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## **Elaboration of water distribution schedules in periods of scarcity**

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**Abstract:** Scarcity of treated water is a global problem that directly impacts the quality of life and, therefore, brings to light the need for more careful management of water resources in locations that are affected. Although there is a vast literature on the problem of design and operation of treated water distribution networks, few studies consider the issue of scarcity. In the present paper, we carry out a study on the real water distribution problem of a city located in Northeastern Brazil. In this study, we conceptually and mathematically model the problem addressed as a new specific water distribution optimisation problem, and implement the model developed using LINGO software from LINDO systems. We conclude the study showing that the developed solver is a practical, effective and efficient tool, which can be easily used by a suitably qualified employee.

**Keywords:** mathematical modelling; water distribution schedules; water distribution system; WDS; water scarcity; LINGO.

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**Biographical notes:**

This paper is a revised and expanded version of a paper entitled [title] presented at [name, location and date of conference].

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## 1 Introduction

Water scarcity is a global problem that has been growing over the years due to factors such as population growth, climate variations and living standards (Huang et al., 2021). Specifically in Brazil, in semi-arid regions (such as some regions of Northeast Brazil), this problem is aggravated due to the high variability of rainfall, with rainfall concentrated over time and little spatial distribution (Silva et al., 2019). Such aggravation ends up generating conflicts for the use of water resources, and water distribution becomes a priority concern for public management.

Several scientific studies address the water distribution problem, including the design, calibration, simulation, operation and control of water distribution systems (WDSs). According to Sankar et al. (2015), when it comes to distribution operation and control, the main objectives considered are: minimising the cost of energy required for pumping; regulating pressures for preventing/reducing leakages; and maximising the quality of water supplied to the users by reducing the residence time of water in the network. Few studies have sought to consider the issue of water scarcity. In this scenario, the problem of water distribution is usually restricted to the operation/control of an intermittent WDS with storage facilities. According to Sankar et al. (2015), in the case of water deficient situations it is not possible to meet the demand, so it is also necessary to identify the optimal outflow from demand nodes and it becomes important that the control strategy allocates water so as to minimise the shortfall in supply, and supplies the available water in as equitable a manner as possible. Based on that purpose, the authors present a nonlinear model predictive control (NMPC) technique that determines the optimal control valve settings, and so the optimal outflow rates from demand nodes. Creaco et al. (2019) present an extensive literature review for real-time control of water distribution networks. As explained by the authors, a real-time control system periodically reports corrective actions to the distribution system, based on the measured values of the control variables. These corrective actions can be:

- a discrete actions, such as turning a pump on or off, or fully opening or closing a valve
- b continuous adjustments to the valve closing setting or pump speed.

However, the real-time control of a water distribution network requires implementation of hardware elements in the network, such as various types of sensors and actuators, controllers, and data transmission systems. Usually, in Brazil, the problem of water deficiency is solved with the adoption of distribution schedules and not through dynamic system adjustment. In this context, Kurian et al. (2018) present a mathematical model and a three step decomposition approach to solve the valves and pumps ON/OFF operation problem. The model proposed by the authors determines distribution schedules seeking to minimise energy consumption and meet demand. Luna et al. (2019) and, more recently, Jafari-Asl et al. (2021) proposed, respectively, a hybrid genetic algorithm and an enhanced binary dragonfly algorithm, coupled with the EPANET hydraulic simulation model, for optimisation of pump scheduling programs in water supply systems, also aiming to reduce energy consumption and meet demand. Both papers present an extensive literature review on pump scheduling problems and Jafari-Asl et al. (2021) compare the results found by several algorithms. In our work, we focus on the specific understudied class of water distribution problems described in detail by Kurian et al. (2018), considering, however, conceptual differences related to the definition of the problem.

As a contribution to this domain, we present a detailed description of the WDS in the City of Catende – PE (Brazil) and a new mathematical model for the problem of elaborating water distribution schedules that was specifically developed based on the studied system. The mathematical model was built in parallel to the development of a solver in LINGO. Our objective was to build a model that could be applied with this solver, generating optimal solutions quickly, in order to offer practical support to the water distribution planning of the municipality. As result, we were able to develop a new general mathematical model whose main scientific contribution is its simplicity. This model has the following features:

- a it seeks to determine the status of the valves (ON/OFF) and the ideal values for the flows
- b the aim of the problem is to achieve a distribution as equitable as possible
- c the valves are located at the entrance of reservoirs/zones served
- d parameters are incorporated into the model to define priority rules
- e complex calculations are replaced by the definition of maximum and minimum values for the flows rates
- f flexibility variables were proposed (time of availability of water per shift), which allows the ‘ideal’ planning to be performed in practice.

In the next sections we present: a detailed description of the WDS of Catende; the mathematical model developed; a summary of results of the tests performed using actual company data; a qualitative discussion about aspects of the model and the solver; a brief assessment of the limitation of the solver developed; and finally, conclusions and suggestions for future works.

## 2 Catende WDS

The City of Catende is located in the interior of Pernambuco and has a total area of 207,244 km. According to IBGE data obtained from the large Census carried out in 2010 (IBGE, 2021), the population of the City of Catende on that date was 37,820 inhabitants. Of these, 28,861 were located in the urban area. In this city, the municipality is responsible for supplying the population with treated water. The next sections present in detail the process of collecting, treating and distributing water in the City of Catende, as well as issues related to demand.

### 2.1 Water collection and treatment

The collection of water distributed in Catende is carried out in the Santa Rita and Bálsamo das Freiras weirs. The Santa Rita weir is located in the district of Roçadinho, with a maximum water storage volume of 2,500,000 m<sup>3</sup>. The Bálsamo das Freiras weir is located on the border between Catende and the Municipality of Jaqueira, with a maximum storage volume of 1,500,000 m<sup>3</sup>.

Water treatment is carried out at the Catende water treatment plant (WTP) (Figure 1) in a conventional and mechanical manner (Figure 2). The collection of water is carried out in the weirs arriving at the treatment plant by gravity. With an average flow of 67 l/s, the water from the Santa Rita reservoir goes to conventional treatment, and with a flow of 35 l/s, the water from the Bálsamo das Freiras reservoir is directed to the mechanical treatment plant.

**Figure 1** Catende WTP (see online version for colours)



After the adduction, the water captured at the Santa Rita weir, goes to the treatment phases, being received at the WTP through channels, and passing through a flow

meter called Calha Pashall. In this trough aluminium sulphate and chlorine are added (Figure 3). These two chemicals help in the coagulation step by reacting with particles that are suspended in raw water. At this stage, the water goes through shares called flocculators, where the added reagents transform the impurities into larger particles to be removed during decantation.

