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Integrated and Multiobjective Simulation: A Qualitative and Quantitative Analysis of the Water System Located in the Salgado River Sub-basin in the State of Ceará.

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ABSTRACT : *The main objective of this research is to analyze the water demands and concentrations of the water reservoir system located in the Salgado River basin, State of Ceará, using the integrated and multi-objective simulation model proposed by Vieira (2011). The main parameters of water quality and total quantitative demands of the Lima Campos and Ubaldinho reservoirs were considered. It was considered a time horizon of 1212 months and Class 02 of framing. As for meeting the total quantitative demands, the Lima Campos reservoir had 14 failures, with a reliability of 98.84%; the Ubaldinho reservoir, on the other hand, showed excellent results, without failures, achieving 100% reliability. Regarding the qualitative parameters, the good performance of the Ubaldinho reservoir stands out, which showed levels of Biochemical Oxygen Demand (BOD), Dissolved Oxygen (DO), Total Phosphorus (TF), Chlorophyll-A (CLA), Total Nitrogen (TN) and Thermotolerant Coliforms (TC), mostly adequate to acceptable concentrations for Classes 01 and 02, already in the reservoir Lima Campos presented some favorable results within the simulation analysis, however, regarding BOD, OD, FT, Chlorophyll, and Thermotolerant Coliforms, they presented peak concentrations outside the acceptable limits for classes 01 and 02, and in some moments, even class 03. The parameter that showed the best results over the simulated period was in relation to Total Nitrogen (TN). Therefore, it is noteworthy that the applicability of the simulation model managed to precise resultsin an integrated analysis, from quantitative parameters, such as meeting quantitative demands, as in the simulation of qualitative parameters.*
KEYWORDS: *Water resources, simulation model, demands, concentrations.*

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I. INTRODUCTION

The availability of water is a determining factor not only for human survival, but for the economy and development. Water is not always easily accessible but is found in rivers, lakes, and reservoirs and accounts for a small amount of the total fresh water available in the world. This fresh water is available at different levels all over the planet, with some places facing floods and inundations, and others facing great water scarcity (WWF, 2006).

The great importance of this resource for mankind, in itself, denotes how it is exploited. The poorly planned, inefficient and sometimes irrational use of natural resources aggravates more and more the effects of climate change, interfering significantly in the hydric dynamics, intensifying periods of drought or flooding, causing various social and economic losses.

Thus, it is a complex scenario that involves the way the water resource is used and managed, since the demands tend to increase. Besides the quantitative aspects, the quality of the water available is another challenge in the current context, and it is necessary to consider the way the ecosystems are managed, in which the springs, rivers, lakes, and natural (and artificial) reservoirs are inserted.

The resolution of this problem involves the multiple uses of water, from the demand for human supply, irrigation, industrial consumption, animal and fish farming, tourism, among others (GALVÃO; BERMANN, 2015). Given the various purposes of water use, there are sometimes conflicts between user sectors. Thus, it is essential to manage and regulate water resources, making sustainable the economic, social and environmental demands for water, performing the quantitative and qualitative control of water uses (RIBEIRO et al., 2014).

This is where Integrated Water Resources Management (IWRM) becomes paramount. To make it possible to meet water needs efficiently and minimizing possible conflicts, the optimized management of water resources is necessary. In this sense, research in this area is indispensable, through the use of tools that help in the decision making process, such as software derived from mathematical models.

Through techniques such as simulation and optimization, the dynamics of a hydric system can be represented, keeping the main existing elements with their mathematical behavior representation. In this way a simulation of an approximation of the system behavior reality allowsone to attain the prediction of scenarios involving water quantity and quality. Therefore it is able to provide subsidies for analyzing the behavior of water availability of reservoirs and the quality classification of water bodies, crucial information for decision making and, consequently, better management.

Within this context, the integrated and multi-objective simulation model to be used in this research was developed by Vieira (2011), and has the proposal to bring a broader number of interconnected variables results in which is incorporated water quantity and quality features regarding the operational aspects in an integrated analysis, This model allows to analyze the qualitative and quantitative aspects, in the same platform, of rivers, reservoirs and water uses, incorporating the nonlinearities of hydraulic and operational processes culminating in a multi-objective function that optimizes monthly the meeting the water demands of different uses and the concentrations of different quality parameters in a hydrological system.

The applicability of this model becomes even more relevant when performed in a hydric system with major restrictions on water availability such as the semi-arid region of Northeastern of Brazil that has characteristics that provide more pronounced water limitations, with most of its rivers being intermittent, which requires planning even more focused on its specificities. In order to collaborate with the planning and management of water resources, many studies and researches make use of optimization methods, by means of Decision Support Systems (DSS). Many models are used, in order to portray the complex hydric dynamics of a location, either in watersheds, or in reservoirs connected by specific channels (VIEIRA and CURI, 2022).

The motivation for choosing this watershed is due to its peculiarities regarding its semi-arid region, thus the hydric system is going through a severe hydric crisis, and due to the fact that the State of Ceará has an up-to-date and accessible monitoring and data management,

Based on this context, the main objective of this research is to analyze the efficiency of meeting the total hydric demands and the framing the water quality parameters concentrations of the reservoir systems Ulbadinho and Lima Campos in the hydrographic basin of the Salgado river located in the state of Ceará, using the quali-quantitative, integrated and multiobjective simulation model proposed by Vieira (2011).

II. MATERIALS AND METHODS

a. Characterization of the study area

The present study has as research locus two reservoirs belonging to the Salgado river watershed, located in the southern Ceará State, UTM coordinates 9150000S and 9300000S latitude, and 450000W and 550000W longitude. In this basin, there are 15 strategic reservoirs monitored daily, the main one being the Salgado River, from which it derives its name. It has a length of 308 km, with 12,623.89 km² of drained area, equivalent to 9% of the Ceará territory. The path of this river runs south-north until it meets the Jaguaribe River, in a location near the city of Icó (ANA, 2017). Figure 1illustrates the location of the sub-basin of the Salgado River, highlighting the reservoirs addressed in this research.

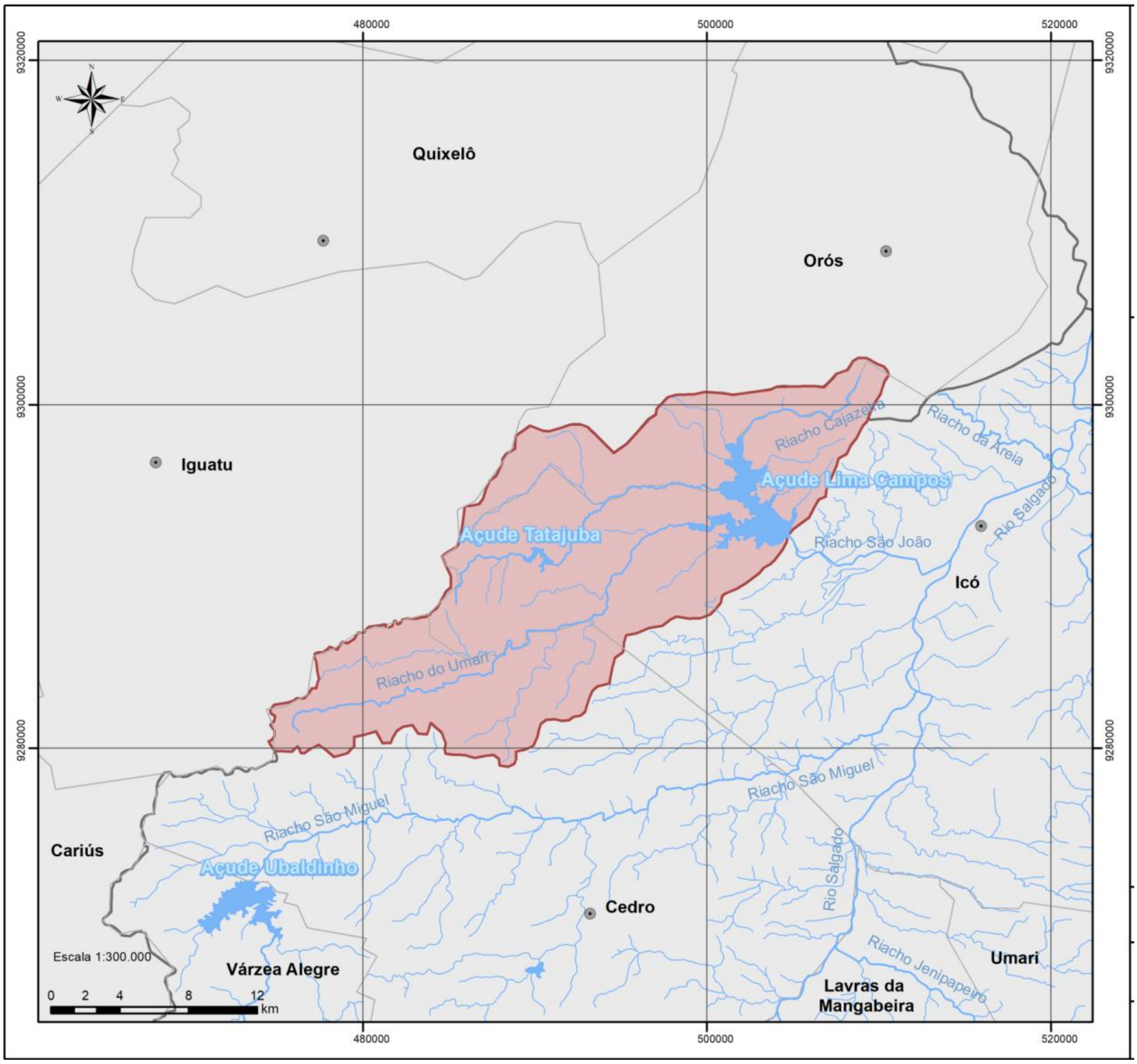

Figure 1. Location map of the Salgado/CE sub-basin highlighting the analyzed reservoirs. Source: ANA, 2017.

