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THE IMPORTANCE OF THE SIZE OF THE RESERVOIR'S USEFUL VOLUME FOR CONSUMPTION AND COST DECREASE IN ELECTRICITY

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Abstract: Current paper analyzes the reservoir's useful water volume for hydropower efficiency in water supply systems. Data, retrieved from the Guanabara Water Supply System of the municipality of Ananindeua, state of Pará, Brazil, were analyzed. Two useful volume sizes were determined following recommendations by NBR 12.217/1994 "Project on the water distribution reservoir for public supply". The former featured the time curve of water consumption and the latter the rate of maximum daily discharge. The latter stage assessed the most adequate useful water volume from the point of view of hydropower efficiency by Epanet 2.0. Dimensions with or without water consumption curve provided useful volumes of 838 m3 and 2.043 m3, respectively. In the case of the lowest volume, 47 hours/day of CMB functioning and 987 kWh/day of electric power consumption in EAT were detected. Volume increase to 2,043 m3 was positive, followed by 30 hours/day of functioning of CMB and consumption at 818 kWh/day in EAT. Hydropower costs were reduced by R$ 35,903.00/year, from R$ 143,108.00/year, with a useful volume of 838 m³, to R$ 107,205.00/year with 2,043 m³. Research revealed the importance of computerized simulation in decision-taking and the need for the updating of NBR 12.217/1994 by criteria of hydropower efficiency in the preparation of projects involving water supply reservoir systems.

Keywords: sizing methods, useful volume, reservoir, efficiency.

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INTRODUCTION

Hydroenergy consumption in most water supply systems (WSSs) is high. Data retrieved from the Alliance to Save Energy (ASE, 2017) demonstrated that between 2 and 3% of power consumption worldwide are used in water pumping and treatment for homes and industries. Due to ever increasing high costs in hydropower (GOMES, 2012), studies on the reservoir's useful volume and the system's electric energy consumption are highly relevant.

Cherchi et al. (2015) and Wallace et al. (2016) underscore that elevated reservoirs (ERs) provide greater stability in water supply. Matrosov et al. (2015) and Fraga (2017) insist that this type of water reservoir may store water for longer periods and significantly decrease hydropower costs. Pereira & Condurú (2014), Zeng et al. (2017) and Marinoski (2018) insist that inadequate size of the reservoir's useful water volume brings about higher construction and operational costs within the system.

Therefore, it is highly relevant that, during the planning phase, several criteria should be established for WSS calculation and operation. Tsutiya (2006), Carrasquer (2017), Iwona et al. (2016) and Solera et al. (2016) underscore the importance of calculating ERs' construction costs and hydropower efficiency. However, ERs' useful volume is normally determined according to daily consumption. Hydropower consumption and costs are frequently ignored. Vilanova & Balestieri (2016), Krajacica et al. (2016) and Coelho & Andrade-Campos (2016) report that different criteria of ER volume provide a greater or smaller impact on the consumption of electric energy. This is compounded by the fact that hydropower consumption and costs are not mentioned in traditional technical norms when the dimension of useful volume on the WSS reservoir is undertaken. Shokri (2013), Mamade et al. (2015) and Menke (2015) insist that this fact has contributed towards high costs in hydropower paid by the provider of the water supply service.

Consequently, hydropower results for different procedures of the reservoir's useful water calculation available in the literature should be compared. Pezzinga (2015), Ghaddar et al. (2015) and Caetano et al. (2017) highlight that hydropower computer simulation determines a greater efficiency to the water reservoir's useful volume.

It is therefore important to improve the reservoir's useful volume, CMB planning and, consequently, the control of reservoir levels to reduce the functioning of pumps for long periods and guarantee water demands with decreasing energy costs. The above are important for the sustainability of the provider of the water supply service, with repercussion on the Brazilian electric system.

Current research compares and evaluates the importance of procedures used in ER calculation through the assessment of useful volume and hydropower consumption and costs.

METHODOLOGY

Research consisted of a computer simulation of hydropower data by variations in capacity of useful volume of ER of the water distribution sector.

Study area comprised the Guanabara Water Supply Sector at Rua Jardim Esmeralda, District of Guanabara, municipality of Ananindeua within the metropolitan region of Belém (RMB), state of Pará, Brazil, represented in **Fig. 1**.