**Figure 2** (a) Conventional (b) Mechanical treatment plants (see online version for colours)



The water, then flocculated, goes to another phase, passing through larger layers called decanters, where the flakes formed are deposited in tubular modules similar to a beehive, making the water almost suitable for consumption. In these stages of treatment, almost all contamination factors are eliminated, filtration is then carried out to further improve the decanted water which, by gravity, passes through filters made of a porous medium with the ability to retain and remove impurities still in the water. In disinfection, physical or chemical agents are used, such as chlorine, used for the destruction of pathogenic organisms that cause diseases, ending with the correction of pH, where products are also added so that the treated water has a suitable pH for consumption. After being treated, the water is deposited in a supported type reservoir with a capacity of 500 m<sup>3</sup> of storage (central reservoir). Treatment is carried out in continuous flow.

The water collected from the Bálsamo das Freiras Reservoir is treated in mechanical filters, where the addition of chemical products is carried out automatically. The disposal of the water treated in these filters is also carried out in the central reservoir.

## 2.2 Water distribution in Catende

For the planning of water distribution, the City of Catende was divided into six zones (Figure 4).

In order to allow water resources to reach consumer units in the most distant neighbourhoods from the WTP, capacity studies were carried out, considering the population increase. Based on these studies, the distribution managers identified the need to install reservoirs that serve as water redistribution points.

The water treated at the WTP – Catende is deposited in a central elevated reservoir (named central reservoir), which has a capacity of 500 m<sup>3</sup>. From this reservoir, it is distributed to another elevated type reservoir with a capacity of 400 m<sup>3</sup>, both located in the WTP. The elevated reservoir is responsible for distributing water

to the Nova Catende and Jaqueira districts. This reservoir receives water from the central reservoir through pumping, but distributes to the aforementioned neighbourhoods through gravitational force.

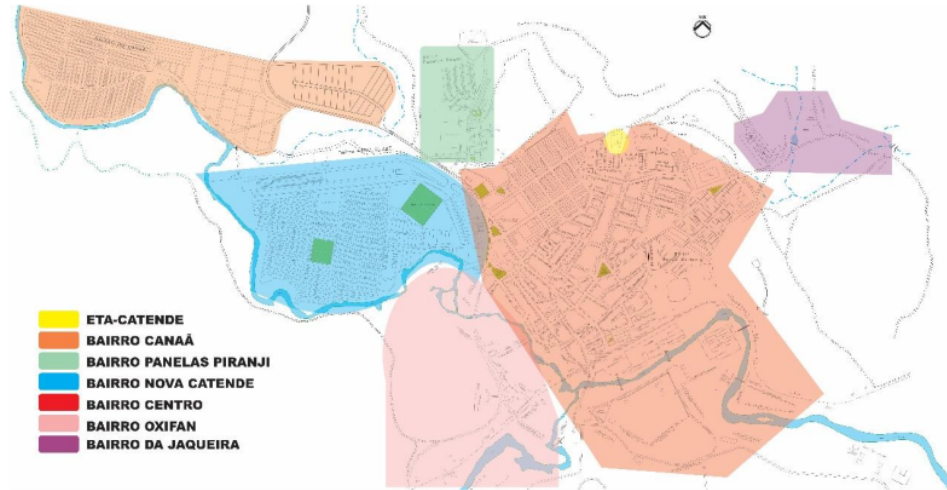
**Figure 3** Parshall gutter, addition of chlorine and aluminium sulphate (see online version for colours)



The central reservoir, in addition to supplying water to the elevated reservoir (in the WTP), also supplies three more reservoirs of the elevated type in the Panelas Piranji, Canaã and Oxifan neighbourhoods, with storage capacities of 100 m<sup>3</sup>, 180 m<sup>3</sup> and 20 m<sup>3</sup>, respectively. The first two mentioned are supplied with the help of two pairs of pumps while the third reservoir is also supplied by gravitational force. The city center, on the other hand, receives water from the central reservoir through gravitational force, as it is directly linked to the WTP.

Figure 6 shows a representation of the water supply network described above. The supplier managers regulates the water supply in Catende, by opening or closing the valves that control the distribution flow. Currently, the company leaves these valves permanently open, maintaining a continuous flow of this resource, with the supply being interrupted only to maintain the treatment filters or the distribution network.



**Figure 4** Catende map by supply zones (see online version for colours)

*Source:* Adapted from the Archives of the Municipality of Catende, consulted in 2016 (subtitles in Portuguese – ETA Catende is the WTP and the neighbourhoods are the distribution zones).

**Figure 5** (a) Reservoirs raised (b) Elevated (see online version for colours)

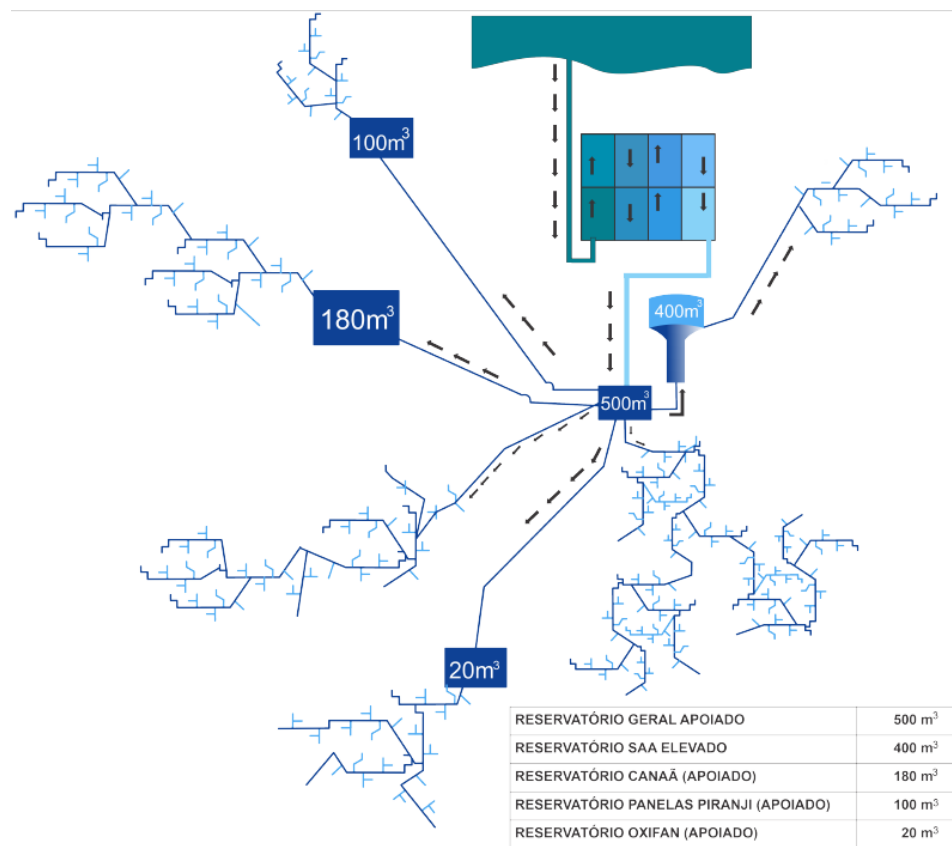
### 2.3 Demand from consumer units

Based on data obtained from the UN (United Nations), Paganine (2013) informs that 110 litres of water per day are enough to meet a person's basic needs. However, in interviews conducted with WTP administrators in Catende, it was informed that the average consumption per inhabitant in the city was around 200 litres per day. Considering the average consumption reported and data from IBGE (2021) obtained from the 2010 Census, it was estimated that an average of 7,473,960.00 litres of water per day is needed to serve the population of Catende.