As can be seen in Figure 1, indicate the two reservoirs analyzed in this research that are in parallel: Lima Campos and Ubaldinho, which are part of the same administrative reference area for water security management, according to the environmental inventory (COGERH, 2017).

The delimitation of the water reservoirs to be studied have a storage capacity exceeding10,000,000 m^3 of water, and the geographical proximity of these, so that they have the similar demands, and meet the water needs of a region with aspects such as climate, soil, average rainfall, among others. Thus, the two reservoirs chosen for the application of this research were: Lima Campos, located in the municipality of Icó, and Ubaldinho, located in the municipality of Cedro, both in the territory belonging to the State of Ceará.

The predominant climate in the hydrographic contribution area of the Lima Campos and Ubaldinho weirs is characterized as Tropical Warm Semi-arid and Tropical Warm Semi-arid, whose rainy season is concentrated from February to April. Temperatures between 23°C and 29°C (average minimum and maximum) are registered in the region. The annual rainfall is generally between 600 and 1,013.96 mm and the rainfall regime is considered quite irregular, with years marked by heavy rains, usually concentrated from January to April, and others by droughts (IPECE, 2011).

The vegetation in the contribution area of the two reservoirs is characterized by dense shrubby caatinga, with arboreal and thorny patches. Some fragments of riparian forest and dry forest are also present (COGERH, 2017).

The soil classes that predominate in the region are Luvisol soil, Argisol soil, Neosol soil and Vertisol soil. Regarding the altitudes recorded in the hydrographic contribution area, the landscape presents smooth shapes in the region of the Sertaneja Depression, with predominant values of 151 to 238 meters. From a geological point of view, in the region there is a predominance of Pre-Cambrian crystalline basement rocks, and there is also a sedimentary sequence of Mesozoic age consisting of conglomerates, sandstones, siltstones and shales. Alluvial deposits can also be detected along the courses of the main rivers, of Quaternary age and composed mainly of sand, silt, clay, and gravel (CPRM, 1998 apud COGERH, 2017).

b. Operational, Quantitative and Qualitative Data of the Studied Hydric System

Lima Campos Reservoir

The Lima Campos reservoir (Figure 2) is located in the municipality of Icó-CE, in the northwestern portion of the Salgado watershed. Its watershed covers an area of 340 km². It has a water storage capacity of 66,800,000 m^3 of water (COSTA et al., 2017).

Figure 1. Lima Campos reservoir. Font: COGERH,2017.

Also according to ANA data (2017), for the Lima Campos reservoir, the types of existing demands and their respective withdrawal percentages, are: urban human supply (5%), rural human supply (1%), animal desedentation (1%), irrigation (93%) and its operating rules are as shown in Figure 3.The operational rule establishes the water management levels and the volume targets that must remain in the reservoir to meet the quantitative and qualitative demands.

The municipalities supplied with water are Icó-CE and Jagiaribe-Ce. The municipality of Icó has an estimated population for 2020 of 68,162 inhabitants, and the municipality of Jaguaribe, 34,636 inhabitants, according to 2010 data from the Brazilian Institute of Geography and Statistics -IBGE Cities. It is worth noting the existence of the Icó-Lima Campos irrigated perimeter.

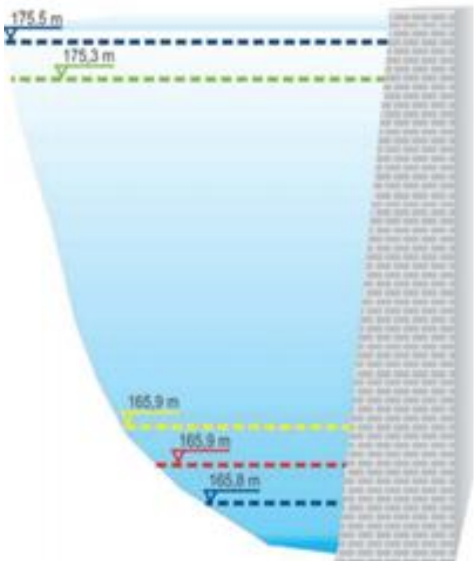

Figure 3. Operational Rules of the Lima Campos Reservoir. Font: ANA, 2017.

Ubaldinho Reservoir

The Ubaldinho reservoir (Figure 4) is located precisely in the district of São Miguel, in the municipality of Cedro-CE, and has a total storage capacity of 31,800,000 m³ of water (COGERH, 2017).

Figure 4. Ubaldinho reservoir. Font: COGERH, 2017.

Thewater demand withdrawal percentages from the Ubaldinho reservoir are: urban human supply (18%), rural human supply (12%), animal watering (20%), irrigation (50%). The operational rules are illustrated in Figure 5, demonstrating the useful volume of the reservoir and possible water management goals to be established.

The water from the Ubaldinho reservoir is destined to supply the São Miguel locality, in the municipality of Cedro, and the localities Naraniú, Barro Vermelho, Lagoa Redonda, Sítio Brejo, Sítio Charneca, Sítio do Meio, Vara da Prensa and Sítio Mundo Novo, in the municipality of Várzea Alegre. The municipality of Cedro has an estimated population for 2020 of 25,585 people (IBGE, 2019).

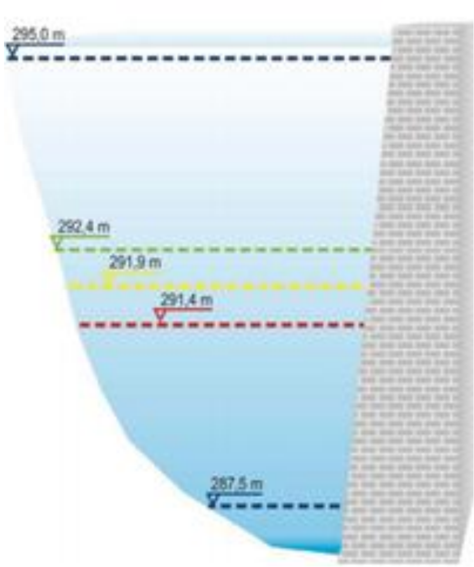

Figure 5. Operational Rules of the Ubaldinho Reservoir. Font: ANA, 2017.

c. Quality Data of the Studied Hydric System

When it comes to water resources, it is not only the quantitative aspects that need to be considered, since human action, in any of its water applications and uses, causes several damages to the springs, causing restrictions on water quality. In this sense, it is of great relevance to consider the water qualitative approach using the available data for application in this research.

According to theNational Environment Council – CONAMA, resolution Nº. 357/2005, water quality class is the set of required conditions and standards for water quality to meet the classes of water uses. When the respective classifications are not approved, the fresh waters will be considered class 2 and the saline and brackish waters will be considered class 1. In this sense, the average data of water quality parameters concentrations of the Ubaldinho and Lima Campos dams, made available in the Environmental Inventory of the State of Ceará (COGERH, 2017), was used. Based on this Inventory, several time series were generated for water quality planning such as Biochemical Oxygen Demand (BOD), Dissolved Oxygen (DO), Total Nitrogen (TN), Total Phosphorus (TF), Chlorophyll-A (CLA) and Thermotolerant Coliforms (TC), which were foreseen in the simulation model used in this study.

d. Quali-quantitative Simulation Model Used

The simulation model was developed by Vieira (2011), combines simulation and optimization techniques, uses sequential linear programming to incorporate the nonlinearities of hydraulic and operational processes, and includes the multi-objective character (optimization of allocations and concentrations) and the application to a water resources system. Its purpose is to simulate the allocation of water to meet the requirements of its multiple uses and concentrations, while respecting the limitations of the components (reservoirs and rivers) and maintaining the required standard of quality of water bodies.

