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Qualitative and Quantitative Assessment of the Alto Piranhas River Sub-basin Located in the Brazilian Semiarid Region

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ABSTRACT
The present study the application of a water resources simulation model, based on a monthly multiobjective sequential linear programming, to provide water resources analysis for the Engenheiro Ávidos and São Gonçalo reservoirs located in the Alto Piranhas river basin in the State of Paraíba, Brazil. The São Gonçalo reservoir receives loads of untreated domestic sewage from the city of Nazarezinho through the Catolé stream. Due its water use requirements, the concentration of the main water quality parameters should be classified as Class II according to CONAMA’s Brazilian law. A simulation was carried out for a span of time of 360 months. The optimized results attended all the physical and operational constraints as well as almost all the quantitative requirements, which were met with a 100% guarantee, except the irrigation of seasonal crops with water of the São Gonçalo reservoir. Regarding the water quality, the São Gonçalo reservoir initially presented excess of biochemical oxygen demand and total phosphorous and they were minimized to couple with CONAMA’s law Class II requirement. The new simulation model proved to efficiently perform integrated water quali-quantitative analysis and can be an important tool to water resource managers in possible decision-making processes.

***Keywords* -** Water resources, Simulation Model, System, Linear programming

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I. INTRODUCTION

Generally speaking, water resources simulation models are more suitable for performance analysis of long-term operational alternatives while the optimization ones are more suitable to design operation policies. There are various available water resources simulation and optimization models, using, some of them, a combination of both techniques, such as MIKE BASIN (DHI, 2001), ACQUANET (Azevedo et al., 1998), MODSIM (Labadie et al., 2004), among others. Despite being versatile, none of them can represent accurately the reality of all water systems. This is due to no consideration, in some cases, of some hydraulic components or the nonlinearities of some hydraulic processes; limitations of the applied programming technique or the representation of some necessary operational requirements, such as meeting water qualitative and quantitative goals; the use of an integrated quali-quantitative approach, and so on.

In addition, some simulation models used in several studies incorporate specific physical and operational characteristics such or widespread as the study by Yu et. al. (2020) that uses an data set we selected was fifteen water quality parameters for simulation and prediction of water quality state change of chlorophyll-a concentration in Dianchi Lake based on wavelet analysis and long-short term memory network. As well as the work of Lee et. al. (2020) they employed the Stochastic simulation for producing long-term records and assessing the impact of climate change on hydrological and climatological variables in the future and observed that traditional modeling often underestimates the variability and correlation structure of larger timescale due to the preservation of long-term memory. Therefore it is necessary that we use parsimonious simulation models and that consume the least amount of computational time possible.

To meet the required qualitative and quantative water allocation performance and of the concentrations analysis of the São Gonçalo and Engenheiro Ávidos reservoirs, which are part of the Alto Piranhas river basin, located in a semiarid region of Paraíba State, Brazil, was used integrated quali-quantitative multiobjective simulation model. This monthly based water resources simulation model, which makes use of sequential linear programming techniques to couple with the linearization of nonlinear processes through an interactive process until it reaches a desired convergence tolerance, was used to solve the water allocation problem for a span of time of 360 months. The monthly water allocation optimization problem involves meeting the required urban and agricultural water quantity supply demands, even during dry season, while keeping the concentration level of some water quality parameters at the levels established by CONAMA standards 357/2015 Brazilian law regarding to its Class II requirements.

II. MATERIALS AND METHODS

2.1 A description structure of the new simulation model

The model used to solve the problem is a monthly based water resources quali-quantitative multiple users allocation structured as a multiobjective sequential linear programing. Its variables are related to hydro-climatic aspects (precipitation and evaporation), hydraulic components characteristics, the water demands (urban supply, agricultural, between others.) and water quality parameters concentrations (biochemical oxygen demand, dissolved oxygen, total nitrogen, total phosphorus, chlorophyll-a and fecal coliforms) (Vieira, 2011).

The mass conservation laws, either the water volumes or water quality parameters concentration, are applied to reservoirs and control node points along the river. The physical behavior, as well as operational constraints for each hydraulic component, are taken into consideration. The water demand for irrigation purposes is determined by the application of water balance equation in the soil according to climate, type and requirement of each culture and irrigation system performance. The water quality parameters concentrations are monthly determined in an integrated manner with the available water volumes in reservoirs or flows in control points, while seeking to meet required targets of Class II water quality standards, according to CONAMA 357/05 Brazilian law.

The multi-objective function can integrate, at the same time, both the water qualitative and quantitative decision variables. This function is based on weighting its decision variables, which, given the characteristics of the problem, requires the normalization of each objective function's decision variable. The objective function weighting parameters allows one to define the system's operations priorities.

Given the nature of the main water pollutant sources that are, in general, originated from domestic city sewers and irrigation drainage flows; the developed model considers basic water quality parameters such as: the biochemical oxygen demand (DBO), total nitrogen (NT), total phosphorus (FT), dissolved oxygen (OD), chlorophyll-a (CLA) and fecal coliforms (CF). To estimate the water quality parameters concentration in reservoirs and river control points, the required mass balance and hydraulic components self-depuration processes, described by Streeter-Phelphs equations (Von Sperling, 1996), were considered. The model's solution mechanism starts carrying out a quantitative simulation (which is based on a sequential linear programming) to determine optimum hydraulic components monthly volumes and flows, which will be used to determine the initial water quality parameters concentrations at required water system points and to carry out an integrated quali-quantitative simulation.

To analyze the water system performance under study, indexes, such as reliability, resilience and vulnerability of the fulfillment of water quali-quantative multi-users demand requirements were included in the simulation model. Moreover, the model allows one to visualize, through charts, the water quali-quantitative behavior on reservoirs, control points and withdrawals points.

2.2 Study Area

The water resources study area, the Upper Piranhas sub-basin, is the most upstream one of seven sub-basins of the Piranhas-Açu river basin, which is located at the western end of Paraíba state, in Brazil. The Engenheiro Avidos and São Gonçalo reservoirs (Figure 1), with capacities of 255 hm3 and 44.6 hm3, respectively, are located within this sub-basin. The São Gonçalo irrigated perimeter has a potential irrigation area of 2500 ha, while the water supply to the city of Cajazeiras comes from the Engenheiro Avidos reservoir. The region monthly average temperature is 26.6°C, the average total annual evaporation reaches 3000 mm and the average annual precipitation is 800 mm (PERH/PB, 2007).