Through the visits carried out at the WTP in Catende in 2016, it was also possible to obtain information on the daily production capacity and the number of households

served, separated by the supply zones. Table 1 shows the water demand for each zone (neighbourhood), where the necessary amount of water per household was defined considering that each household resides on average 3.9 inhabitants [average established by IBGE (2021) through the last large demographic census of 2010]. Information on the number of households/zones and the average water consumption per inhabitant were provided by the WTP managers, considering the average use of 200 litres of water per inhabitant. It was also informed that almost 100% of households have reservoirs ranging between 500 and 1,000 litres. These are activated when water is not supplied, either due to maintenance in the distribution network, or in periods when the water flow for treatment is low, thus limiting the daily supply.

**Figure 6** Water distribution scheme in Catende (subtitles in Portuguese) (see online version for colours)



Although Catende is located in a region that does not suffer so much from the lack of water, it has been observed over the years, a considerable drop in its water sources, alerting the population and managers about the need to save this resource. The production capacity of treated water is 288.00 m<sup>3</sup> of water per hour. Observing the total daily demand required, it is concluded that the productive capacity does not meet the daily needs of the population, which highlights the need for good management of water distribution.



**Table 1** Demand by sector – Catende (data from 2016)

<i>Supply sector</i>	<i>Number of households</i>	<i>Average consumption (m<sup>3</sup>/day)</i>
Centro	5,431	4,236.18
Nova Catende	1,043	813.54
Jaqueira	976	761.28
Panelas Piranji	459	358.02
Canaã	1,538	1,199.64
Oxifan	135	105.30
Total	9,582	7,473.96

Based on this issue, the water distribution problem was then defined, as discussed in the next section.

### 3 Problem of elaborating water distribution schedules in periods of scarcity

This water distribution problem arises in times of scarcity, in which it becomes necessary to draw up a distribution schedule for the different zones of the city, based on the limitation of this precious resource. Such schedule informs the shifts in which the inhabitants will be able to acquire treated water, generating their reserves for the periods in which there will be no supply. The following section presents a mathematical model for the problem considered in this work.

#### 3.1 Mathematical modelling

The symbols used in the model are shown in Table 2. And the mathematical model is presented as follows:

$$\begin{aligned}
& \text{Maximise } C1 * TVD - C2 * \sum_{z=NR+1}^{NL} |PDem_z - PDist_z| \\
& - \sum_{d=1}^{ND} \sum_{s=1}^{NS} \sum_{l=1}^{NL} (C3(d, s) * (1 - X_{dsl})) - C4 * IdleCEWSum
\end{aligned} \tag{1}$$

Subject to

$$InF_{dsl} - V_l * X_{dsl} = 0, \quad \forall d, s, l \tag{2}$$

$$V_l - InFR_l * T = 0, \quad \forall l \tag{3}$$

$$InFR_l - MaxInFR_l \leq 0, \quad \forall l \tag{4}$$

$$InFR_l - MinInFR_l \geq 0, \quad \forall l \tag{5}$$

$$OutF_{dsr} - \sum_{l=1}^{NL} (InF_{dsl} * Y_{rl}) = 0, \quad \forall d, s, r \tag{6}$$

$$VRes_{dsl} - VRes_{(d-1)(NS)l} - InF_{dsl} + OutF_{dsl} = 0, s = 1, \quad \forall d, l \tag{7}$$

$$VRes_{dsl} - VRes_{d(s-1)l} - InF_{dsl} + OutF_{dsl} = 0, s = 2, \dots, NS, \forall d, l \tag{8}$$

$$VRes_{dsl} - IRV_l = 0, d = 0, s = NS, \quad \forall l \quad (9)$$

$$VRes_{dsl} \geq 0, \quad \forall d, s, l \quad (10)$$

$$VRes_{dsr} - C_r \leq 0, \quad \forall d, s, r \quad (11)$$

$$VRes_{dsz} - AZC_z * NH_z \leq 0, \quad \forall d, s, z \quad (12)$$

$$OutF_z - D_z \leq 0, \quad \forall z \quad (13)$$

$$OutF_z - \sum_{d=1}^{ND} \sum_{s=1}^{NS} OutF_{dsz} = 0, \quad \forall z \quad (14)$$

$$TDV - \sum_{z=NR+1}^{NL} OutF_z = 0 \quad (15)$$

$$PDist_z - \frac{OutF_z}{TDV} = 0, \quad \forall z \quad (16)$$

$$IdleC_{dsl} - C_l + VRes_{dsl} = 0, s = NS, d = ND, \quad \forall l \quad (17)$$

$$IdleCEWSum - \sum_{l=1}^{NL} (IdleC_{(ND)(NS)l})^{RF_l} = 0 \quad (18)$$

$$X_{dsl} \in \{0, 1\} \quad (19)$$

$$V_l \in \mathbb{R}_+ \quad (20)$$

The objective function (1) at the same time:

- a maximises the volume distributed to the zones (first term)
- b makes the distribution of water between the different zones as fair as possible (second term)
- c minimises the idle capacity of the reservoirs (fourth term).

The third term is used to force the uniqueness of the solution (or at least reduce the number of possible solutions). Using the  $-$  sign before the term makes the valves<sup>1</sup> remain open as long as possible. The parameters  $C1$  and  $C2$  are used to regulate the order of importance of the first and second terms.  $C4$  is used to ensure that the algorithm prioritises meeting demand and that the remaining volume in the reservoirs becomes a secondary concern. And  $C3(d, s)$  is a function used to prioritise water distribution shifts. Equations (2) and (3) are used to, respectively, determine the water inflow and ideal inflow rate based on the evaluated solution. Constraints (4) and (5) limit the inflow rates values. Equation (6) guarantee that the reservoirs outflows are exactly the amount of water that each reservoir distributes to other reservoirs or zones.<sup>2</sup> Equations (7) and (8) are the well-known flow constraints, being the equation (9) boundary conditions. Constraints (10), (11) and (12) limit the values of the remaining volumes of the reservoirs. Constraint (13) ensure that the total volume distributed to each zone will not exceed its total demand. Equations (14), (15) and (16) calculate the total volume delivered to each zone, the total volume delivered to all zones and the proportions of volume distributed to each zone, respectively. Equations (17) and (18) calculate the idle capacities of the reservoirs in the last shift of the last day, and an exponentially weighted sum of these values, respectively. Finally, constraints (19) and (20) inform the nature of the primary decision variables.