This simulation model works with a monthly time scale and has at its core, an optimization algorithm, which uses Sequential Linear Programming and Linear Approximation Method techniques. It is a simulation model, even though an optimization process is included. The planning is performed in month t and is a function of the system conditions in month t-1, it does not consider other data a priori of month t-1 and a posteriori of month t. The execution of the mathematical model begins with the quantitative simulation (linearized in the iterative process), determining the optimal volumes month by month. With theoptimal allocated volumes found, the concentrations in reservoirs and control points of the system are determined, which serve as the initial value of the consequent iterative process. In this iterative process, where all the equations of water balance and mass balance are linearized and integrated, the volumes and concentrations are changed simultaneously in order to satisfy the imposed restrictions and optimize the proposed qualitative-quantitative objective function month by month. The programming language used is MATLAB (Matrix Laboratory) version 6.5 with the Interior Point Method for the search of the optimal solution (VIEIRA, 2011).

In this way, for each proposed hydric scenario, the model will trace the probable hydric behavior of the reservoir, in quantitative and qualitative terms, due to the demands considered, supplying data for further analysis.

The time horizon used to simulate the behavior of the reservoirs addressed in this research, the Lima Campos and Ubaldinho dams, was 1,212 months, or 101 years, contemplating the period that corresponds from 1918 to 2019 and the operation scenario with the main priorities being quantitative demands.

III. RESULTS AND DISCUSSION

a. Lima Campos reservoir

Starting the presentation and analysis of the results, Table 1 shows the performance indicators of the quantitative demands according to the simulation. It is important to emphasize that, for the purposes of this research, the demands were analyzed jointly, that is, the simulation approached, in an integral way, the behavior of the Lima Campos reservoir, for the fulfillment of all existing demands, namely, urban human supply (18%), rural human supply (12%), animal watering (20%), irrigation of perennial and seasonal crops (50%). It is worth noting, however, that the model developed by Vieira (2011) has the capacity to analyze the behavior of the monthly quantitative demands individually and by sector.

Table 1. Performance indexes for the Limas Campos reservoir water demands.

Lima Campos Reservoir	
Performance indicators	Urban water supply + Perennial Crops Irrigation + Seasonal Crops Irrigation + livestock (hm^3/mês)
Number of failures	14
Number of times recovering from failures	2
Reliability (%)	98.84
Resilience (%)	14.29
Vulnerability (%)	82.98
Sustainability (%)	2.404

Initially, it can be ascertained that, during the simulated period, 14 failures occurred, that is, in 14 periods (months), the reservoir was not able to meet all the existing demands (urban and rural human supply, animal feeding, irrigation of perennial and seasonal crops), this occurred due to the large volume of water demanded for irrigation. However, when analyzing the times when the reservoir was able to recover from the availability failure (right after the hydric restriction episode), in 2 periods there was a recovery, and, therefore, its resilience is around 14.29%.

From these findings, it is easy to understand that the reliability value presented, which corresponds to 98.84%. That is, in almost 99% of the simulated periods, the reservoir fully attended to the existing water demand requests, with a vulnerability of 82.98%, given the 12 times in which there was no immediate failure recovery evidencing the water deficit and consequently presenting a sustainability is 2.40%.

The results obtained in the qualitative-quantitative simulation of the Lima Campos reservoir behavior are presented below, by means of the figures and respective analyses, considering, initially, hydric availability, spilled volume, and meeting the total quantitative demands, and later, the qualitative parameters.

Figure 6 shows the behavior of the hydric volume of the Lima Campos reservoir along the simulated period, emphasizing its minimum and maximum volumes.

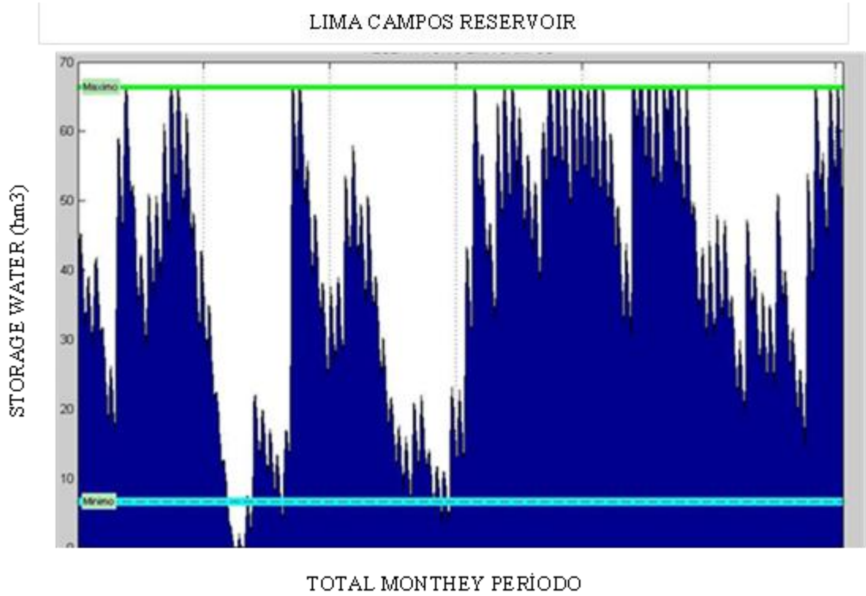

Figure 6. Lima Campos reservoir storage volumes'behavior.

It can be observed that, in most of the simulated period for analysis, the reservoir presented results above the minimum volume, alternating with oscillations of hydric volume recovery and reaching, in some periods, the maximum volume. It is evident, here, what was highlighted in the quantitative performance indicators (Table 1), being possible to observe the failures that occurred, as the minimum volume was reached, and thus, generated a loss of reliability around 1.36%.

The operational restrictions were met in most periods. It is also possible to verify that the Lima Campos reservoir has a great oscillation in its volume throughout the simulated years, due to demand requirements. It is notorious, when emphasizing that the volume rupture in some months (below the minimum volume) of the referred reservoir, probably occurs, besides the demand needs, due to the drought periods, characteristic of the semi-arid climate. It should also be emphasized that for the occurrence of such situations there was in advance a period of representative decrease.

Figure 7 shows the spilled volume, that is, the volume lost to the downstream river, from the moment that the maximum volume of the Lima Campos reservoir is reached.

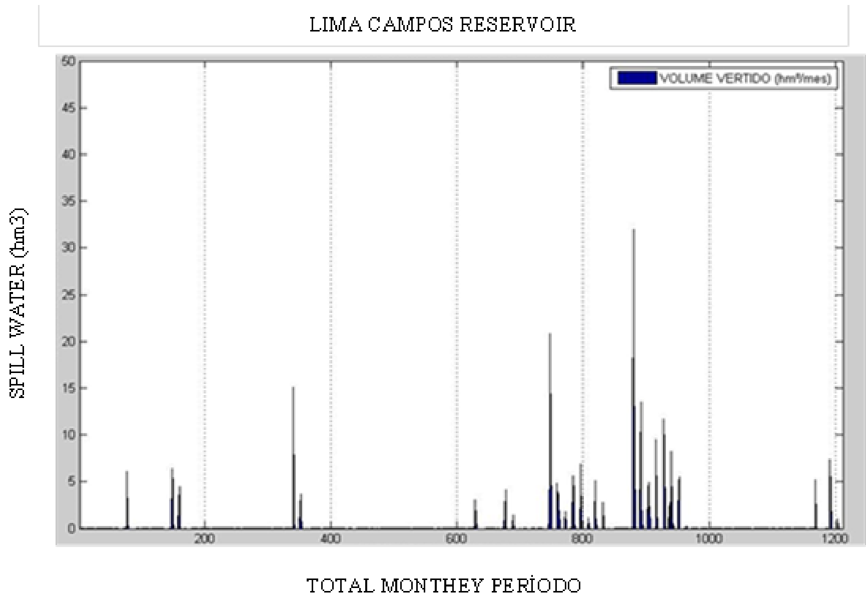

Figure 7. Lima Campos reservoir spillages'behavior.

From the results, it can be identified that the presented spilling results correspond to what was observed in the previous analysis (Figure 7), and that, after reaching the maximum volume in some periods, in which probably occurs a peak of rains that stand out, that is, there were also months with abundant rains, which allowed the arrival of large affluent flows, and, for this reason, there were water losses by spilling. This spilled volume is drained into the downstream river, and as it is not integrated in series with the Ubaldinho reservoir, there is no quantitative contribution, as the two reservoirs mentioned above operate in parallel.

Continuing the quantitative analyses, Figure 8 presents the withdrawn volumes (in hm^3, which is equivalent to 1,000,000,000 liters), to meet the demands inherent to the Lima Campos reservoir.

