \times 1 \times 10^8 + 0.99 \times (1 - 0.99) \times 1 \times 10^8}{0.01 + 0.99} \\ &= \frac{1,000,000 + 990,000}{1} = 1,990,000 \\ &= 1.9900 \times 10^6 \text{ MPN/100 mL}\end{aligned}$$

Thus, in both cases (with and without disinfection), the order of magnitude of coliforms in the total sewage flow (treated + untreated) discharged in the receiving water body is 10^6 MPN/100 mL. To reach the bathing standard of 10^3 MPN/100 mL in the receiving body, very high dilution ratios (river flow/sewage flow), in the order of 1,000 to 10,000, would be required, along with an excellent water quality in the river, upstream of the discharge. These dilution ratios are seldom achieved in rivers that cross urban areas and are the immediate receiving bodies of sewage discharge.

The calculations also show that the component related to untreated sewage load has a great influence on the result of the concentration in the discharge mixture and, as a consequence, in the river water. Therefore, lower values of coliforms in discharged effluents would only be reached if, in addition to disinfection, there was a very high coverage of collected and treated sewage (negligible flows of untreated sewage discharged to the water body).

Table 2 is a follow up of this hypothetical example, showing the resulting concentration of coliforms in the mixture, for different percentages of coverage of treatment of the generated sewage and of coliform removal efficiency in sewage treatment. The difficulty in reaching overall low values is clear. Concentrations in the order of 10^4 MPN/100 mL or lower in the final mixed effluent are only reached with treatment coverage of over 99.99% and treatment removal efficiencies also exceeding 99.99% (shaded area on the table).

A similar reasoning can be made for WWTPs, which at certain times are forced to overflow or by-pass raw sewage to the receiving water body during storm events or lack of electric power. If a small fraction overflows or by-passes, the weighted average of the coliform concentration in the flow discharged to the water body (treated flow + by-passed flow) will have very high values, as determined by the equations above. If the WWTP receives 100% of the generated sewage from a community and offers highly efficient disinfection (removal of 6 logarithmic units), but allows the overflow or by-pass of 1% of its flow, the resulting concentration in the overall discharge will be very high, equal to 1.0001×10^6 MPN/100 mL (identical to the above calculations). This simple calculation shows the enormous difficulty in reaching low global average discharge values of coliforms.

Coming back to the study on the das Velhas River, it can be said that, in terms of $Q_{7,10}$, the flow of the das Velhas River near the confluence with the Arrudas and Onça streams is slightly more than twice the flow of sewage discharged by these two sub-basins. Thus, the potential for dilution is minimal (besides the fact that the das Velhas River is already polluted). Therefore, the mixture of raw

Table 2 | Resulting coliform concentrations in the raw sewage/treated sewage mixture discharged in the river, for different percentages of coverage of treatment of the generated sewage and of coliform removal efficiencies in the WWTP (hypothetical example, with concentration of coliforms in raw sewage = 1.00×10^8 MPN/100 mL)