**Table 2** Symbols used in the mathematical model

<i>Indexes</i>	
$d$	Used to designate a day, $d = 1, \dots, ND$
$s$	Used to designate a shift of a day, $s = 1, \dots, NS$
$l$	Used to designate a location that are part of the water supply system (either zones, reservoirs or WTPs), $l = 1, \dots, NL$
$r$	Used to designate a WTP or a reservoir, $r = 1, \dots, NR$
$z$	Used to designate a zone, $z = NR + 1, \dots, NL$
<i>Parameters</i>	
$ND$	Number of days
$NS$	Number of daily distribution shifts
$NL$	Number of locations
$NR$	Number of reservoirs (reservoirs and WTPs)
$T$	Time per shift
$IRV_l$	Initial volume of reservoir at the location $l$
$C_l$	Capacity of reservoir at the location $l$
$AZC_z$	Average reservoir capacities of the households in the zone $z$
$NH_z$	Number of households in the zone $z$
$HC$	Housing coefficient
$IAC$	Represents the average daily consumption per inhabitant
$MaxInFR_l$	Maximum inflow rate of the pipeline that reaches the reservoir at the location $l$
$MinInFR_l$	Minimum inflow rate set for the pipeline that reaches the reservoir at the location $l$
$Y_{rl}$	Binary variable that informs the physical structure of the water distribution system $Y_{rl} = 1$ if water is supplied directly from the reservoir $r$ to the location $l$ and $Y_{rl} = 0$ if that does not happen
$RF_l$	Importance attributed to maintaining water in reservoir at location $l$ , since there is a surplus of water to fill the reservoirs. It is important that the values of these parameters are greater than and close to 1.00.
$C1, C2$	Relevance factors for the total volume distributed and fair distribution, respectively
$C3(d, s)$	Relevance factor for the adjustment of the valves
$C4$	Irrelevance factor for idle capacity
$D_z$	Demand of zone $z$ , $D_z = IAC * NH_z * HC * ND$
$TD$	Total demand, $TD = \sum_{z=NR+1}^{NL} D_z$
$PDem_z$	$z$ zone percentage demand, $PDem_z = \frac{D_z}{TD}$
<i>Decision and secondary variables</i>	
$X_{dsl}$	Binary variable that receives value 1 when the inlet valve of location $l$ is open on the $s^{\text{th}}$ shift of day $d$ , and receives value 0 when it is closed in the same period
$V_l$	Ideal volume of water distributed to the location $l$ in any shift in which the corresponding valve remains open
$InF_{dsl}$	Water inflow received by location $l$ on the $s^{\text{th}}$ shift of day $d$
$OutF_{dsr}$	Water outflow delivered by reservoir $r$ on the $s^{\text{th}}$ shift of day $d$
$InFR_l$	Ideal inflow rate of location $l$
$VRes_{dsl}$	Volume of water remaining in the reservoir at location $l$ at the end of the $s^{\text{th}}$ shift of the day $d$
$OutF_z$	Total outflow of zone $z$
$TVD$	Total volume distributed
$PDist_z$	Percentage distributed to zone $z$
$IdleC_{dsl}$	Idle capacity of reservoir at location $l$ at the end of the $s^{\text{th}}$ shift of the day $d$
$IdleCEWSum$	Exponentially weighted sum of idle capacities

### 3.2 Distribution time adjustment

In order to guarantee a fair distribution, in specific cases where the actual flows are greater than the ideal flows informed in the initial model solution, and cannot be reduced in practice, it is necessary to limit the water distribution time for certain locations. In this case, the proper distribution time per shift for local  $l$ ,  $T_l^*$ , can be defined according to equation (21). In practice, once delivery times are adequately limited, water delivery will proceed as planned.

$$T_l^* = T * (InFR_l / MaxInFR_l), \quad \forall l \quad (21)$$

## 4 Tests and results

To validate the proposed model, a LINGO code was developed and ran in the 'global solver' mode, using the parameter values recommended by the software LINGO (2021) (with the exception of the Precision parameter, on the Interface tab, whose value was set to 9). The tests were performed on a notebook with an Intel i7 processor. The input data were prepared based on the considerations presented in Subsections 4.3, 4.4 and 4.5 and using the data collected during this work, as summarised in Subsection 4.1. The results found as well as an analysis of these results are presented along the following sections together with the considerations studied.

### 4.1 Data collected

Tables 3, 4, 5 and 6 present a synthesis of the data referring to the weirs, reservoirs, zones and the network of studied water distribution, respectively. The conceptual and mathematical model presented in this paper, as well as the solver used to validate the model, were developed through a recent effort. However, the data presented in this section were collected in 2016 as part of an extension project carried out by the authors of this article, through which a detailed study of the water distribution process presented in Section 2 was carried out (Candido et al., 2016).

- Number of locations (NL) = 12 (6 zones)
- Number of reservoirs (NR) = 6 (1 WTP)
- Housing coefficient (HC) = 3.9 inhabitants/household
- Average daily inflow per inhabitant (IAC) = 0.20 m<sup>3</sup>/inhabitant \* day.

Note: each weir supplies water to an WTP (conventional or mechanical). However, both supply water to the central reservoir. For this reason, in this work we consider only a single WTP.