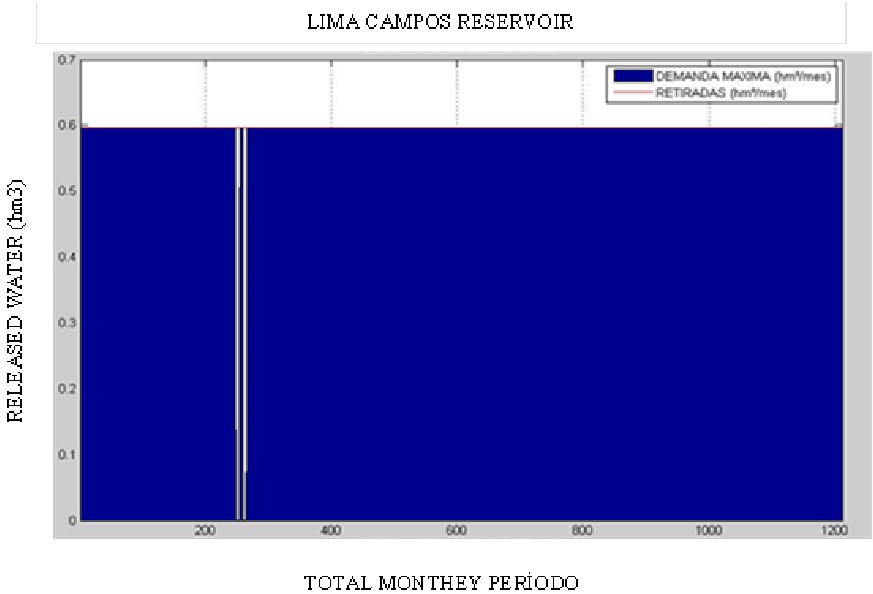

Figure 8. Lima Campos reservoir total released flows.

Corroborating the quantitative results presented so far Figure 9 indicates that the aforementioned reservoir has met, in most of the simulated periods, all the required demands, in an analysis of total withdrawals. There were, however, specific periods when demands were not met, corresponding to the failures indicated previously, as well as the moments when the volume reached its minimum quota and stayed below it.

Therefore, and as previously indicated, there are possible causes, such as hydric restriction caused by periods of little rainfall, and large demand requirements, causing the rupture in meeting the demands, namely, urban and rural human supply, animal watering, irrigation of perennial and seasonal crops, among which, the demand for irrigation stands out. In this sense, from the diagnosis of a large demand for irrigation, which can cause failures and losses, it is possible to point out possible solutions, mitigating measures to minimize this problem, such as the insertion of the practice of water reuse in irrigation, in order to save available water, and consequently reduce the environmental impacts caused by them, when dumped in the open air, in the soil and consequently in groundwater. It is worth pointing out that in terms of priorities, we have the demand for human and rural supply, and animal dessentation.

As for the simulation results for the analysis of qualitative parameters, the following analyses include the results for Biochemical Oxygen Demand (BOD), Dissolved Oxygen (DO), Total Phosphorus (TF), Chlorophyll-A (CLA), Total Nitrogen (TN) and Thermotolerant Coliforms (TC).

Regarding the Biochemical Oxygen Demand (BOD) that, according to Valente, Padilha and Silva (2000), is an indicator that seeks to determine the amount of dissolved oxygen (DO) consumed by microorganisms to decompose the organic matter present in a water body, i.e., the concentration of biodegradable organic matter through the oxygen demand used by microorganisms through their respiration, the results are presented in Figure 9 below.

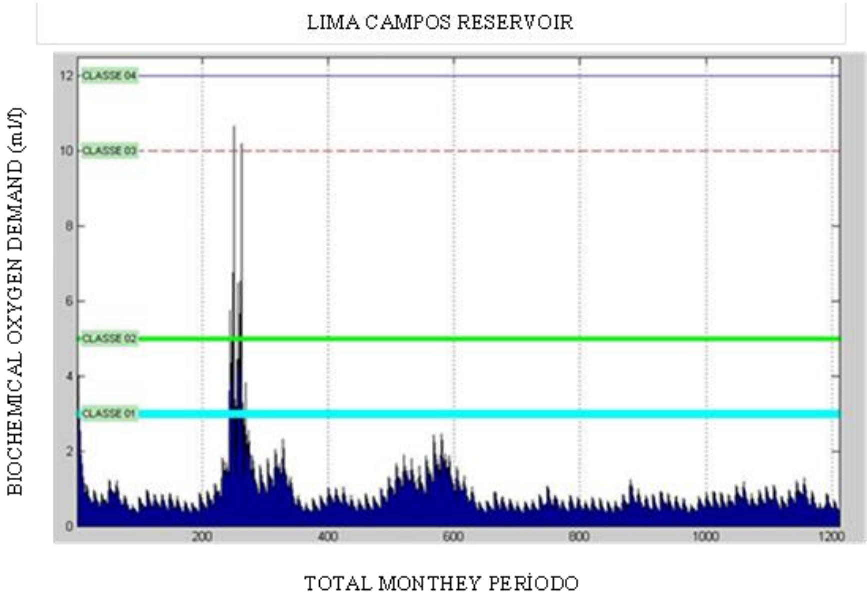

Figure9. Lima Campos reservoir BDO concentration.

Analyzing Figure 9, in which the values of BOD concentrations (ml/l) are shown, from the perspective of the ranges allowed for Classes 01 and 02, 03 and 04, according to resolution CONAMA No. 357, of March 17, 2005 (as amended by resolutions CONAMA No. 393/2007, No. 397/2008, No. 410/2009 and No. 430/2011), from which, in this study, we highlight the compliance with Class 01 (which is intended for drinking water supply, with simplified treatment; the protection of aquatic communities; the recreation of primary contact; and the irrigation of vegetables and fruits that are consumed raw), and Class 02 (use intended for the supply of human consumption, after conventional treatment; the protection of aquatic communities; the recreation of primary contact, the irrigation of vegetables, fruit plants, with which it may have direct contact; and aquaculture and fishing) (BRASIL, 2005).

In this sense, it can be seen that the simulated behavior presented, for the most part, acceptable BOD levels, within the Class 01 limit. In specific moments, which are correlated with episodes in which the reservoir volume was below the minimum, BOD concentrations were in higher proportions, exceeding the limit stipulated for classes 02 and 03, and even reaching levels only acceptable for the destination of fresh water to Class 04, with uses for navigation and landscape harmony (BRASIL, 2005).

It is estimated that due to the low concentration of DO, given the deficit in the local water volume, or by an increase in the proportion of effluents, pollution load incompatible with the level of water contained in the period, not meeting, in specific period, the pre-established goal of having, at most, 5 mg/l.

Figure 10 shows the simulated values for Dissolved Oxygen (DO), which, according to CETESB (2021), is the concentration of oxygen (O2) contained in water, an essential factor for maintaining aquatic life and self-depuration processes in hydric systems, such as the reservoir under analysis. According to the Blue Water Program - PAA (2015), dissolved oxygen can be interpreted as an essential parameter in the differentiation of the effects of pollution by organic inputs and to ensure oxygen for aquatic ecosystems.

Figure10. Lima Campos reservoir DO concentration.

It is possible to see, by analyzing Figure 10, that the reservoir has high concentrations of DO, there is satisfactory presence of oxygen during most of the analysis period, suitable for classes 01 to 02, being, however, a little below the saturation line. Thus, it is worth emphasizing that oxygen saturation consists of the maximum amount of oxygen that can be dissolved in water at a given pressure and temperature, and chloride concentration (PAA, 2015).

It is noted, however, that in a given stretch of the simulated period, there was a significant drop in the concentration of DO in Lima Campos reservoir, which may be correlated to the high levels of BOD concentration analyzed in the previous figure (Figure 9), this, given the scenario of low volume availability in the aforementioned weir, because there was a greater consumption of DO by microorganisms to decompose organic matter, there was a reduction in the oxygen available in the water body, with restriction to meet the levels for Class 01.

About the TF (Total Phosphorus) concentrations, these are presented in Figure 11.

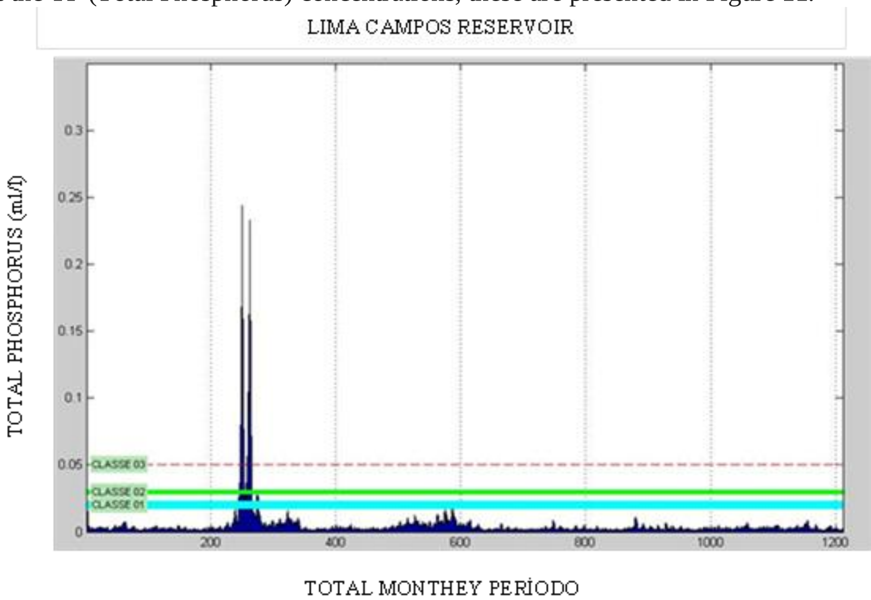

Figure 11. Lima Campos reservoir TF concentration.