	Coliform removal efficiency in sewage treatment								
Percentage of the generated sewage that is collected and treated (%)	**0% 0 log**	**90% 1 log**	**99% 2 log**	**99.9% 3 log**	**99.99% 4 log**	**99.999% 5 log**	**99.9999% 6 log**	**99.99999% 7 log**	**99.999999% 8 log**
0%	1.0000×10^8	1.0000×10^8	1.0000×10^8	1.0000×10^8	1.0000×10^8	1.0000×10^8	1.0000×10^8	1.0000×10^8	1.0000×10^8
10%	1.0000×10^8	9.1000×10^7	9.0100×10^7	9.0010×10^7	9.0001×10^7	9.0000×10^7	9.0000×10^7	9.0000×10^7	9.0000×10^7
20%	1.0000×10^8	8.2000×10^7	8.0200×10^7	8.0020×10^7	8.0002×10^7	8.0000×10^7	8.0000×10^7	8.0000×10^7	8.0000×10^7
30%	1.0000×10^8	7.3000×10^7	7.0300×10^7	7.0030×10^7	7.0003×10^7	7.0000×10^7	7.0000×10^7	7.0000×10^7	7.0000×10^7
40%	1.0000×10^8	6.4000×10^7	6.0400×10^7	6.0040×10^7	6.0004×10^7	6.0000×10^7	6.0000×10^7	6.0000×10^7	6.0000×10^7
50%	1.0000×10^8	5.5000×10^7	5.0500×10^7	5.0050×10^7	5.0005×10^7	5.0001×10^7	5.0000×10^7	5.0000×10^7	5.0000×10^7
60%	1.0000×10^8	4.6000×10^7	4.0600×10^7	4.0060×10^7	4.0006×10^7	4.0001×10^7	4.0000×10^7	4.0000×10^7	4.0000×10^7
70%	1.0000×10^8	3.7000×10^7	3.0700×10^7	3.0070×10^7	3.0007×10^7	3.0001×10^7	3.0000×10^7	3.0000×10^7	3.0000×10^7
80%	1.0000×10^8	2.8000×10^7	2.0800×10^7	2.0080×10^7	2.0008×10^7	2.0001×10^7	2.0000×10^7	2.0000×10^7	2.0000×10^7
90%	1.0000×10^8	1.9000×10^7	1.0900×10^7	1.0090×10^7	1.0009×10^7	1.0001×10^7	1.0000×10^7	1.0000×10^7	1.0000×10^7
99%	1.0000×10^8	1.0900×10^7	1.9900×10^6	1.0990×10^6	1.0099×10^6	1.0010×10^6	1.0001×10^6	1.0000×10^6	1.0000×10^6
99.9%	1.0000×10^8	1.0090×10^7	1.0990×10^6	1.9990×10^5	1.0999×10^5	1.0100×10^5	1.0010×10^5	1.0001×10^5	1.0000×10^5
99.99%	1.0000×10^8	1.0009×10^7	1.0099×10^6	1.0999×10^5	1.9999×10^4	1.1000×10^4	1.0100×10^4	1.0010×10^4	1.0001×10^4
99.999%	1.0000×10^8	1.0001×10^7	1.0010×10^6	1.0100×10^5	1.1000×10^4	2.0000×10^3	1.1000×10^3	1.0100×10^3	1.0010×10^3
99.9999%	1.0000×10^8	1.0000×10^7	1.0001×10^6	1.0010×10^5	1.0100×10^4	1.1000×10^3	2.0000×10^2	1.1000×10^2	1.0100×10^2
99.99999%	1.0000×10^8	1.0000×10^7	1.0000×10^6	1.0001×10^5	1.0010×10^4	1.0100×10^3	1.1000×10^2	2.0000×10^1	1.1000×10^1

and treated sewage would require much lower values of coliforms, i.e. it would be paramount in these two basins to have very high percentages of collection/treatment and coliform removal efficiencies.

Even during rainy seasons (Q_{10} flow), the river flow at this point is only about 10 times the sewage flow arising from these two basins. As a result, even if the das Velhas River was clean upstream, the dilution of the sewage from the two sub-basins would reduce coliform concentrations by only about 10 times (an order of magnitude), which is clearly unsatisfactory in this scenario.

Scenario 2. Excellent sewerage infrastructure. Treatment of 95% of the generated sewage and disinfection in the sewage treatment plants in all municipalities

This scenario is the one in which all municipalities of the area under study implement an excellent sanitary infrastructure (95% of coverage of treatment of the generated sewage and disinfection in all WWTPs). Figure 3 presents the calculated coliform concentration profiles for the three reference flows: $Q_{7,10}$ (dry period), Q_{50} (average), Q_{10} (rainy period). In all cases, the resulting concentrations are much higher than the 1,000 MPN/100 mL standard. Peaks at each discharge point are associated mainly with the untreated sewage component (5% of the total flow in each municipality). Once again, the difficulty in reaching the standard for coliforms can be observed, in spite of the implementation of a very good sewerage infrastructure. Even with greater dilution potential (Q_{50}, and even Q_{10}), coliform concentrations remain very high and well above the 1,000 MPN/100 mL standard.