**Table 3** Weirs data – Catende (data from 2016)

<i>Weir</i>	<i>Name</i>	<i>Distribution flow rate (<math>m^3</math>/hour)</i>
1	Santa Rita Weir	241.20
2	Bálsamo das Freiras Weir	126.00
Total		367.20

**Table 4** Reservoirs data – Catende (data from 2016)

<i>Reservoir (<math>r</math>)</i>	<i>Name</i>	<i>Capacity (<math>C_r</math>) (<math>m^3</math>)</i>	<i>Maximum inflow rate (<math>MaxInFR_r</math>) (<math>m^3</math>/hour)</i>
1	WTP	2,500.00	367.20
2	Central	500.00	288.00
3	Elevated	400.00	Uninformed
4	Panelas Piranji	100.00	Uninformed
5	Canaã	180.00	Uninformed
6	Oxifan	20.00	Uninformed

**Table 5** Zones data – Catende (data from 2016)

<i>Zone (<math>z</math>)</i>	<i>Name</i>	<i>Number of households (<math>NH_z</math>)</i>
7	Centro	5,431
8	Nova Catende	1,043
9	Jaqueira	976
10	Panelas Piranji	459
11	Canaã	1,538
12	Oxifan	135

**Table 6** Physical distribution structure – Catende (data from 2016)

<i>(<math>Y_{rl}</math>)</i>	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>	<i>6</i>	<i>7</i>	<i>8</i>	<i>9</i>	<i>10</i>	<i>11</i>	<i>12</i>
1	0	1	0	0	0	0	0	0	0	0	0	0
2	0	0	1	1	1	1	1	0	0	0	0	0
3	0	0	0	0	0	0	0	1	1	0	0	0
4	0	0	0	0	0	0	0	0	0	1	0	0
5	0	0	0	0	0	0	0	0	0	0	1	0
6	0	0	0	0	0	0	0	0	0	0	0	1

#### 4.2 Benchmarks

For testing the developed SOLVER, we have considered 36 cases. In cases 01 to 21 we used the data from Subsection 4.1, varying the number of days (between 1 and 7) and the number of shifts (between 1 and 3). In cases 22 to 28, we also considered a minimum inflow value for the Oxifan's reservoir ( $MinInFR_6 = 10.00$   $m^3$ /hour), varying the number of days (between 1 and 7) and using 3 shifts. Case 29 is like case 03, except that a maximum inflow rate was informed for Centro's

zone ( $z = 7$ ),  $MaxInFR_7 = 130.00 \text{ m}^3/\text{hour}$ . Case 30 to case 36 are like cases 22 to 28, respectively, except that a maximum inflow rate was informed for Centro's zone, as in case 29. For all cases we used the following values for the parameters:  $C1 = 10/ND$ ,  $C2 = 100,000$ ,  $C3(d, s) = a * ((NS - s) * ND + ND - d + 1)$ , with  $a = 1$ ,  $*a = 2$  or  $**a = 3$ ,  $C4 = 5.27\text{E-}5$ ,  $RF_r = 1.13$ ,  $r = 1, 2$ ;  $RF_r = 1.12$ ,  $\forall r | r \neq 1, 2$ ; and  $RF_z = 1.00$ ,  $\forall z$ . A template for the data file (data.ldt) is available at 'https://github.com/tbfraga/gamos-journal/tree/main/EWDSPS'.

### 4.3 Initial considerations

Figure 7 presents the optimal solution for the data summarised in Subsection 4.1 and using the parameter values presented in Subsection 4.2 (with  $ND = 1$ ,  $NS = 1$  and  $a = 1$ ), calculated with the aid of the 'LibreOffice Calc' software, considering the maximum daily distribution value (in a 24-hour shift), limited by the outflows of the weirs and the WTP.

**Figure 7** Determination of optimal distribution values with 'LibreOffice Calc', considering a daily 24-hour distribution period (see online version for colours)

	A	B	C	D	E	F	G	H	I
number of days					1 day				
number of shifts per day					1 shift				
time per shift					24 (hours)				
average capacity of reservoirs in the zones					1.000 (m <sup>3</sup> )				case 01
average consumption per inhabitant					0.200 (m <sup>3</sup> / day)				
housing coefficient					3.900 (inhabitants / household)				
C4					5.270E-05				
	local	households	demand (m <sup>3</sup> )	unmet (m <sup>3</sup> )	capacity (m <sup>3</sup> )	initial vol. (m <sup>3</sup> )	RF	idle capacity * (m <sup>3</sup> )	inflow (m <sup>3</sup> )
ETA					2,500.000	0.000	1.130	599.200	8,812.800
R1					500.000	0.000	1.130	500.000	6,912.000
R2					400.000	0.000	1.120	400.000	1,456.411
R3					100.000	0.000	1.120	100.000	331.101
R4					180.000	0.000	1.120	180.000	1,109.440
R5					20.000	0.000	1.120	20.000	97.383
Z1		5,431	4,236.180	318.514	5,431.000	0.000	1.000	5,431.000	3,917.666
Z2		1,043	813.540	61.169	1,043.000	0.000	1.000	1,043.000	752.371
Z3		976	761.280	57.240	976.000	0.000	1.000	976.000	704.040
Z4		459	358.020	26.919	459.000	0.000	1.000	459.000	331.101
Z5		1,538	1,199.640	90.200	1,538.000	0.000	1.000	1,538.000	1,109.440
Z6		135	105.300	7.917	135.000	0.000	1.000	135.000	97.383
total		9,582.000	7,473.960	561.960				13,438.743	weir outflow (m <sup>3</sup> )
weir									8,812.800
					total volume distributed to zones	6,912.000			
					fitness (optimal value)	69,119.292			
					relevance factors:				
					C1	10			
					C2	100,000			
					C3	(1)			
					* at the end of the day				
						local		average volume received per inhabitant (m <sup>3</sup> / day)	inflow rate (m <sup>3</sup> / hour)
						WTP			367.200
						R1			288.000
						R2			60.684
						R3			13.796
						R4			46.227
						R5			4.058
						Z1		0.185	163.236
						Z2		0.185	31.349
						Z3		0.185	29.335
						Z4		0.185	13.796
						Z5		0.185	46.227
						Z6		0.185	4.058

As we can see in this figure, the optimal daily water distribution volume per inhabitant, considering a daily 24-hour distribution period, is  $\approx 185.00$  litres/(day \* inhabitant).



Therefore, we can conclude that, in fact, the flow of the pipeline that transports water from the WTP to the central reservoir is not sufficient to meet the average daily consumption of the population informed by the company (200 litres/(day \* inhabitant)).

Another important piece of information that we observe in this figure are the ideal inflow rates, which would result in a fair distribution for the population of Catende. These values are basically defined as a function of water availability, demands, and initial volumes in the reservoirs. Such values were identified using the following calculation logic:

- 1 As the part of the inflow received by the WTP and not distributed is completely used to fill its reservoir and, as the inflow rate of the central reservoir is lower than the inflow rate of the WTP, so  $InF_{dsr}$ , for the WTP ( $r = 1$ ) and the central reservoir ( $r = 2$ ), are calculated according to equations (22):

$$InF_{dsr} = MaxInFR_r * T, d = 1, s = 1, r = 1, 2 \quad (22)$$

- 2 The total availability of water, released by the central reservoir, which directly or indirectly supplies all other reservoirs and zones, is less than the total demand. Therefore, the volume of water received by the central reservoir is completely distributed to the zones (and not to fill the reservoirs), with the fair distribution being proportional to the number of households in each zone:

$$InF_{dsz} = InF_{dsr} * \frac{D_z}{TD}, d = 1, s = 1, r = 2, \forall z \quad (23)$$

- 3 As the volumes received by the reservoirs are completely distributed:

$$InF_{dsr} = OutF_{dsr}, d = 1, s = 1, r = 3, \dots, NR \quad (24)$$

being the values of  $OutF_{dsr}$  calculated according to the equation (6) recursively, and the ideal rates (not informed) then calculated based on the equations (2) and (3).