The Total Phosphorus (TF) is an indicator of excess phosphorus contained in a water body or water sample. Phosphorus is an essential nutrient for biological processes, i.e., for plants and animals, however, in large quantities can cause the eutrophication of waters, the rampant proliferation of algae, which is responsible for limiting and depleting oxygen for fish and other aquatic organisms (CENTER FOR ENVIRONMENTAL SCIENCE, 2019).

As can be seen from the analysis of Figure 11, is that the TF showed concentrations compatible with the parameters indicated for Class 01 for most of the simulated period, however, aligned to the results for DO and BOD, the simulation pointed to a drop in quality with respect to TF, due to the low level of the reservoir volume, which reached levels that exceeded the uses for classes 01, 02 and 03, leaving, in qualitative terms, in a given stretch, inadequate for use; however, with the recovery of the hydric volume, the TF volumes remained within the acceptable range for the rest of the simulated period.

For analysis of the Chlorophyll-A concentrations (CLA) in Lima Campos reservoir, Figure 12 shows the results obtained.

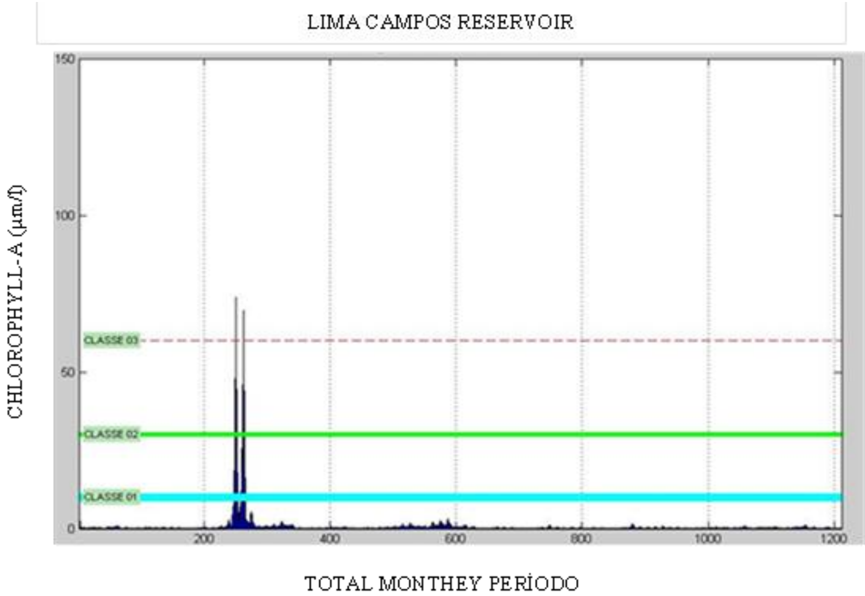

Figure 12. Lima Campos reservoir CLA concentration.

Chlorophyll-A is a pigment found in all groups of plants and autotrophic organisms (plants, algae, and some bacteria) responsible for capturing light and ensuring that photosynthesizing organisms can produce their food through the process of photosynthesis and, therefore, presents as a characteristic coloration in shades of green, often used as an indicator of phytoplankton biomass in aquatic environments. CONAMA Resolution 357/2005 established quality standards for chlorophyll-A for fresh waters, special classes 1, 2 and 3, thus existing legal limits for its concentration in these aquatic environments (CETESB 2014; BRASIL, 2005). Within this context, the simulation results show that the chlorophyll-A indexes are within acceptable parameters for classes 01 and 02 during almost the entire simulated period.

It is evident, however, that at times when the reservoir was at or below its minimum volume level, as well as the availability of DO was more scarce, and BOD consumption was higher, a greater eutrophication occurred in the studied water body, with two sudden peaks in a short period during the analysis, but soon after returning to adequate concentrations, as shown in Figure 12. Probably, in this period, the reservoir had a higher amount of algae, and presented a greenish coloration in its water sheet, which was later remedied by the inflow of effluent flows, coming from rainy periods.

During the simulated period, the Total Nitrogen (TN) levels present in the Lima Campos weir were also analyzed within the water quality parameters, as shown in Figure 13.

Before establishing analyses on this parameter, it is valid to inform what it is about. Benevides and Vargas (2016) explain that nitrogen compounds are important nutrients for biological processes, because, after carbon, it is the element required in larger quantities by living cells and that, in situations of discharges in natural waters - and associated with phosphorus and other nutrients present in effluents- cause the enrichment of the water body, leaving it more fertile and enabling the eutrophication process. In this sense, the total nitrogen content is, therefore, the addition of ammoniacal and organic nitrogen, plus the concentrations of nitrite and nitrate. In high concentrations they can cause intoxication in the aquatic fauna.

O it is possible to observe, the behavior of Lima Campos reservoir regarding TN concentrations, showed a small peak in a specific period, but without great relevance, because it is within the admissible levels for classes 01 and 02.

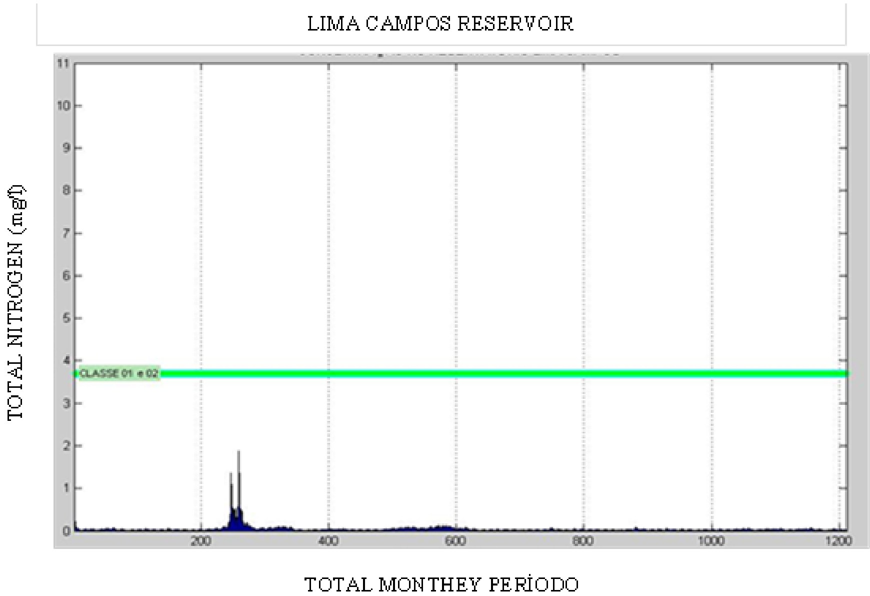

Figure 13. Lima Campos reservoir TN concentration.

The last qualitative data approached, for the Lima Campos reservoir in this study, refers to the Thermotolerant Coliforms (TC), as can be seen in Figure 14.

According to FUNASA (2013), thermotolerant coliforms are a subgroup of bacteria of the coliform group that ferment lactose to 44.5 ± 0.2°C in 24 h; and have as the main representative, Escherichia coli, which has fecal origin. According to Santos (2020), thermotolerant bacteria, previously called fecal coliforms consist of a group of bacteria that are not always found in feces, which is why CONAMA resolution 375/2005 indicates a new nomenclature.

Vieira and Curi (2022), explains that FC is an important parameter to be analyzed in studies that address hydric systems, because it is directly linked to public health. As shown in Figure 14, the behavior of the concentration levels of TC for Lima Campos reservoir, it is evident the oscillation between the concentrations compatible with the limits established for Classes 01 and 02, and extrapolating, at a moment, and entering the goal established for Class 03.