Scenario 3. Definition of percentages of treatment and removal efficiencies by a mathematical optimization process

This scenario took into consideration varying percentages for the sewage treatment coverage and for coliform removal in the treatment, for each municipality, and these percentages were obtained using a mathematical optimization method (Solver tool from Excel). The values obtained for the percentages of treated sewage and coliform removal efficiencies in each municipality are not shown here due to space limitations. In upstream towns, high percentages of collection and treatment are needed (coverage from 99 to 99.998%), along with sewage disinfection (coliform removal efficiencies from 99 to 99.9998%). For locations with greater sewage flow, the need for disinfection and for very high percentages of sewage collection and treatment remains. For the smaller municipalities, located in the downstream reach of the das Velhas River, the treatment coverage (from 80 to 99%) and coliform removal efficiency in the treatment (from 80 to 99%) requirements are much smaller, approaching minimum restriction values.

Figure 4 presents the concentration profiles of thermotolerant coliforms in the das Velhas River, based on the solutions proposed by the optimization algorithm. The strict fulfilment of the quality standard of 1,000 MPN/100 mL can be observed for $Q_{7,10}$, with some points where the maximum concentrations approach the standard (most cost-effective solution). The vertical steps at each discharge point are now much smaller (please note that the *Y*-axis scale is different from the previous graphs). Figure 4 also shows the resulting concentration profile for the same

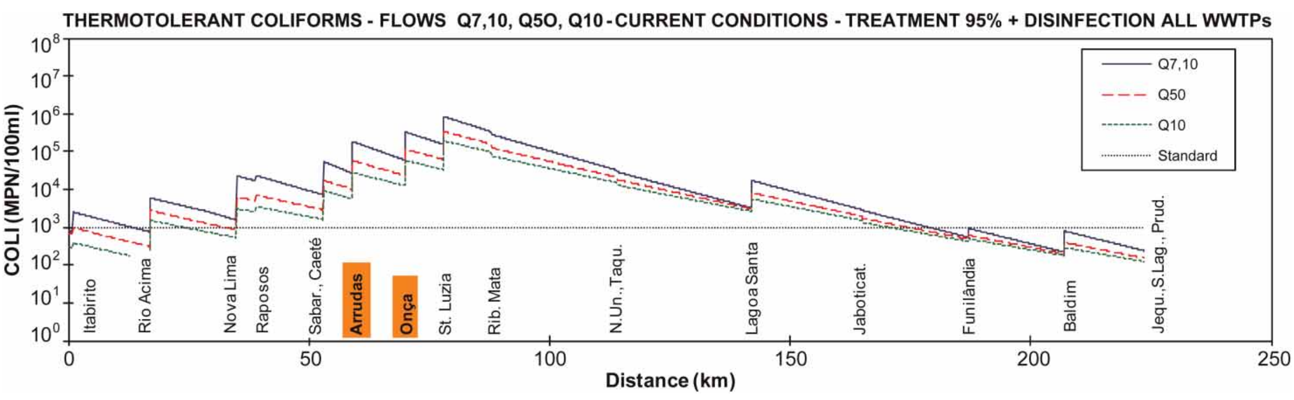

Figure 3 | Simulation of thermotolerant coliforms in das Velhas River. Current conditions. Scenario with 95% of treatment of the generated sewage and disinfection of all treated effluents in all municipalities of the study area. Flows: $Q_{7,10}$ (dry), Q_{50} (average), Q_{10} (rainy).