After performing the calculations shown in Figure 7, we run the solver in LINGO, using the same inputs. The values 367.200 and 288.000 were used as the values of the maximum inflow rates informed for the WTP and for the central reservoir, respectively. No limit values for inflow rates were informed for the other reservoirs and zones. Table 7 displays the values found by the solver. As we can see in this table, the solver found the calculated optimal values very quickly and without any errors observed.

The same values were found for volumes distribution when the solver in LINGO was run considering 3 shifts of 8 h (case 3). In this case, the inflow is distributed between the shifts, keeping the same ideal inflow rates.

#### 4.4 Practical aspects

It would be ideal if the company could regulate the flow rates for water distribution, adjusting these rates according to each ideal solution found by the solver for the different cases evaluated by the planners. However, in practice this becomes very difficult. The following situations will be faced when looking for solutions to real problems:

- 1 real flow rates of the pipelines smaller than the calculated ideal flow rates
- 2 actual pipelines flow rates greater than the calculated ideal flow rates
- 3 very small ideal flow rates, making the supply unsatisfactory.

Situations 1 and 3 can be easily solved by indicating maximum and minimum values, respectively, for the inflow rates calculated by the solver. However, care must be taken not to set values that make the problem unresolvable. The planner must always keep in mind that the water distribution network and the flow rates form a single system, with values that are essentially integrated.

**Table 7** Summary of results generated by the solver developed in LINGO for case 1

<i>Location</i>	<i>Total demand (m<sup>3</sup>)</i>	<i>Capacity (m<sup>3</sup>)</i>	<i>Initial vol. (m<sup>3</sup>)</i>	<i>Idle capacity** (m<sup>3</sup>)</i>	<i>Total inflow (m<sup>3</sup>)</i>
WTP		2,500.000	0.000	599.200	8,812.800
R1		500.000	0.000	500.000	6,912.000
R2		400.000	0.000	400.000	1,456.411
R3		100.000	0.000	100.000	331.101
R4		180.000	0.000	180.000	1,109.440
R5		20.000	0.000	20.000	97.383
Z1	4,236.180	5,431.000	0.000	5,431.000	3,917.666
Z2	813.540	1,043.000	0.000	1,043.000	752.371
Z3	761.280	976.000	0.000	976.000	704.040
Z4	358.020	459.000	0.000	459.000	331.101
Z5	1,199.640	1,538.000	0.000	1,538.000	1,109.440
Z6	105.300	135.000	0.000	135.000	97.383
Total	7,473.960		Exp. weighted sum: 13,438.743		
<i>Shift data</i>	<i>Location</i>	<i>Valve status</i>	<i>Ideal inflow rate (m<sup>3</sup>/hour)</i>		
1 day	WTP	Open	367.200*		
1 shift	R1	Open	288.000*		
24 hours/shift	R2	Open	60.684		
	R3	Open	13.796		
Total zones outflow (m <sup>3</sup> ) 6,912.000	R4	Open	46.227		
	R5	Open	4.058		
	Z1	Open	163.236		
	Z2	Open	31.349		
	Z3	Open	29.335		
	Z4	Open	13.796		
Optimal value (fitness) 69,119.292	Z5	Open	46.227		
	Z6	Open	4.058		

Notes: Computational time = 0.41 sec, total number of iterations = 1,342, \*values reported for maximum inflow rates and \*\*at the end of the evaluated period.

In the case of situation 1, the volume of distribution (limited by the inflow rate) in a given location will be transferred to other locations seeking to meet the demand and /or distributed to reduce the idle capacity of the reservoirs, according to the setting of the parameter values. For example, Table 9 presents the results found by the solver for case 29, in which the same data used in case 3 were considered, except that a maximum inflow rate was informed for Centro's zone ( $z = 7$ ),  $MaxInFR_7 = 130.00 \text{ m}^3/\text{hour}$ .

**Table 8** Summary of results generated by the solver developed in LINGO for case 3

Location	Total demand (m <sup>3</sup> )	Capacity (m <sup>3</sup> )	Initial vol. (m <sup>3</sup> )	Idle capacity** (m <sup>3</sup> )	Total inflow (m <sup>3</sup> )
WTP		2,500.000	0.000	599.200	8,812.800
R1		500.000	0.000	500.000	6,912.000
R2		400.000	0.000	400.000	1,456.411
R3		100.000	0.000	100.000	331.101
R4		180.000	0.000	180.000	1,109.440
R5		20.000	0.000	20.000	97.383
Z1	4,236.180	5,431.000	0.000	5,431.000	3,917.666
Z2	813.540	1,043.000	0.000	1,043.000	752.371
Z3	761.280	976.000	0.000	976.000	704.040
Z4	358.020	459.000	0.000	459.000	331.101
Z5	1,199.640	1,538.000	0.000	1,538.000	1,109.440
Z6	105.300	135.000	0.000	135.000	97.383
Total	7,473.960		Exp. weighted sum: 13,438.743		

Shift data	Location	Valve status	Ideal inflow rate (m <sup>3</sup> /hour)
		T1, T2 and T3	
1 day	WTP	Open	367.200*
3 shift	R1	Open	288.000*
24 hours/shift	R2	Open	60.684
	R3	Open	13.796
	R4	Open	46.227
Total zones outflow (m <sup>3</sup> ) 6,912.000	R5	Open	4.058
	Z1	Open	163.236
	Z2	Open	31.349
	Z3	Open	29.335
	Z4	Open	13.796
Optimal value (fitness) 69,119.292	Z5	Open	46.227
	Z6	Open	4.058

Notes: Computational time = 0.21 sec, total number of iterations = 661, \*values reported for maximum inflow rates and \*\*at the end of the evaluated period.

For situation 3, once a minimum value is indicated for the inflow of a given location, the solver will propose solutions in which the inflow of some locations will be null or concentrated in one or a few shifts. For example, Table 10 presents the results found by the solver for case 22, in which the same data used in case 3 were considered, except that a minimum inflow rate was reported for the reservoir  $R5$  ( $r = 6$ ),  $MinInFR_6 = 10.000$  m<sup>3</sup>/hour. As we can see in Table 10 the restriction related to the minimum inflow in  $R5$  causes the flow to be restricted to a single shift (with tripled inflow value), forcing the valves to be closed in the other two shifts.