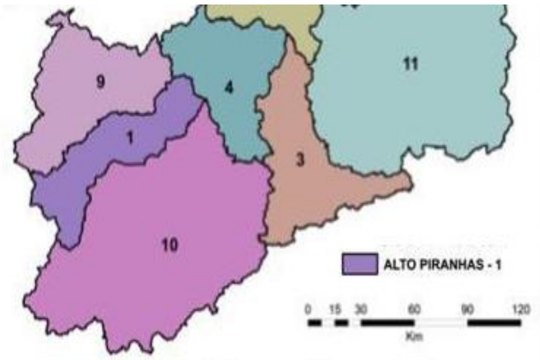
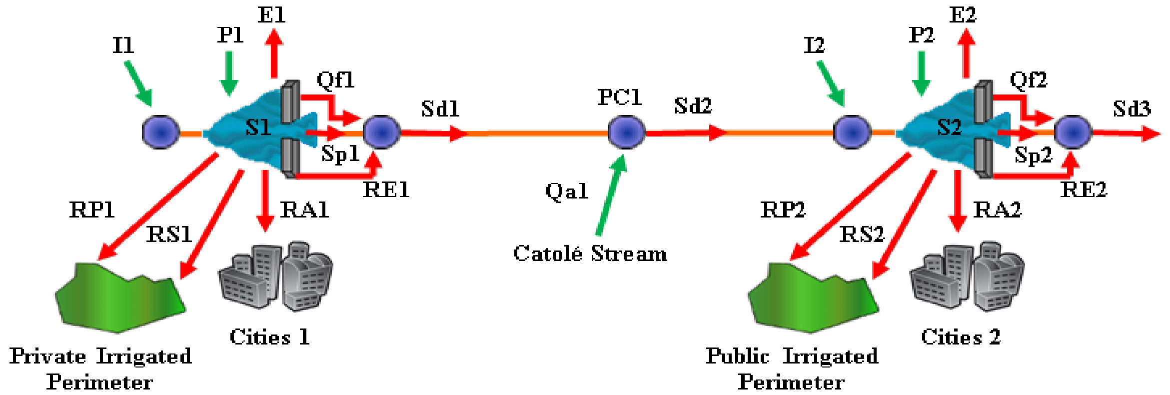


Fig 1. Studied water resources system (Source: ANA, 2016).

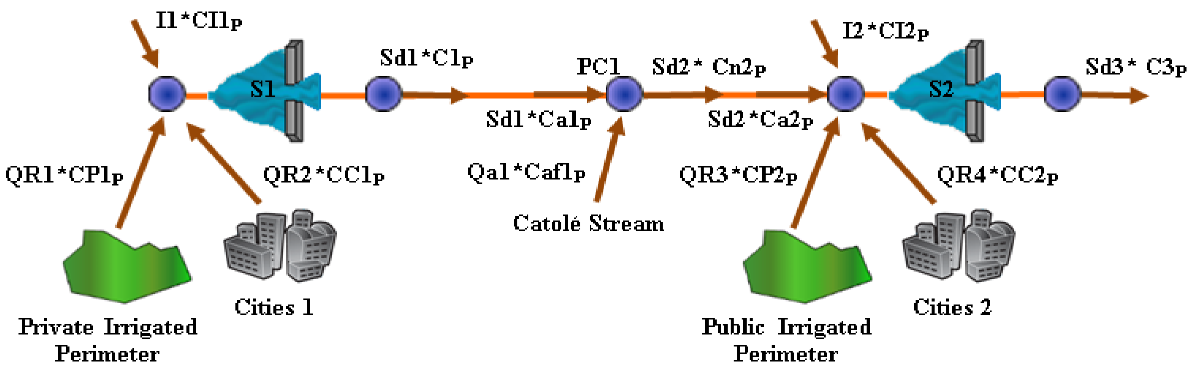
2.3 Data and variables of the system

The data of the subsystem presented in Figure 02, such as precipitation, evaporation, stream flows, reservoirs physical characteristics, water demands estimation and initial conditions were collected from the Piancó-Piranhas-Açu Water Resources Master Plan (ANA, 2016) and from Paraíba Water Resources State Plan (AESA, 2007) and HIDROWEB software (ANA,2014) websites. Water quality components self-depuration decay and aeration coefficients were adjusted according to some attained data, the average flow regimen and temperature were attained from specialized books, such as the Von Sperling (1996) and Tucci (2005). Water quality parameters concentrations for Class II standards were obtained from CONAMA 375/05 Brazilian law. The return flows from cities and irrigated perimeters were estimated via application of methodologies for return flow presented by Von Sperling (1996) and the rational method, respectively.

To better understand the new simulation model, a sketch of the water resources system, presented in Figure 2, was made to identify its main components and their decision variables to, latter, assign values to components parameters as well as assign priority levels to each objective.



(a)



(b)

Fig. 2. Serial reservoir system layout: (a) Quantitative variables; (b) Qualitative variables

The Figure 2 captions, related to the variables, are: S- reservoir; PC node or control point; RA - water supply flow; RP - perennial crops irrigation water flow; RS - seasonal crops irrigation water flow; RE - river flow to meet the aquatic ecosystems requirements; Sd - reservoir or control points outflow; Qf - discharger monthly released water flow; Sp - reservoir spilled water flow; I - reservoir inflows from tributaries; P - precipitation in the reservoirs; E - evaporation in reservoirs; CI - concentration of a given water quality parameter P of an inflow; C - concentration of a given water quality parameter P in reservoir and its outflow; Ca - concentration of a given water quality parameter P of a reservoir outflow that reaches control point PC1 or the outflow of control point PC1 that reaches a reservoir; Cn - is the concentration of water quality parameter P in control point PC1; QR - return flow (effluents) that reaches a reservoir or control point; CP or CC - is the concentration of a given water quality parameter P of the return flow; and Caf - is the concentration of a given water quality parameter P of a inflow that reaches control point PC1.