The Sector Guanabara, the 37th sector within the Planning Directory of the Water Supply System (PDSAA) of the RMB, is administered and commercialized by the Business Unit BR 316 (UNIBR) of the Pará Water Supply Company (COSANPA). The sector receives treated water from the secondary water pipeline Bolonha – Expansion Zone (300 mm, 1,188 m), with RA (850 m³), Treated Water Station (TWS) (2+1), ER (500 m³) and water distribution center, with a planned extension in the capacity of reservoir unit to attend 27,250 inhabitants (final stage), with per capita consumption of 150 l/inhab.day.

Research stages

Research was conducted at the Operation Characterization Stages of the Sector Guanabara (Stage 1), by the Useful Volume Calculation of ER (Stage 2) and Computer Simulation for Comparing Hydropower Consumption (Stage 3). Stage 1 comprised data for in-depth knowledge on the conditions of pumping operations and water storage in the Sector Guanabara. Reports, technical sheets and operational control maps

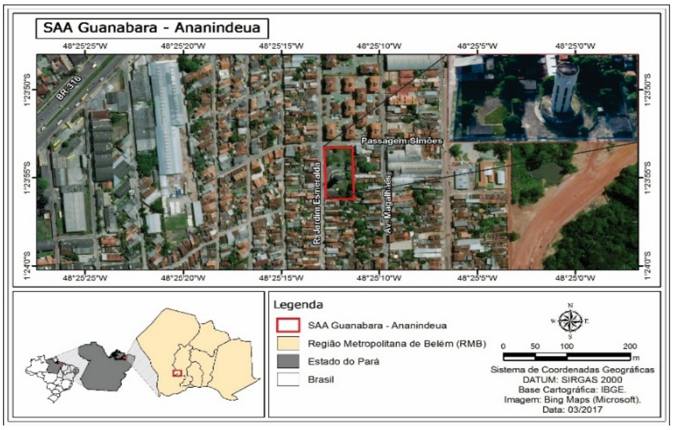

Fig 1. The Guanabara sector in the municipality of Ananindeua, Brazil.

of COSANPA and of the Energy and Water Efficiency Laboratory in Public Works (LENHS) were consulted, coupled to the main information on units, tubes and equipments. Operational data on hourly discharges of pumped water and distributed in ER were obtained and systematized during this stage. Mean pumping discharge and hourly water consumption variation were determined for the sector Guanabara. Stage 2 measured the ER's useful volume, following recommendations by NBR 12.217/1994 "Project on the water distribution reservoir for public supply", with calculations, according to item 5.1.2, and without data of water consumption curve, according to item 5.1.3. Pumping and storage of water distribution for 24 hours in the Sector Guanabara was thus provided.

Calculation 1 (with consumption curve) was undertaken by elaborating a consumption curve with data on hourly discharges of pumped water (entrance volume in ER), retrieved from COSANPA and LENHS/UFPA technical reports. Pumping Discharge (PD) was subtracted by Distribution Discharge (DD) at one-hour intervals during 24 hours. Addition of the twenty-four results determined the useful volume of ER storage. Storage volume was multiplied by 1.2, following safety instructions of item 5.1.2 of NBR 12217 (1994). ER's useful volume was thus obtained.

Further, Calculation 2 (without any consumption curve) was deducted by Equation 1. Rate of population of the supplied area was obtained from a COSANPA technical document. Rates 150 l/inhab.day and 1.2 respectively comprised mean daily consumption per capita and the coefficient of the day with the highest consumption.

$$Q_{\max} = \frac{P \times q}{86400} \times k1 \qquad (1)$$

Storage recommendations in ER, equivalent to 1/3 of maximum daily demand, were followed. Similarly, NBR 12.217 (1994) recommendations on the use of factor 1.2 to increase safety in ER's useful volume were followed too. Stage 3 comprised simulations of the operational route with volumes from Calculations 1 and 2 to compare hydropower efficiency in the pumping system and water storage, specifically with regard to electricity consumption and costs.

Epanet 2.0 and data, retrieved at Stage 1, were employed, involving hourly water consumption, tube diameters, CMB features and others. Deployment of CMB 1, 2 and 3 at minimum, medium and maximum levels were taken into account. Electricity bill rates at peak and non-peak hours (R$ 0.27/kWh and R$ 0.40/kWh) established by the Electricity Company of Pará (CELPA) were also investigated.

Simulation results compared the difference between volumes calculated. Impact on the hydropower efficiency was verified according to consumption (in kWh) and electric energy costs (in Brazilian real). Tables and graphs were prepared with Microsoft Office Excel and Minitab 18.