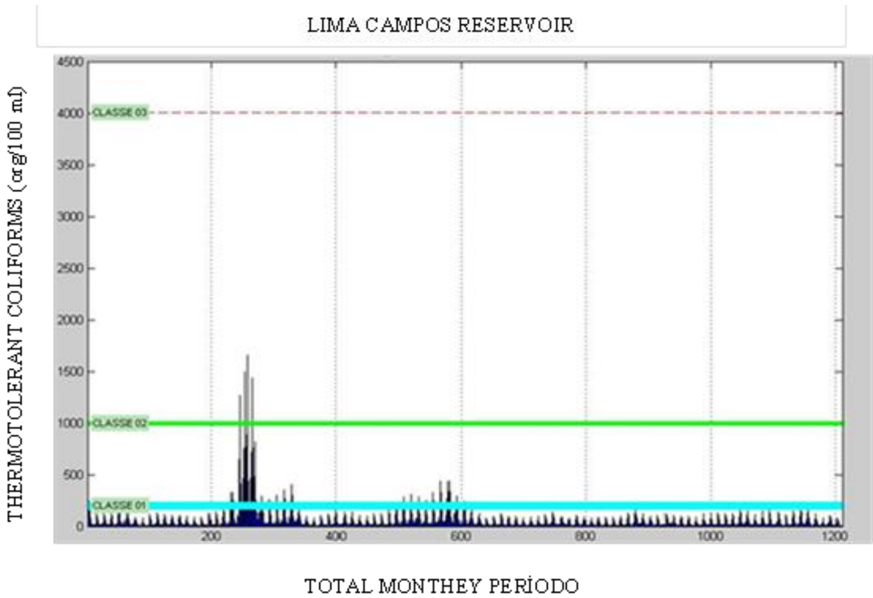

Figure 14. Lima Campos reservoir TC concentration.

b. Ubaldinho reservoir

The in Table 2 shows the performance indicators for total fulfillment of the withdrawals required by all existing demands and supplied by the Ubaldinho reservoir, and their respective withdrawal percentages, consisting of: urban human supply (18%), rural human supply (12%), animal watering (20%), irrigation of perennial and seasonal crops (50%).

Table 1. Performance indexes for the Ubaldinho reservoir water demands.

Ubaldinho Reservoir	
Performance indicators	Urban water supply + Perennial Crops Irrigation + Seasonal Crops Irrigation + livestock (hm³/mês)
Number of failures	0
Number of times recovering from failures	0
Reliability (%)	100
Resilience (%)	100
Vulnerability (%)	0
Sustainability (%)	100

From what is exposed in Table 2, it is concluded that the Ubaldinho reservoir presented, in the simulated time horizon, very satisfactory performance indicators, since there were no service failures, which generated a reliability of 100%, which corresponds to the percentages of 100% corresponding to resilience and sustainability, and consequently, 0 vulnerability.

This means that the reservoir was able, throughout the 101 simulated years, to have sufficient availability to meet the existing withdrawals and, therefore, meeting the demands for rural and urban human supply, animal desendation and irrigation of perennial and seasonal crops were completely satisfied (100%), thus, there were no failures in any sector.

The constant variations in stored volume (Figure 15) are due to the irregular rainfall regime, characteristic of the region with a predominantly semi-arid climate, which implies in tributary outflows with volumes that oscillate, depending on rainier periods, and others, because of more scarce rainfall periods.

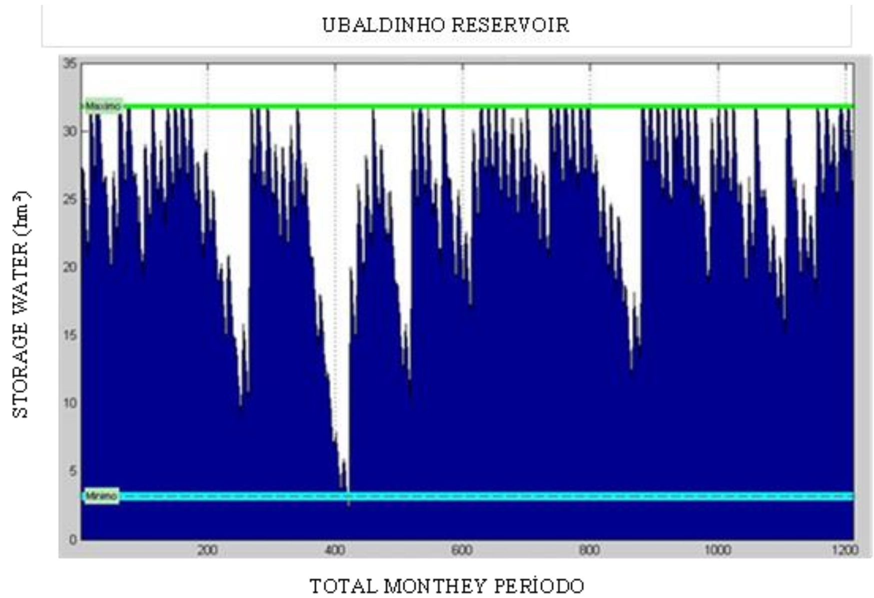

Figure 15. Ubaldinho reservoir storage volumes'behavior.

Thus, it is noteworthy that in several months the water body presents maximum volume, with oscillations and a short period in volume below the minimum, with rapid volume recovery.In this sense, it is worth pointing out that there was a great efficiency regarding the use of the reservoir's hydric availability, which confirms what was exposed in terms of performance indicators (Table 2).

Starting for the presentation and analysis of the results referring to the volume spilled in the Ubaldinho reservoir, the behavior obtained in the simulation for this reservoir is shown in Figure 16.

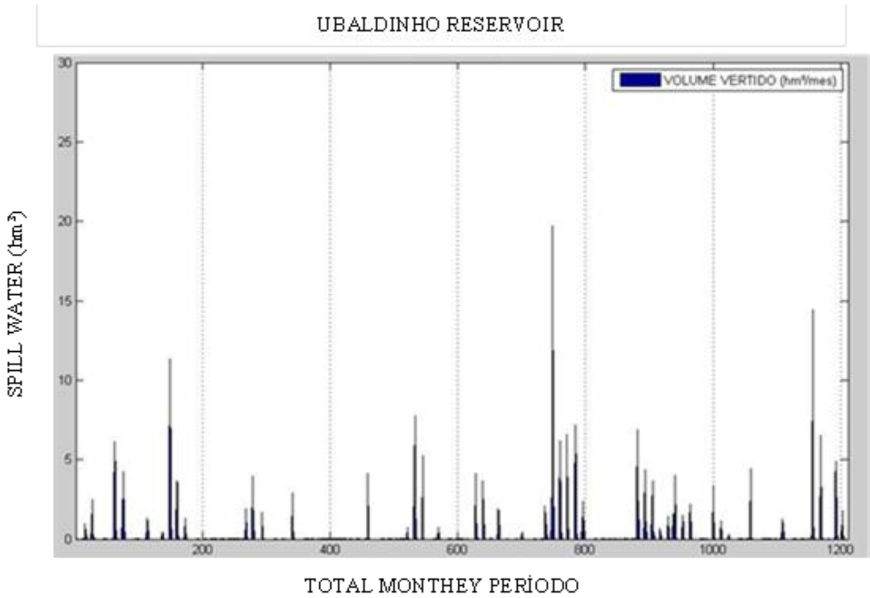

Figure 16. Ubaldinho reservoir spillages'behavior.

Observing Figure 16, it is clear to see that, due to the several moments in which the Ubaldinho reservoir reached its maximum capacity, in several analysis periods, significant rainfall representation occurred, with 3 occurrences above 10 hm³. For this reason, when extrapolating its maximum capacity, there were losses by spilling. Still on this issue, Vieira (2011) points out that spillover losses occur mainly due to factors such as: uncontrolled and controlled inflows of the reservoir. Thus, the water lost by spilling follows a downstream course, being drained into the São Miguel creek.

Concluding the analysis of the quantitative parameters for the Ubaldinho weir, Figure 17 shows the withdrawal volumes for the total demands met, considering the simulation results performed in this research.

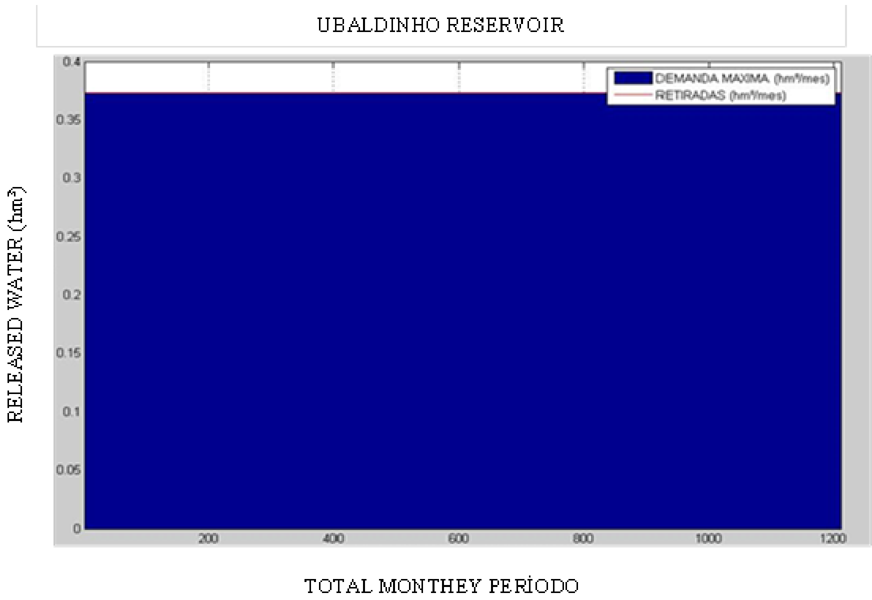

Figure 17. Lima Campos reservoir total released flows.