2.3 Ideal operating rule

A 360 months timespan was used in this water resources system simulation. The priorities are related to meeting the urban supply and irrigation water demand requirements. Moreover, according to local news, is known that the untreated domestic sewage from the city of Nazarezinho, which is rich in DBO and FT, is thrown into the Catolé creek, whose end is the Piranhas river, at control point PC1, upstream and near the São Gonçalo reservoir. To fulfill the water quality parameters standards for CONAMA’s Class II classification, priorities were also assigned to fulfill the requirements for DBO and FT in the São Gonçalo reservoir and in control point PC1. In the Table 01 presents the priority levels of each decision variable considered in the model. Urban water supply, ecological river flow, biochemical oxygen demand, dissolved oxygen, total phosphorus and reservoir minimum storage volume and target volume have the first priority. Irrigation of perennial and seasonal crops have second priority and third priority respectively. The water that is left in the system comes with the installation of Effluent treatment station (ETE) will be distributed proportionally and flexible to meet the other objectives that have not been assigned any priority. Vieira (2011) analyzed that the ideal operating rule for the studied sub-basin follows the established priority levels proposed in Table 1 below.

Table 1. Water resources system objectives priorities.

Objectives	**Priorities**		
	S1*	**PC1****	**S2*****
Urban supply	1º	-	1º
Perennial crops irrigatioin	2º	-	2º
Seasonal crops irrigation	3º	-	3º
Ecological river flow (acquatic ecosystems)	1º	-	1º
Biochemical Oxigen Demand (DBO)	1º	1º	1º
Dissolved Oxigen (OD)	1º	1º	1º
Total Nitrogen (NT)	-	-	-
Total phosphorus (FT)	1º	1º	1º
Chlorofyl-a (CLA)	-	-	-
Thermotolerant Coliforms (CF)	-	-	-
Minimum reservoir volume	1º	-	1º
Reservoir target volume	1º	-	1º
Reservoir discharge	-	-	-
Reservoir spillage	1º	-	1º

Note: * Engenheiro Ávidos Reservoir; ** Control Point; ***São Gonçalo Reservoir

It is important to note that the city Nazareth launches its domestic sewage into the Catolé creek, which is 3 km upstream far from the São Gonçalo reservoir. So, this scenario considered the installation of a wastewater treatment station (ETE), as a stabilization pond type, with 85% efficiency, targeting the removal of part of DBO, FT and CLA. The maximum monthly urban water supply demands were estimated. With respect to irrigation demands, it was considered the cultivation of regions cultures, such as, coconut, mango, guava, papaya, lemon, watermelon, melon and tomatoes, and the soil water balance was monthly performed by the model.

Different sizes of the irrigated area were considered for the reservoirs: for the Engenheiro Avidos reservoir was used an area of approximately 70 ha, being 50% of it destined to perennial crops and 50% for seasonal crops, and for the São Gonçalo reservoir was used an irrigable area suggested by Farias (2004), that is, approximately 1100 ha, being 50% of the area destined to perennial crops and 50% for seasonal crops. The irrigation system considered for all cultures is of drip type with a distribution system efficiency of 92% and irrigation application efficiency of 90%. The flow for the maintenance of aquatic ecosystems was considered to be 10% of the maximum river regulated flow, which is used as parameter for stablishing water rights.

III. RESULTS AND DISCUSSION

The results of the qualitative and quantitative simulation are presented in the following sequence of the studied system components: Engenheiro Avidos reservoir -S1, control point -PC1 and São Gonçalo-S2 reservoir, and, finally, an integrated analysis is also performed.

3.1 Engenheiro Avidos Reservoir – S1

In Figure 3 can be observed that all operational constraints for the Engenheiro Avidos reservoir were met, including the target volume. The Figure 4 shows that there were months with reservoir spillages, due to rainy months and the arrival of large tributaries flows.

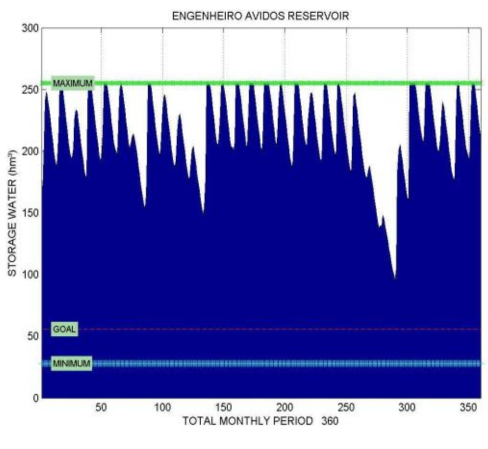


Fig. 3. Engenheiro Avidos reservoir storage volumes'behavior.

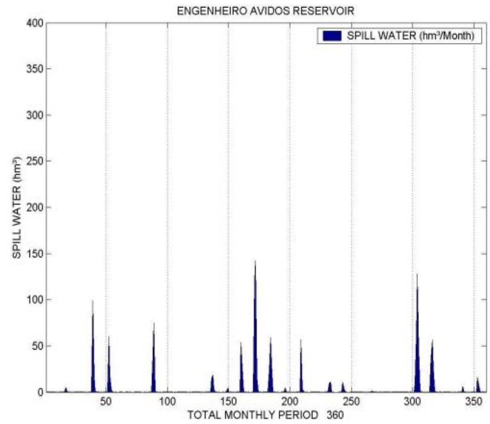


Fig. 4. Engenheiro Avidos reservoir spillages'behavior.

The flow rate released by the Engenheiro Avidos reservoir bottom discharge, despite not having any operational priority in the objective function, obeyed the integrated system operation requirements, as well as, the restriction of its maximum monthly discharge, which was limited by its hydraulic quota each month t, as showing in Figure 5. Water demands for supplies were all met, as shown in Figure 6.

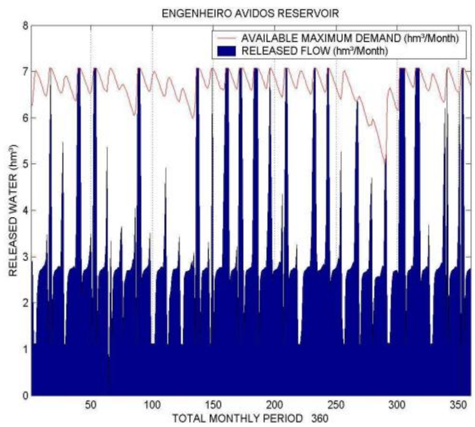


Fig. 5. Engenheiro Avidos reservoir released flows.