As for situation 2, the developed solver does not present a good answer. The value found by the solver will always be an ideal value, based on the informed restrictions. If the ideal value is lower than the real value, the respective zone will have an excess amount of water. And there will be no sure way to prevent the volume consumed by that zone from being the desired volume. Except limiting distribution time. In this case, the ideal distribution time (within the period of a shift) can be calculated using the equation (21).

**Table 9** Summary of results generated by the solver developed in LINGO for case 29

<i>Location</i>	<i>Total demand (m<sup>3</sup>)</i>	<i>Capacity (m<sup>3</sup>)</i>	<i>Initial vol. (m<sup>3</sup>)</i>	<i>Idle capacity** (m<sup>3</sup>)</i>	<i>Total inflow (m<sup>3</sup>)</i>
WTP		2,500.000	0.000	391.868	8,812.800
R1		500.000	0.000	0.000	6,704.668
R2		400.000	0.000	0.000	1,559.877
R3		100.000	0.000	0.000	363.686
R4		180.000	0.000	0.000	1,063.550
R5		20.000	0.000	0.000	97.555
Z1	4,236.180	5,431.000	0.000	5,431.000	3,120.000
Z2	813.540	1,043.000	0.000	1,043.000	599.185
Z3	761.280	976.000	0.000	976.000	560.693
Z4	358.020	459.000	0.000	459.000	263.686
Z5	1,199.640	1,538.000	0.000	1,538.000	883.550
Z6	105.300	135.000	0.000	135.000	77.555
Total	7,473.960		Exp. weighted sum: 10,433.624		

<i>Shift data</i>	<i>Location</i>	<i>Valve status S1, S2 and S3</i>	<i>Ideal inflow rate (m<sup>3</sup>/hour)</i>
1 day	WTP	Open	367.200*
3 shift	R1	Open	279.361
8 hours/shift	R2	Open	64.995
	R3	Open	15.154
Total zones outflow (m <sup>3</sup> )	R4	Open	44.315
5,504.669	R5	Open	4.065
	Z1	Open	130.000*
	Z2	Open	24.966
	Z3	Open	23.362
Optimal value (fitness)	Z4	Open	10.987
55,046.139	Z5	Open	36.815
	Z6	Open	3.231

Notes: Computational time = 0.49 sec, total number of iterations = 702, \*values reported for maximum inflow rates and \*\*at the end of the evaluated period.

#### 4.5 Solver and model limitations

LINGO is an incredible software, indispensable for mathematical modelling of any real problem. With the help of LINGO, it is possible to notice a series of initial errors in the model, which could easily go unnoticed. Additionally, the elaborated mathematical model strongly influences the solver efficiency. This forces the modeler to think about issues that limit the model's solutions, and to work with functions that make the model robust and functional.

However, LINGO is not a magic tool, LINGO's processing power is limited, due to limitations associated with exact solving techniques for optimisation problems, especially when defined as nonlinear and NP-hard. For most problems, the computational effort increases as the number of decision variables increases, according to functions that are not polynomials. In other words, there is an explosion in the number of possible solutions, and current exact methodologies have not yet found a way to deal with this, in the case of problems with larger dimensions.

**Table 10** Summary of results generated by the solver developed in LINGO for case 22

<i>Location</i>	<i>Total demand (m<sup>3</sup>)</i>	<i>Capacity (m<sup>3</sup>)</i>	<i>Initial vol. (m<sup>3</sup>)</i>	<i>Idle capacity** (m<sup>3</sup>)</i>	<i>Total inflow (m<sup>3</sup>)</i>
WTP		2,500.000	0.000	599.200	8,812.800
R1		500.000	0.000	500.000	6,912.000
R2		400.000	0.000	400.000	1,456.411
R3		100.000	0.000	100.000	331.101
R4		180.000	0.000	180.000	1,109.440
R5		20.000	0.000	20.000	97.383
Z1	4,236.180	5,431.000	0.000	5,431.000	3,917.666
Z2	813.540	1,043.000	0.000	1,043.000	752.371
Z3	761.280	976.000	0.000	976.000	704.040
Z4	358.020	459.000	0.000	459.000	331.101
Z5	1,199.640	1,538.000	0.000	1,538.000	1,109.440
Z6	105.300	135.000	0.000	135.000	97.383
Total	7,473.960		Exp. weighted sum: 13,438.743		

<i>Shift data</i>	<i>Location</i>	<i>Valve status closed</i>	<i>Ideal inflow rate (m<sup>3</sup>/hour)</i>
1 day	WTP	-	367.200*
3 shift	R1	-	288.000*
24 hours/shift	R2	-	60.684
	R3	-	13.796
Total zones outflow (m <sup>3</sup> )	R4	-	46.227
6,912.000	R5	S1/S2	12.173
	Z1	-	163.236
	Z2	-	31.349
	Z3	-	29.335
Optimal value (fitness)	Z4	-	13.796
69,109.292	Z5	-	46.227
	Z6	S1/S2	12.173

Notes: Computational time = 5.35 sec, total number of iterations = 39,685, \*values reported for maximum inflow rates and \*\*at the end of the evaluated period.

The model presented in this work is a nonlinear, mixed-integer mathematical programming model. Nonlinearity happens due to the objective function and the constraints (2), (16) and (18). The non-polynomial nature of the model arises due to the binary decision variables  $X_{dsl}$ . In this section, we present an initial discussion about the limitations of the developed solver and mathematical model. It is important to emphasise that many of the limitations presented here could be mitigated through adjustments to the model, or even through a better use of the LINGO software.

Table 11 presents some tests carried out to analyse the efficiency of the developed model and solver. C1, C2, C3 and C4 relevance/irrelevance parameters referring to total distributed volume, fair distribution, valve status and reservoir idle capacity were defined based on an extensive study. Such definition had the following purposes: to define as priorities meeting the demand, then fair distribution and finally filling the reservoirs; in order to test the ruggedness of the model, we also had the clear intention of distributing the flow among all shifts, allowing the valves to be turned off only when flow restrictions impose this condition. As we can see in this table, although the computational effort varies according to the flow restrictions considered, the solver is

able to propose solutions in acceptable times. In some cases the solver was not able to find good solutions for reasons that are still unknown, however these difficulties were solved with only a small adjustment in the value of parameter  $a$ . In general, we could observe that the solver is really quite robust and adequately meets the proposed objective (elaboration of water distribution schedules in periods of scarcity, also defining the ideal flows and distribution times).