As presented in Figure 17, the total demands were totally satisfied in all the simulated 1212 months, even in periods of greater scarcity. One of the factors that may be associated with this behavior is due to the smaller volume of water applied in the irrigation of seasonal and perennial crops (50%), when compared to Lima Campos reservoir, which has a withdrawal percentage for irrigation of 93%.

Analyzing the qualitative parameters of the Ubaldinho reservoir, the results regarding Biochemical Oxygen Demand (BOD), Dissolved Oxygen (DO), Total Phosphorus (TF), Chlorophyll (CLA), Total Nitrogen (NT) and Thermotolerant Coliforms (TC) are presented and discussed below.

The behavior of the Ubaldinho reservoir, in terms of BOD, can be observed in Figure 18, below.

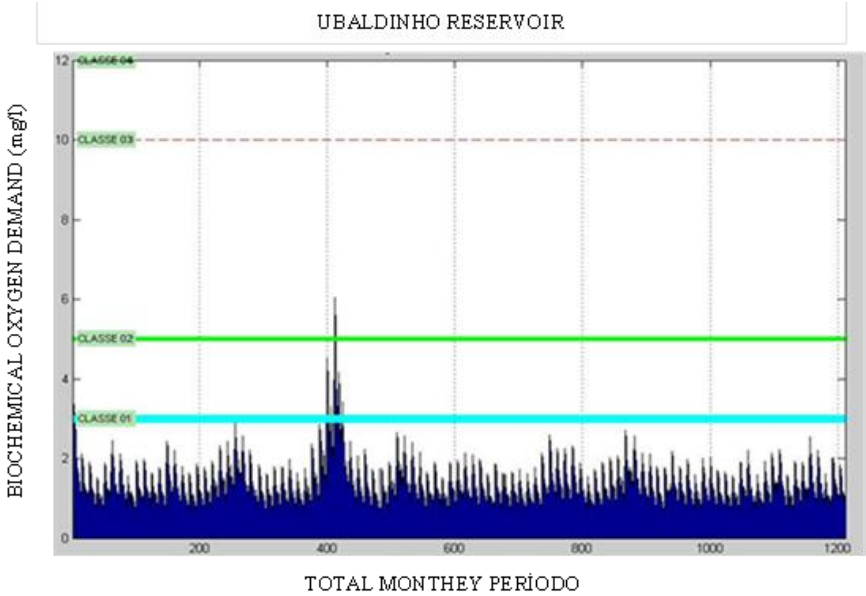

Figure 18. Ubaldinho reservoir BDO concentration.

As shown in Figure 18, the BOD reaches varied volumes, but remained almost throughout the simulated period, within the levels compatible with class 01, with variations similar to a standard, with only one peak above class 01 and class 02. Considering that this indicator determines the amount of dissolved oxygen (DO) consumed by microorganisms to decompose organic matter, it is possible to verify that this parameter is within the pre-established limit of 5 mg/l.

As BOD is directly correlated with DO (dissolved oxygen), it is possible to see from Figure 19 the behavior of this parameter.

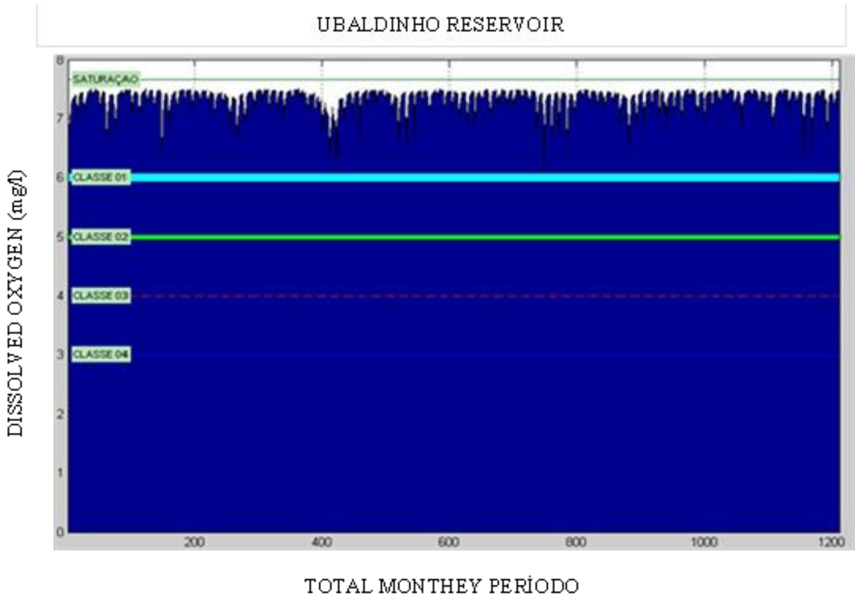

Figure 19. Ubaldinho reservoir DO concentration.

It can be seen from the analysis of Figure 19 that the hydroelectric volumes did not reach saturation of DO, however, in some points it is noted the proximity and similarity, almost as a standard, remaining within the appropriate concentrations for all classes considered, and this is correlated to the good hydric performance in relation to the volumes stored over the months, as well as the assimilated BOD. Therefore, even though there was a peak in the consumption of DO, as seen in Figure 18, the BOD did not cause a representative decrease in the levels of DO.

When analyzing the Total Phosphorus (TF) levels presented in the simulation, Figure 20 presents such results.

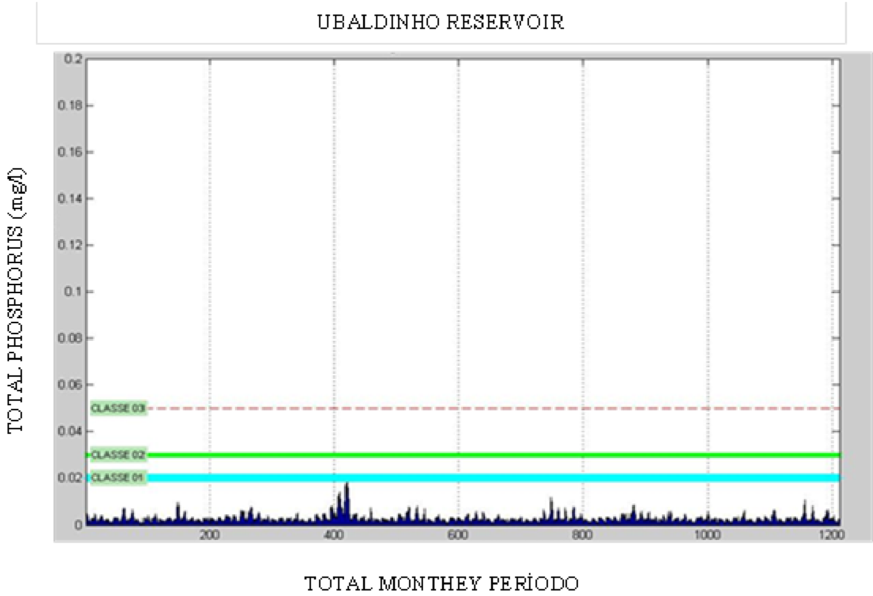

Figure 20. Ubaldinho reservoir TF concentration.

According to PNQA (2019), among main sources of phosphorus, domestic sewage stands out, which among the component substances are superphosphate detergents and fecal matter.As shown in Figure 20, which still allows to analyze that there was only one period in which the levels were more representative, being, in the vast majority of the simulated months, with acceptable levels of FT. As for the results obtained for the levels of Chlorophyll-A (CLA), these are represented by means of Figure 21.

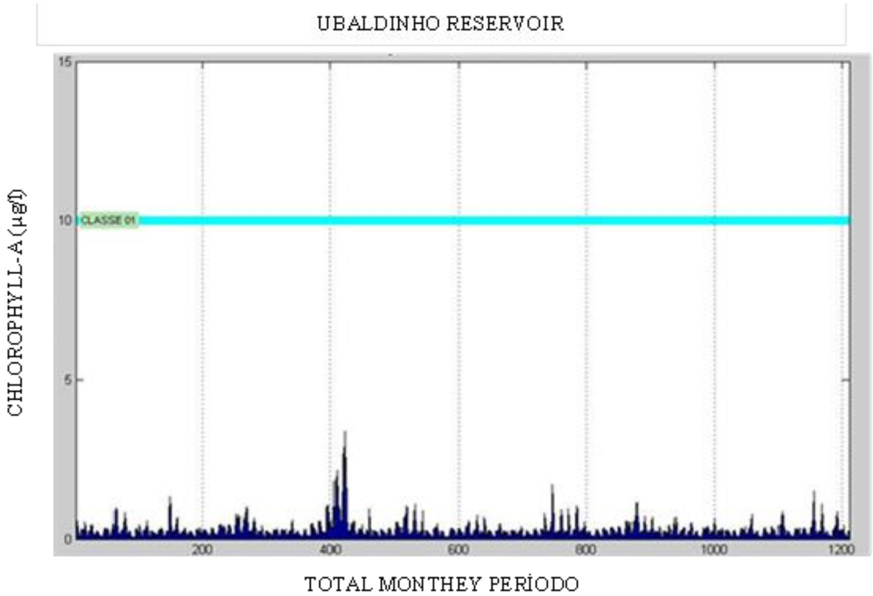

Figure 21. Ubaldinho reservoir CLA concentration.