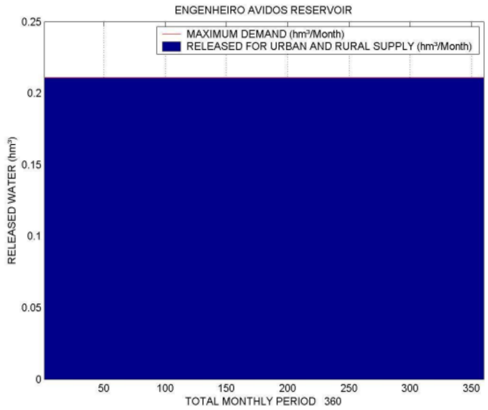


Fig. 6. Engenheiro Avidos reservoir urban supply withdraws.

In the Figure 7 shows the fulfillment of the need for ecological flow of the river released downstream from the Engenheiro Avido reservoir.

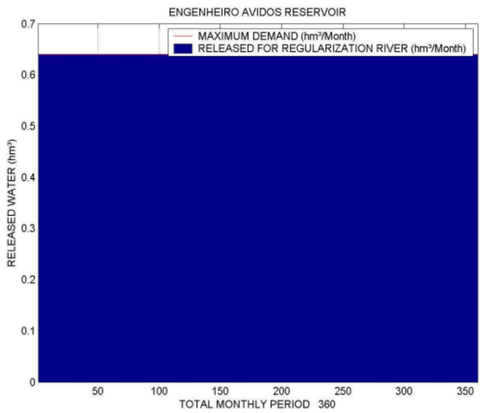


Fig. 7. Engenheiro Avidos reservoir ecological flow realeases.

The demands for irrigation of perennial and seasonal crops were fulfilled in every month, as can be seen in Figures 8 and 9, respectively.

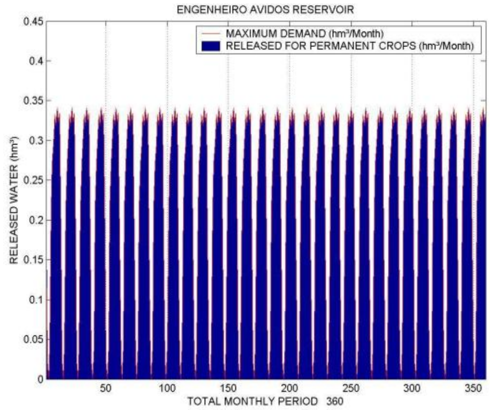


Fig. 8. Engenheiro Avidos reservoir flows withdraws for perennial crops irrigation.

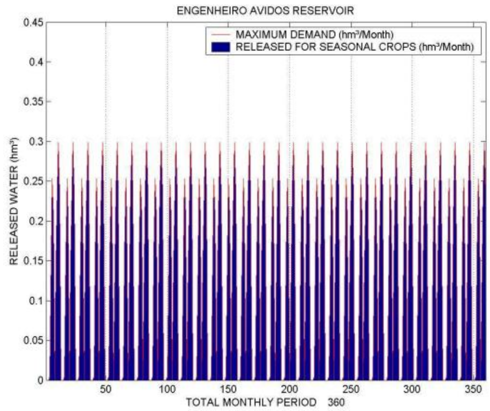


Fig. 9. Engenheiro Avidos reservoir flows withdraws for seasonal crops irrigation.

The Table 2 table shows the performance indicators of Engenheiro Avidos reservoir water demands, which were completely satisfied (sustainability of 100%).

Table 2. Performance indexes for the Engenheiro Avidos reservoir water demands.

Engenheiro Ávidos Reservoir				
Performance indicators	Urban water supply hm³/mês	PerennialCrops Irrigation hm³/mês	Seasonal Crops Irrigation hm³/mês	Ecological River flow hm³/mês
Number of failures	0	0	0	0
Number of times recovering from failures	0	0	0	0
Reliability (%)	100	100	100	100
Resilience (%)	100	100	100	100
Vulnerability (%)	0	0	0	0
Sustainability (%)	100	100	100	100

With respect to water quality almost all parameters met the requirement for Class I of CONAMA. Figure 10 shows that the biochemical oxygen demand (DBO) in the Engenheiro Avidos reservoir met the requirement of stated by CONAMA's law for waters of Class II, which is being less than 5mg/l. Already the Figure 11 shows that the concentration levels of oxygen dissolved (OD) were also satisfactory, also being classified in Class I.

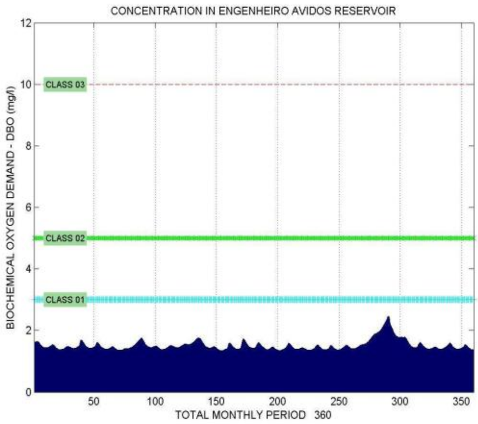


Fig. 10. Engenheiro Avidos reservoir DBO concentration.

It is important to remember that the DBO is directly related with OD, in other words the smaller the amount of matter in the larger reservoir is the oxygen dissolved quantity.

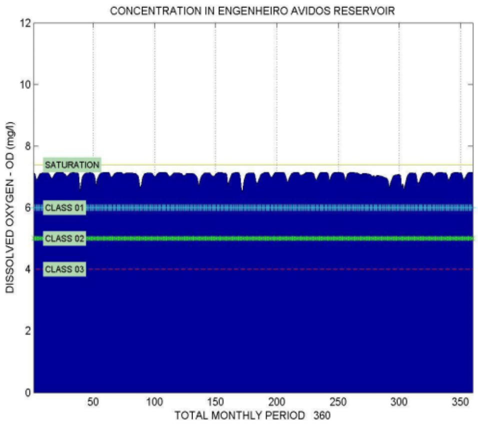


Fig. 11. Engenheiro Avidos reservoir OD concentration.

Figure 12 shows that total nitrogen (NT) concentrations levels over time are also in accordance with the Class II goal. For the parameter total phosphor (FT), Figure 13 shows that concentration levels were also satisfactory.