RESULTS AND DISCUSSION

Analyses of documents and technical visits have demonstrated water distribution during 24 hours per day in the Sector Guanabara. Three CMBs have been installed in parallel (2+1) in the TWS, each with 3.2 m of ductile cast iron tubes 300 mm in the suction line and 37.93 m of cast iron 400 mm in the calque line.

ER was built in concrete, in a round shape, with a capacity of 500 m3 and useful height of 7.0 m, bottom at 45.15, and maximum and minimum levels at 52.15 and 45.15, respectively, featuring land area at 19.80 m and discharge level at 52.15. ER's exit tubes (cast iron 400 mm) are connected to the water distribution network of the Rua Jardim Esmeralda.

Further, population increase and delay in expansion public works of the storage unit jeopardized the operational route of the sector Guanabara. In fact, ER became a mere passage reservoir without any function in water storage. The useful volume of the ER was reevaluated according to NBR 12.217 (1994) so that the situation could be solved.

Calculation 1 – with data of consumption curve

Hourly discharge curve of water supplied to the distribution network was calculated, foregrounded on data from the previous stage. Mean pumping discharge rate of 349 m^3/h was calculated (**Fig. 2**). Curve refers to the measurement period and represents pumping condition during filling and discharge periods. The above is different from the curve established for the ER project.

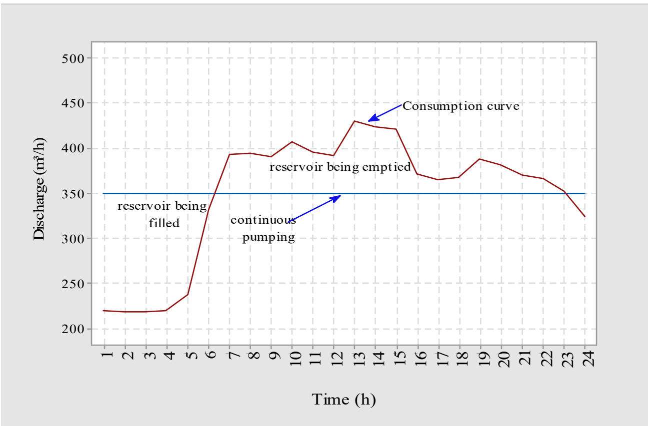

Fig. 1. Hourly water consumption curve of the Sector Guanabara – continuous pumping.

Data of hourly discharges for supply and distribution of the Sector Guanabara were compared for the calculation of water storage capacity of the ER. Total daily discharges (∑Q) were divided by 24 hours (T) and mean discharge rate of daily consumption (QM) was calculated by Equation 2, corresponding to 349 m³.

$$QM = \frac{\sum Q}{T} = \frac{8390.15}{24} = 349 \text{m}^3 / h \qquad (2)$$

QM is the rate of pumped discharge to ER, whilst consumption rates per hour were calculated for exit (distribution) discharges. The difference between pumping discharge (QB) and distribution discharge (QD) was calculated, as Table 1 shows.

Further, positive rates of difference between pumping and exit discharge (QB – QD) were added together, with a product of 671 m³. Safety factor rate of 1.2 recommended by NBR 12,217 (1994) in item 5.1.2 was applied, with a useful volume of ER at 838 m³.

Table 1. Calculation of useful volume of reservoir – differential volumes.

Hour	Pumping discharge QB (m³/h)	Distribution discharge QD (m³/h)	QD - QB	
			+	-
00:30:00	349.59	218.72	130.87	
01:30:00	349.59	218.69	130.90	
02:30:00	349.59	219.86	129.73	
03:30:00	349.59	222.35	127.24	
04:30:00	349.59	287.15	62.44	
05:30:00	349.59	361.03		-11.44
06:30:00	349.59	403.13		-53.54
07:30:00	349.59	389.31		-39.72
08:30:00	349.59	400.12		-50.53
09:30:00	349.59	402.91		-53.32
10:30:00	349.59	392.28		-42.69
11:30:00	349.59	407.82		-58.23
12:30:00	349.59	433.72		-84.13
13:30:00	349.59	419.64		-70.05
14:30:00	349.59	399.83		-50.24
15:30:00	349.59	366.52		-16.93
16:30:00	349.59	364.96		-15.37
17:30:00	349.59	377.60		-28.01
18:30:00	349.59	389.814		-40.23
19:30:00	349.59	374.96		-25.37
20:30:00	349.59	369.77		-20.18
21:30:00	349.59	360.74		-11.15
22:30:00	349.59	343.24	6.35	
23:30:00	349.59	265.97	83.62	
Total	8,390.13	8,390.13	671.14	-671.14
Mean discharge (8,390.13/24)		349.59		
Useful Volume – ER (m³) + 1.2			838	