**Table 11** Study on the efficiency of the mathematical model and the solver

<i>Case</i>	<i>ND</i>	<i>NS</i>	<i>1° term</i>	<i>2° T</i>	<i>3° T</i>	<i>4° T</i>	<i>Fitness</i>	<i>Time</i>	<i>Iterations</i>
1	1	1	69,120.00	0.00	0.00	0.71	69,119.29	0.41 s	1,342
2	1	2	69,120.00	0.00	0.00	0.71	69,119.29	0.17 s	550
3	1	3	69,120.00	0.00	0.00	0.71	69,119.29	0.21 s	661
4	2	1	69,120.00	0.00	0.00	0.64	69,119.36	0.17 s	539
5	2	2	69,120.00	0.00	0.00	0.64	69,119.36	0.35 s	1,086
6	2	3	69,120.00	0.00	0.00	0.64	69,119.36	0.53 s	1,298
7	3	1	69,120.00	0.00	0.00	0.64	69,119.36	0.24 s	778
8	3	2	69,120.00	0.00	0.00	0.64	69,119.36	0.53 s	1,342
9	3	3	69,120.00	0.00	0.00	0.64	69,119.36	2.45 s	4,827
10	4	1	69,120.00	0.00	0.00	0.64	69,119.36	0.42 s	1,447
11	4	2	69,120.00	0.00	0.00	0.64	69,119.36	0.81 s	1,576
12	4	3	69,120.00	0.00	0.00	0.64	69,119.36	2.08 s	2,890
13	5	1	69,120.00	0.00	0.00	0.64	69,119.36	0.50 s	1,385
14	5	2	69,120.00	0.00	0.00	0.64	69,119.36	1.28 s	2,235
15	5	3	69,120.00	0.00	0.00	0.64	69,119.36	12.07 m	272,631
16	6	1	69,120.00	0.00	0.00	0.64	69,119.36	0.50 s	1,148
17	6	2	69,120.00	0.00	0.00	0.64	69,119.36	9.12 m	134,540
18	6	3	69,120.00	0.00	0.00	0.64	69,119.36	19.20 m	134,540
19	7	1	69,120.00	0.00	0.00	0.64	69,119.36	0.59 s	1,257
20	7	2	69,120.00	0.00	0.00	0.64	69,119.36	2.02 m	105,430
21	7	3	69,120.00	0.00	0.00	0.64	69,119.36	15.44 m	442,965
22	1	3	69,120.00	0.00	10.00	0.71	69,109.29	5.35 s	39,685
23	2	3	69,120.00	0.00	30.00	0.64	69,089.36	1.08 m	347,190
24	3	3	69,120.00	0.00	58.00	0.64	69,061.36	29.54 m	2,288,288
25	4	3	69,120.00	0.00	94.00	0.64	69,025.36	37.71 m	5,290,914
26*	5	3	69,120.00	0.00	244.00	0.64	68,875.36	1.13 h	3,272,716
27*	6	3	69,120.00	0.00	344.00	0.64	68,775.36	4.48 h	37,967,422
28	7	3	69,120.00	0.00	230.00	0.64	68,889.36	3.89 h	49,650,061
29	1	3	55,046.69	0.00	0.00	0.55	55,046.14	0.49 s	702
30	1	3	55,046.66	0.00	2.00	0.54	55,044.11	4.69 s	41,568
31	2	3	55,046.70	0.00	12.00	0.42	55,034.28	1.82 m	403,389
32	3	3	48,930.37	0.00	128.00	0.37	48,802.00	14.80 m	750,189
33	4	3	55,046.72	0.00	66.00	0.29	54,980.43	20.99 m	2,047,134
34	5	3	55,105.90	121.94	86.00	0.29	54,897.67	25.66 m	1,116,250
35**	6	3	55,103.04	116.05	378.00	0.29	54,608.70	4 h	5,016,544
36	7	3	55,046.66	0.00	198.00	0.29	54,848.37	1.01 h	4,535,449

Notes: \*These cases did not work using  $a = 1$  for the definition of C3, so we used  $a = 2$ .

\*\*This case did not work using  $a = 1$  and  $a = 2$  for the definition of C3, so we used  $a = 3$ . In this case, we also stopped SOLVER without it signalling that it found the optimal solution, after the 4 h period.



An important issue to be considered is that the adjustment of the parameters C1, C2, C3 and C4 strongly influence the efficiency of the solver as well as the solution found. The main aspect of the relevance/irrelevance parameters adopted is that they allow the planner to interfere in the solution presented by the solver, so that this solution meets the planning objectives (e.g., prioritisation of filling reservoirs or meeting demand). However, this requires that the planner has good experience in applying the solver and a good understanding of how the solver reacts to the adjustment of these parameters. Therefore, the good performance of the developed solver will depend largely on the qualification of the planner for this purpose. We understand that it is possible to build formulas for automatic calculation of suitable values for these parameters, using quantitative and qualitative analyses referring to the decision-making process (e.g., formulas defined according to answers given for some questionnaire). It is also possible, of course, to develop a user-friendly graphical interface. These efforts would make using the solver much simpler, however they depend on the continuity of this project, with a strong commitment of time and dedication of qualified professionals.

The solver developed in LINGO language (EWDSPS.lng) as well as the files generated with the results found (results/\*.lgr) are available at '<https://github.com/tbfraga/gamos-journal/tree/main/EWDSPS>'.

## **5 Conclusions and future works**

In the present work, a detailed description of the WDS of a city in northeastern Brazil and a conceptual and a new mathematical model for the problem of water distribution in periods of scarcity was presented. The validation of the mathematical model was performed using a solver developed with the LINGO software from LINDO systems. Through the tests carried out, we concluded that the developed model and solver fit perfectly to the studied reality, and are capable of, in a short time, proposing solutions that make the distribution of water volumes for the different zones fair, in periods of scarcity, through the control of flows and distribution times. Such solutions take into account the restrictions of the system and present alternatives for when the channelings are to be modulated optimally (with flow rates that optimally regulate the distribution). However, it was verified that, for the solver to present good results, it must be used by a suitably qualified employee. What may become less relevant through new advanced studies for high-level calculation of relevance/irrelevance parameters adopted in the model, as well as through the construction of a friendly graphic interface. Additionally, due to the limitations of the exact methodologies developed so far for solving non-polynomial optimisation problems (such as the studied problem), the developed solver naturally presented limitations related to its ability to solve larger problems. Such limitations justify the need to develop solution algorithms based on heuristics applied to optimisation problems. These efforts will be the focus of our next works.

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**Notes**

- 1 In some cases the valves are replaced by pumps. In these cases, the pumps can be compared to open valves, when activated, and closed valves, when not activated. Therefore, the simplification adopted (considering only valves) does not generate any implications for the developed model.
- 2 Note that, in the case of zones, each zone  $z$  is considered to have a single reservoir, whose capacity is defined by the sum of the capacities of the various housing reservoirs in the zone.