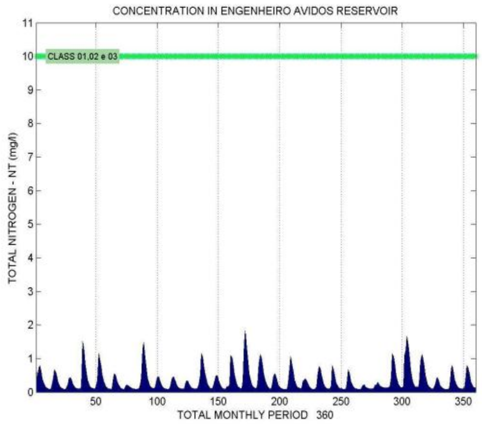


Fig. 12. Engenheiro Avidos reservoir NT concentration.

Both the total phosphorus and total nitrogen are parameters of water quality that indicate the presence of algae in the water, case present above the acceptable levels the manancia enters a process called eutrophication.

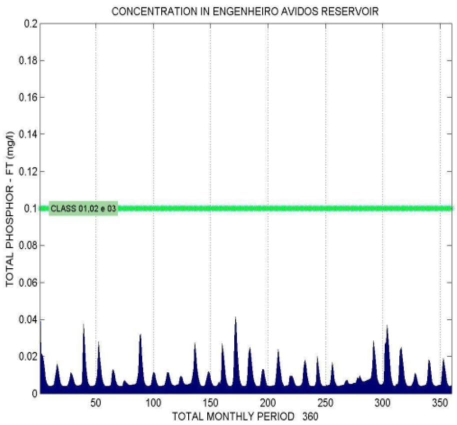


Fig. 13. Engenheiro Avidos reservoir FT concentration.

Figure 14 shows the behavior of the CLA concentrations over time and are in satisfactory condition. The CF, as shown in Figure 15, is the only one that did not meet Class I CONAMA's water quality standards, although it complies with the requirement of Class II.

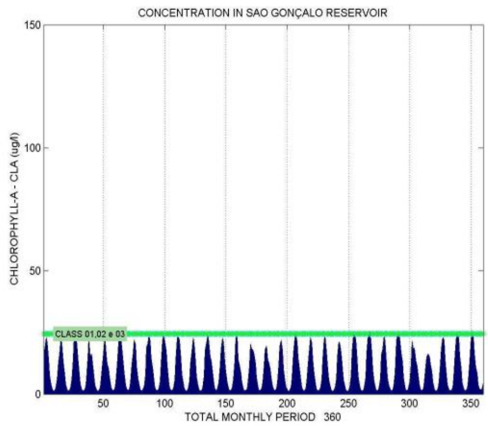


Fig. 14. Engenheiro Avidos reservoir CLA concentration.

The parameter of thermotolerant coliform allows visualize the biological contamination level of a particular source and is directly linked to public health.

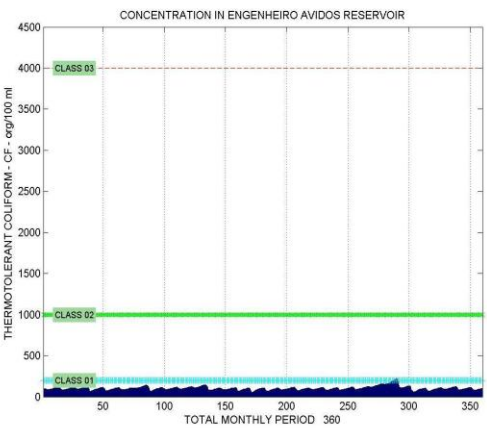


Fig. 15. Engenheiro Avidos reservoir CF concentration.

3.2 Control Point - PC1

The water quality parameter in the control point PC1 depends on their concentrations, after self-depuration in reach 1, of the flows released by Engenheiro Avidos reservoir, the flows of Catolé creek and the ones from Nazarezinho city. Figure 16 shows the Catolé creek flows that reaches control point PC1. The behavior of the flow in reach 1 and flow behavior in reach 2 feature Large peak flows according to the results obtained and analyzed in the simulation model used.

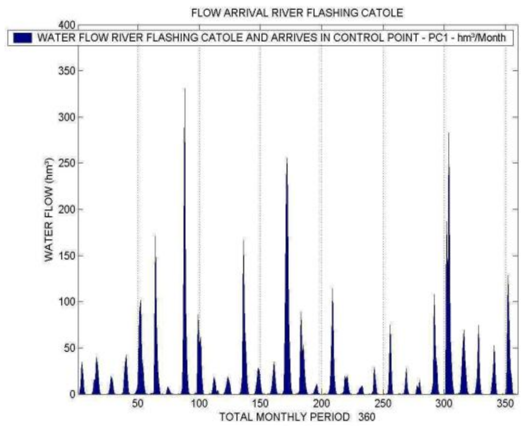
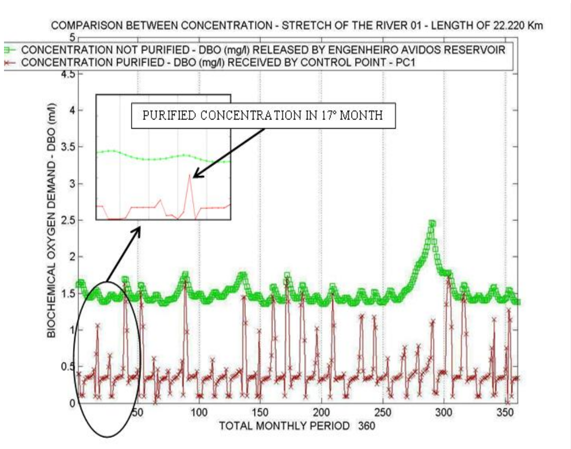


Fig. 16. Catolé creek flows towards control point PC1.

Figure 17(a) shows the process of self-depuration the concentration of DBO in reach 1. The expansion of the Figure 17(a) giving emphasis to the 17th month shows that there has been a small reduction in the magnitude of self-depuration when compared with the ones of other periods. Mathematically this is explained by the equation that describe the self-depuration in rivers, which is an exponential function and have as independent variables the ratio between the geometry of the river section and its flow. In the Figure 17(b) shows that the levels of BOD concentrations were all minimized to couple with CONAMA's class II requirements. Figure 17(c) shows the self-depuration behavior of the DBO concentrations released by the control point PC1, through reach 2, until the flows reach the São Gonçalo reservoir.