According to Vieira (2011), the SLC is a very relevant parameter in the planning of water resources, because it is from this parameter that one has conditions to verify eutrophication in a water body. This parameter is directly linked to the concentration of FT, which presented concentration levels below the established target. Analyzing the results obtained (Figure 21), what can be concluded is that they remained well below the appropriate levels for the reference class in this research (class 01), which represents a good result in terms of water quality in the Ubaldinho weir, corresponding to what was obtained for the FT data.

Regarding the simulated behavior for the levels of Total Nitrogen (TN), the results are presented according to Figure 22.

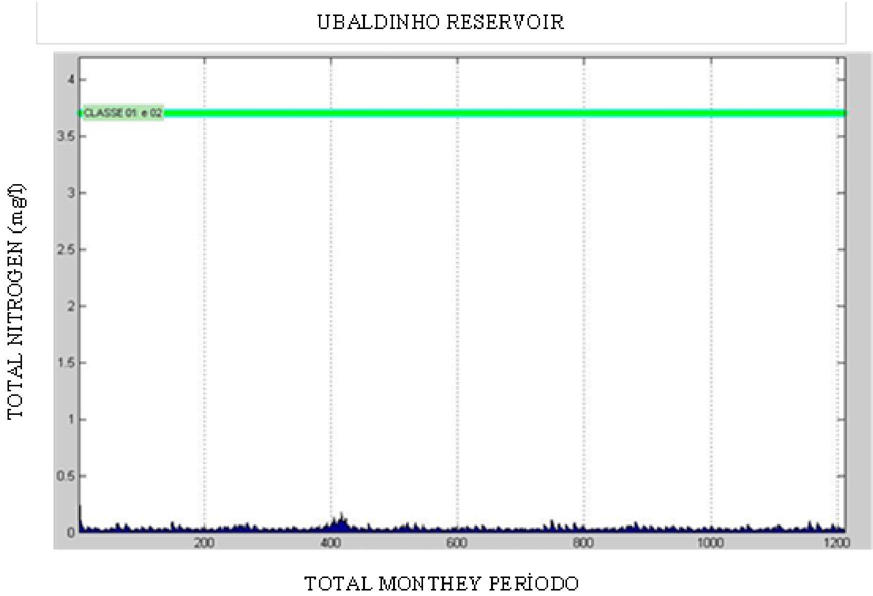

Figure 22. Ubaldinho reservoir TN concentration.

According to Gonçalves et al. (2015), the presence of total nitrogen in a body of water, in high values, hinders the development and functioning of aquatic organisms, also affecting their variety and abundance. In this sense, the results obtained for the levels of Chlorophyll-A and FT, the levels of NT showed to be at optimal levels.

The last parameter simulated in this study corresponds to the levels of thermotolerant coliforms (org/100ml), as presented in Figure 23.

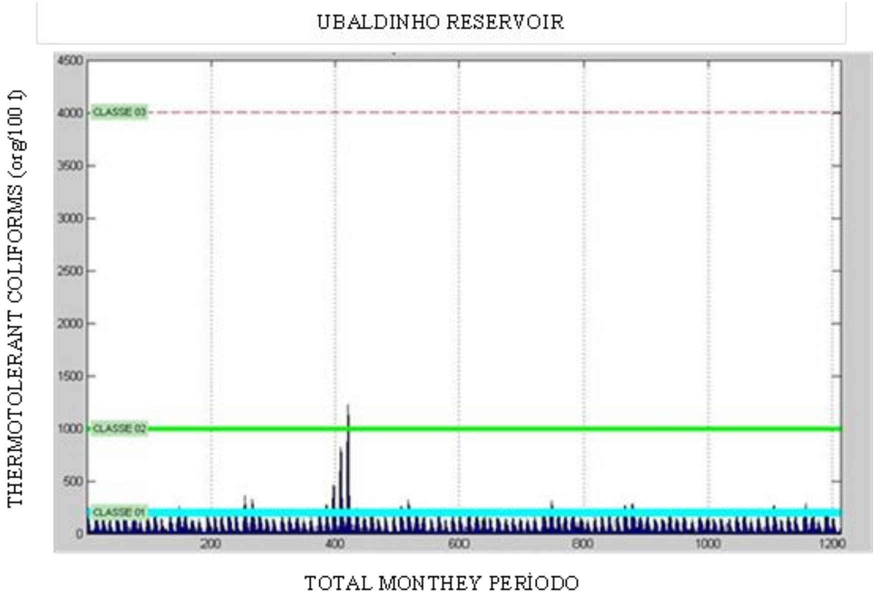

Figure 23. Ubaldinho reservoir TC concentration.

IV. CONCLUSION

The organization of this type of research, which provides the combination of simulation techniques and optimization and use of performance indicators for analyzing the behavior of water bodies, is of great value for generating alternatives in solving problems of planning of complex quali-quantitative systems of water resources, allowing the demonstration of important results that can support the decision-making process and strengthen the integrated management of water resources.

In this sense, this research presented as main purpose, to analyze the hydric behavior in meeting the hydric demands and concentrations of the system of water reservoirs located in the Salgado River located in the State of Ceará, using the simulation model proposed by Vieira (2011). The necessary data were collected from the publications of the water resources management agencies, such as ANA and COGERH- CE and applied to the model.

From what was exposed, it can be concluded that the system of reservoirs analyzed, the Lima Campos and Ubaldinho dams, have significant variations in their hydric volumes between the periods, so as not to remain at their maximum volume and at some moments reach close to the volume considered as the minimum quota for their operation. However, it is worth pointing out the differences regarding the quantitative results presented for these reservoirs, since Lima Campos, in spite of having a storage capacity (66,800,000 m^3 of water) more than double that of Ubaldinho (31,800,000 m^3 of water), presented greater periods of volume below that required, which was reflected in failures in meeting total demand, which was not observed with respect to Ubaldinho.

Regarding the qualitative parameters of the water in the reservoirs addressed in this research, the good performance of the Ubaldinho reservoir is highlighted, which presented levels of Biochemical Oxygen Demand (BOD), Dissolved Oxygen (DO), Total Phosphorus (TF), Chlorophyll (CLA), Total Nitrogen (TN) and Thermotolerant Coliforms (TC) in its majority, adequate to the acceptable concentrations for Classes 01 and 02, being directly related to the quantitative results, i.e., it is concluded that, by keeping volumes mostly within the adequate levels for operation and meeting the demands, this was reflected in the quality of the available water.

Still regarding the qualitative analyses, it is important to point out that, although located in the same hydrographical region as Ubaldinho, Lima Campos reservoir presented some inadequate results within the simulation analysis. Regarding the Biochemical Oxygen Demand (BOD), Dissolved Oxygen (DO), Total Phosphorus (TF), Chlorophyll (CLA), and Thermotolerant Coliforms (TC), they presented concentration peaks outside the acceptable limits for classes 01 and 02, and in some moments, even class 03. The parameter that presented the best results throughout the simulated period was in relation to Total Nitrogen (TN).

In conclusion, this study can serve as a parameter for the development of strategies to minimize the impacts of storage capacity oscillations, as well as to better control the meeting of demands, the search for the quality of available water, from greater monitoring of quality standards, which also reflects in the more appropriate use of water, and control of effluent disposal, thus avoiding losses of diversity of aquatic organisms, whether fauna or flora, and the minimization of possible pathologies of waterborne diseases.

With the results of this study, it is recommended that research be carried out at the site and that the responsible bodies develop methodologies for better storage and quality of the hydric resources present in the Lima Campos and Ubaldinho reservoirs.

Finally, it is emphasized that the applicability of the integrated and multiobjective model developed by Vieira (2011), is precise and versatile, minimizing mathematical simplifications, being able to offer an analysis in specific databases, which contemplate more parameters, from the quantitative ones, as an analysis of the meeting of quantitative demands in rivers in reservoirs, with the possibility of creating operation scenarios with prioritization of sectors in detriment of others, as in the simulation of other parameters of qualitative order.

In this sense, it is worth highlighting suggestions for future research, such as applying the model with other priority operation rules and analyzing other features (rivers and control points) of the hydrographic basin studied.

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