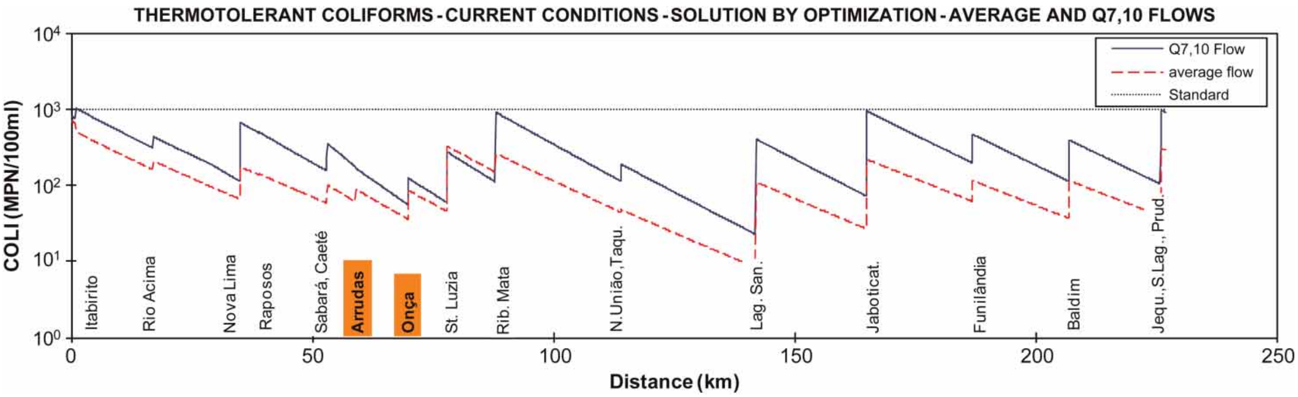

Figure 4 | Simulation of thermotolerant coliforms in the das Velhas River. Current conditions. Scenario with the percentage of sewage treatment and coliform removal efficiency, in each municipality, defined by an optimization algorithm. Flows: $Q_{7,10}$ and Q_{50}.

percentages of treatment and removal efficiencies, but applied to average flow conditions (Q_{50}). In this case, with the higher dilution capacity provided by the river, the resulting concentration values are slightly lower and below the quality standard.

CONCLUSIONS

The results of the simulations of thermotolerant coliforms indicated that the simple sewage disinfection in the two main WWTPs, which account for 92% of the wastewater flow in the study area, is not enough to ensure bathing in the das Velhas River.

The simulations also indicated that, even under hypothetical conditions of great sanitary infrastructure (95% coverage of collection and treatment of the generated sewage, and treatment with disinfection in all 25 WWTPs), concentrations of thermotolerant coliforms in das Velhas River are likely to be orders of magnitude above the maximum allowable value of 1,000 MPN/100 mL. Flow conditions (dry period, average conditions, rainy period) and hence dilution capacity showed little influence in terms of the relative degree of difficulty in complying with coliform standards for bathing.

The definition of the percentages of sewage collection and treatment and coliform removal efficiency in the WWTPs by means of mathematical optimization indicated the need for a very high coverage of sewage treatment (near 100%, i.e. universal availability of treatment) and for the implementation of disinfection in most WWTPs (with greater emphasis for upstream municipalities and larger towns).

Both the high percentage of sewage collection and treatment and the need for disinfection in the WWTPs play equally important roles. In this regard, it is worth remarking that the implementation of only disinfection will bring insufficient positive impacts regarding coliforms in the das Velhas River. In fact, disinfection becomes more important as the percentages of collection and treatment increase. Therefore, it is clear the need to continue investing in the pursuit of the universal coverage in sewage treatment in the area under study.

If this infrastructure, which approaches an idealized situation, is not implemented, it will be difficult to have consistent bathing conditions in the das Velhas River, in the stretch under study. Despite the large dimensions of the river, its dilution capacity is small compared with the substantial sewage flow that it receives. This situation is similar to several other watercourses that cross urbanized areas elsewhere. As coliforms are present in very high concentrations in sewage, values compatible with bathing standards can only be reached with great effort and with the implementation of a very good sewage collection, treatment and disinfection infrastructure. In terms of water quality parameters, coliforms are among the most difficult ones to conform to the legislation on water bodies that cross urbanized areas.

The confirmation of the high degree of difficulty in complying with the bathing standards should not serve as a deterrent to the continued expansion of the sanitary infrastructure in water basins. The benefits, in terms of the environment and public health are numerous and, even though outside the scope of this analysis, are easily recognizable by the population and are depicted by various environmental indicators.

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