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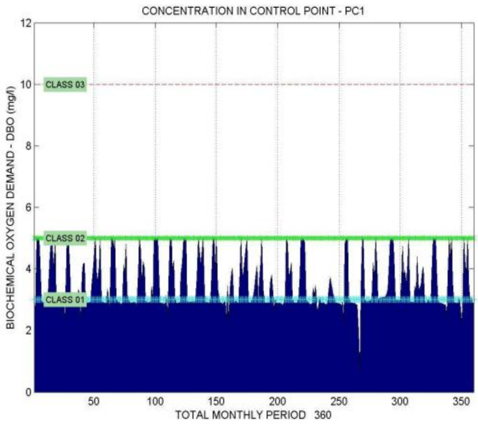

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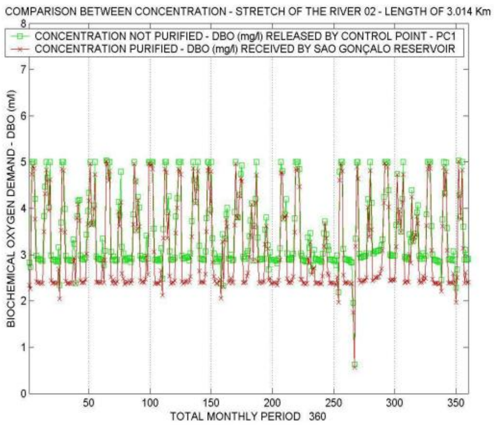
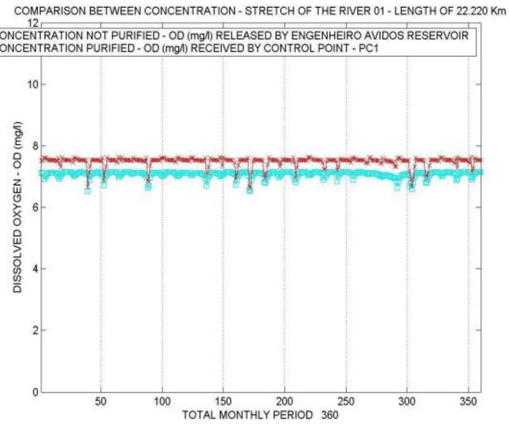


(c)

Fig. 17. Biochemical oxygen demand (DBO) concentration behavior: (a) in reach 1; (b) in control point - PC1; and (c) in reach 2.

Analyzing the OD concentration behavior on reach 1, shown in Figure 18(a), a significant aeration took place along it on the flow rates released by Engenheiro Avidos reservoir. Figure 18(b) shows the behavior of the OD concentration in control point PC1. Figure 18(c) shows that the levels of concentrations of OD in reach 02 had little improvements, probably due to the small rate of DBO concentration self-depuration and its large flows.



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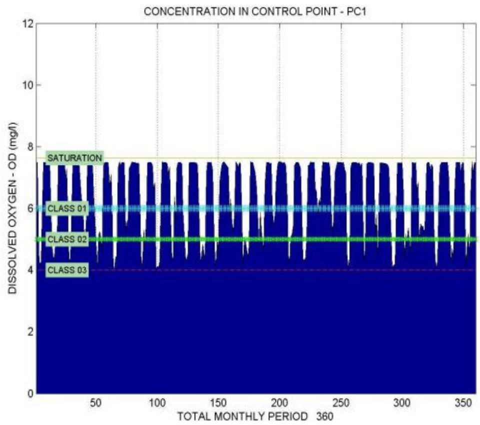

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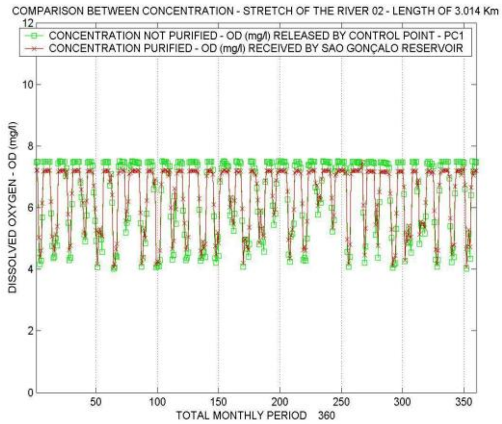


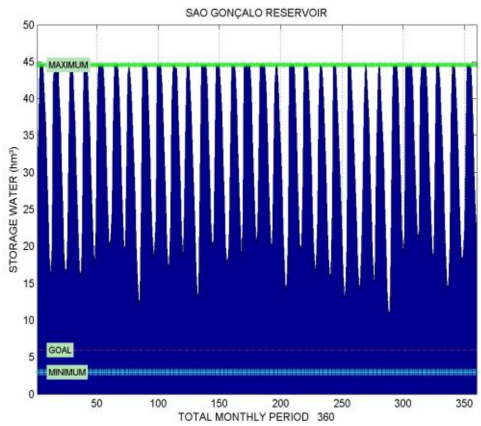
(c)

Fig. 18. Oxygen dissolved (OD) concentration behavior: (a) in reach 1; (b) in control point - PC1; and (c) in reach 2.

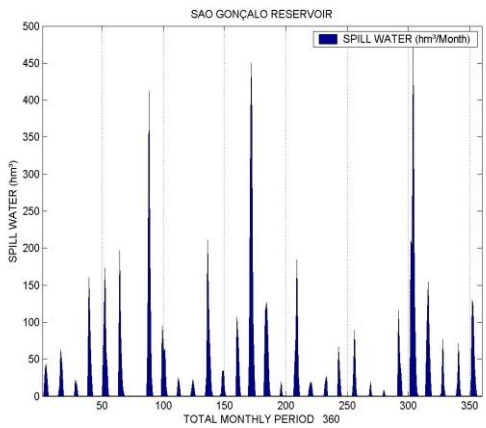
Analyzing other quality parameter was observed that all of them showed to be within the required limits for CONAMA's Class II, indicating that the river in this section isn't polluted.

3.3 São Gonçalo Reservoir-S2

The behavior of the volume stored in the São Gonçalo reservoir presented a great variability, including great amount of spillage besides being minimized by the model, characteristic of dams of small and medium sizes geometries, as can be observed in Figure 19. The target volume constraint was satisfied.



(a)



(b)

Fig. 19. São Gonçalo reservoir volumes'behavior: (a) Storage' water; (b) Spillages' water.

The São Gonçalo reservoir water discharge, shown in Figure 20, satisfied its constraint of maximum discharge.

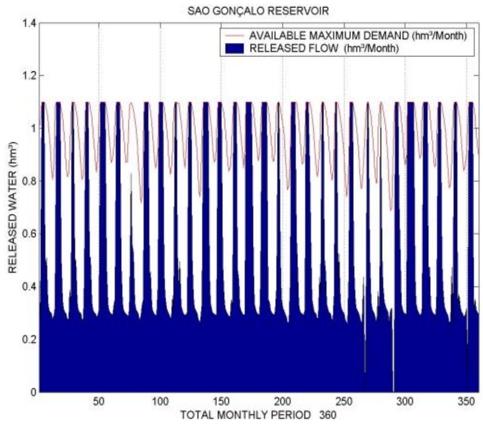


Fig. 20. São Gonçalo reservoir released flows.

Urban and Rural supply water demands were all satisfied, even in dry months, as shown in Figure 21.

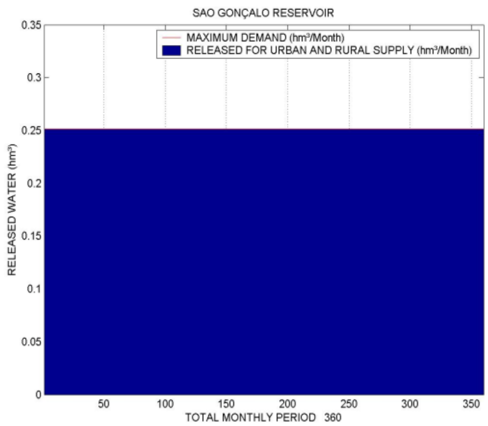


Fig. 21. São Gonçalo reservoir urban and rural supply withdraws.

Water requirements for downstream aquatic ecosystems were met, as can be seen in Figure 22.

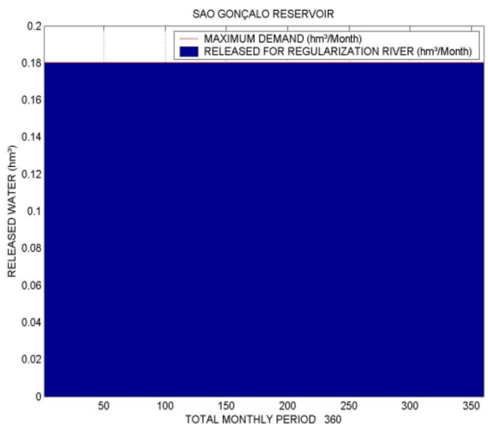
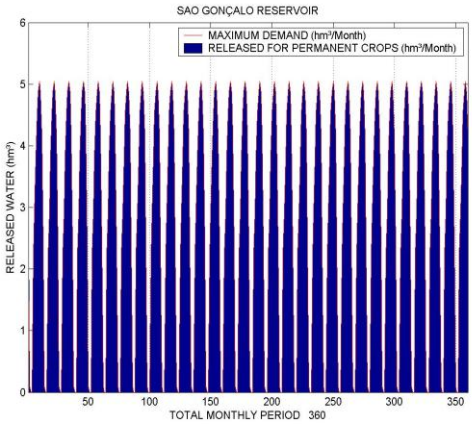


Fig. 22. São Gonçalo reservoir ecological flow realeases.

Figure 23(a) shows that the requirements for the irrigation to perennial crops were also met. No failures have occurred for these demands, even in months in the reservoir received small tributaries flow rates. On the other hand, the demand for the irrigation of seasonal crops, which has smaller priority, were not, as shown in Figure 23(b).



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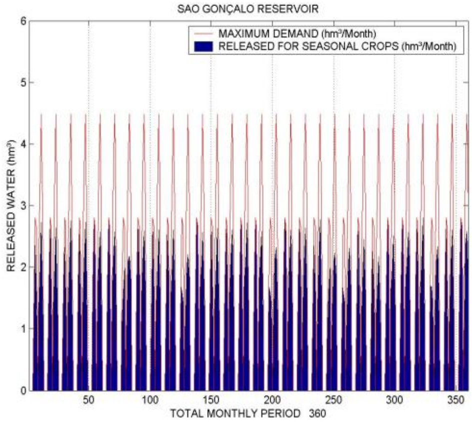

(b)

Fig. 23. São Gonçalo reservoir flows withdraws for irrigation: (a) Perennial crops; (b) Seasonal crops.

Table 03 shows the performance indexes for the São Gonçalo reservoir water demands. Except for the irrigation of seasonal crops, all water demands were met. Regarding to the irrigation of seasonal crops, 60,35% of its requirement were met, being in failure state for an average of 3 months, which ended up in a low sustainability index performance. Moreover, by failing to comply with the seasonal crops requirement, the perennial crops requirements were fully met, otherwise would be risk to lose them and having to wait more than three year to start producing again.

Table 3. Performance indexes for the São Gonçalo reservoir water demands.

São Gonçalo Reservoir				
Performance indicators	Urban water supply hm³/mês	PerennialCrops Irrigation hm³/mês	Seasonal Crops Irrigation hm³/mês	Ecological River flow hm³/mês
Number of failures	0	0	160	0
Number of times recovering from failures	0	0	53	0
Reliability (%)	100	100	55,56	100
Resilience (%)	100	100	33,13	100
Vulnerability (%)	0	0	39,65	0
Sustainability (%)	100	100	11,11	100

With respect to the water quality parameters concentration in the São Gonçalo reservoir, Figure 24 represent the behavior of DBO, OD, NT, FT, CLA and CF concentrations, respectively. Meeting CONAMA's Class II requirements were included in the objective function and all the studied water quality parameters concentrations met the required concentration levels. Its worth to point out that most of them met CONAMA's Class I requirement, except the DBO concentration. Moreover, there were months that FT and CLA reached near their limit levels due the hydric scarcity period.

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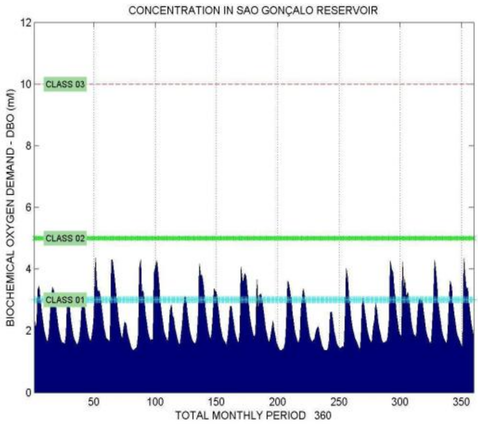
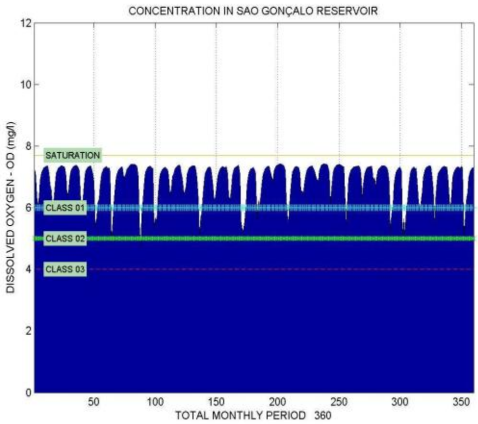
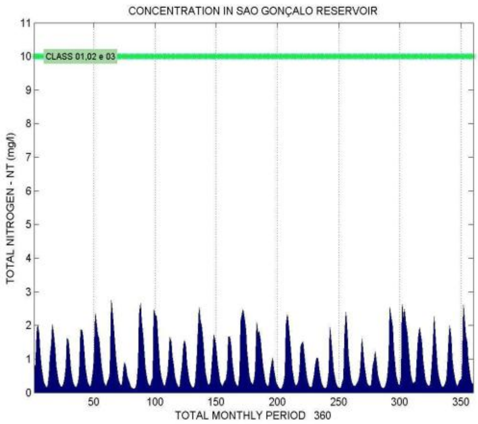


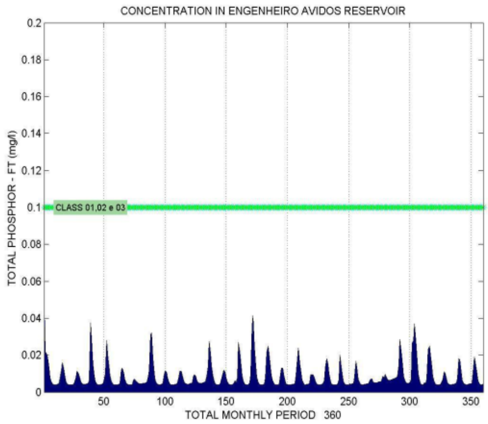
(a)



(b)

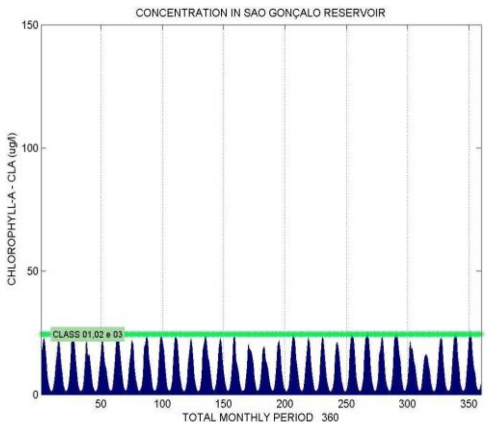


(c)

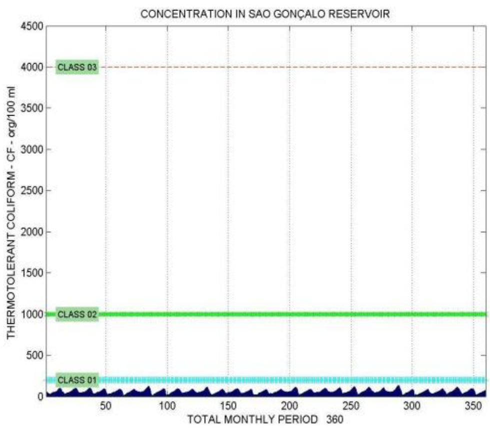


(d)

Fig. 24. São Gonçalo reservoir flows withdraws for irrigation: (a) Perennial crops; (b) Seasonal crops.



(e)



(f)

Fig. 24. Concentrations behavior in São Gonçalo reservoir: (a) Biochemical Oxigen Demand (DBO); (b) Dissolved Oxigen (OD); (c) Total Nitrogen (NT); (d) Total phosphorus (FT); (e) Chlorofyl-a (CLA); and (f) Thermotolerant Coliforms (CF).

3.4 Integrated Analysis

Analyzing the water resources system in an integrated manner, under the quantitative aspect it was observed that there is a major contribution from the Engenheiro Avidos reservoir to the control point PC1 to the meet the system requirements, either related to quantitative or qualitative variables. When water from the reservoirs are released from their bottom discharger, the goal, most times, is to satisfy the water demands requirements or levels of downstream water quality parameters concentrations, which have greater priorities. Regarding to the water qualitative aspects, it was observed that the control point PC1 may present problems of pollution with relation to the DBO, FT and CLA and low levels of OD water quality concentration due to Nazareth city untreated sewer flows. Herein it was considered a certain level of sewer treatment and, although the water quality parameters were set to be optimized, they only met CONAMA’s Class II required level of water quality. Other water quality parameters in reservoirs and control point met the established goals.

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IV. CONCLUSION

Most simulation models available in the literature, although most of them are fairly versatile, presents a wide range of limitations, whether being with respect to the representation of a water resource system, the used mathematical approach (to describe its components, as well to computationally solve the problem), the simplified treatments of non-linearities, or the lack of the inclusion of some variables or procedures related to hydraulic components or water use. Other aspects to be considered are related to the search of operational goals through a multiobjective optimization. Within this context, to try to fill some of these gaps, was designed, developed and tested an integrated new multi-use, quali-quantitative water resources multiobjective simulation model to support the planning and management of water resources systems.

Regarding to FT and BOD concentration levels for the São Gonçalo reservoir and control point PC1 they have all been minimized and met CONAMA’s Class II water quality levels. To achieve this goal for the FT and the BOD levels, a certain amount of water quantity had to be kept in the reservoirs, which directly affected the water allocation to seasonal crops irrigation. It is important to remember that irrigation demands possess lower priority than ones of the concentration levels of the FT.

It is believed that the new simulation model used in this work reached its proposed goals and may provide less intuitive, more rational and efficient water uses allocation. So this could be an invaluable tool in water resources decision support, since it is able to provide an integrated planning tool, which was applied to a sub-basin that contains the Engenheiro Avidos and São Gonçalo reservoirs and may be applied to other river basin systems. It is a quali-quantitative tool sought by many managers in their water resources decision processes.

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