Calculation 2 – without consumption curve data

Since there are no reliable data on the assessment of useful volume according to item 5.1.2 of NBR 12,217 (1994), a specific technical and economic analysis should be performed that would justify the rate used in the calculation. In our case, data retrieved from COSANPA and LENHS/UFPA reports were employed, namely, rates of 27,250 inhabitants (P), rate of 150 l/inhab.day of mean daily consumption per capita (q) and rate of 1.2 (k1) of the coefficients of the day with the greatest consumption. Equation 3 calculated maximum demand of water on the day with the greatest consumption rate (Qmax).

$$Q_{\max} = \frac{P \times Q}{86400} \times k1 = \frac{27250}{86400} \times 1.2 = 56.77 \frac{L}{S} = 4905 \text{m}^3 / \text{day} \qquad (3)$$

Following recommendation by NBR 12,217 (1994), rate, equivalent to 1/3 of maximum daily demand (Q_{max}), was calculated by Equation 4.

$$V = \frac{Q\max}{3} = \frac{4905}{3} = 1635 \text{m}^3 \qquad (4)$$

For safety, NBR 12,217 recommends that rate (the result of 1/3) be multiplied by safety factor (1.2). Total useful volume of ER reached 2,043 m, as Equation 5 demonstrates.

$$V_{useful} = 1635 \text{m}^3 \times 1.2 = 2043 \text{m}^3 \qquad (5)$$

Consequently, useful volume of Calculations 1 and 2 are respectively 67% and 308% higher with regard to volume in Sector Guanabara. Difference in calculated volumes reached 58% and indicated the relevance of monitoring.

Comparing electric energy consumption and costs

Epanet 2.0 simulations were used to calculate daily electricity consumption and cost rates for useful volumes of storage 838 m³ (Calculation 1) and 2,043 m³ (Calculation 2), taking into consideration the functioning of CMB 1 and 3 between minimum and maximum water levels (WL), and of CMB 3 between minimum and medium WL. The 838 m³

ER's useful volume was used to verify all CMBs at peak hours (Figure 3) and identified 2, 2 and 3 operations per day of CMB 1, 2 and 3 respectively. On the other hand, increase in the useful volume of RE (2,043 m³) improved significantly operational route, since the functioning of CMB 3 was not required. Further, the other two CMBs (1 and 2) were not employed in peak hours. A greater volume enhanced the identification of only 1 and 3 operations of CMB 1 and CMB 2, respectively (**Fig. 4**).

Increase in ER's useful volume was verified, with a decrease in the total number of CMBs' operation hours, ranging between 47 h/day, with a volume of 838 m3, and 30 h/day, with a volume of 2,043 m³. **Table 2** demonstrates function times of each CMB for the simulations employed. Simulated route demonstrated 987 kWh/day in electric energy consumption, with a useful volume of 838 m³, namely 49% for CMB 1, 40% for CMB 2, and 11% for CMB 3. It should be highlighted that 15 kWh (2%) of electric energy consumption in TWS occurred during peak hours.

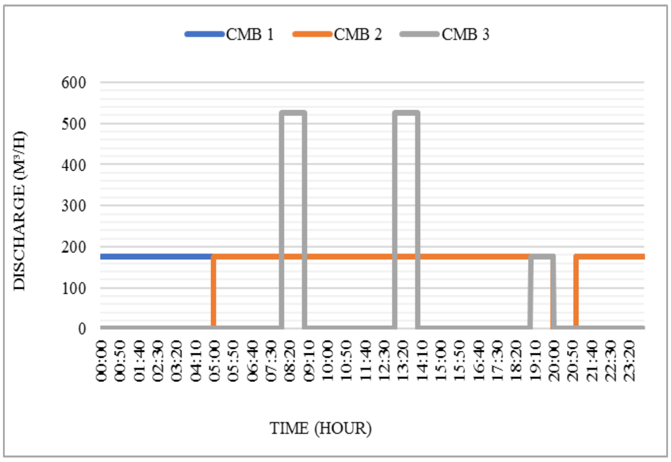

Fig. 2. Number of operations for Calculation 1 - CMBs 1, 2 and 3 (838 m³).

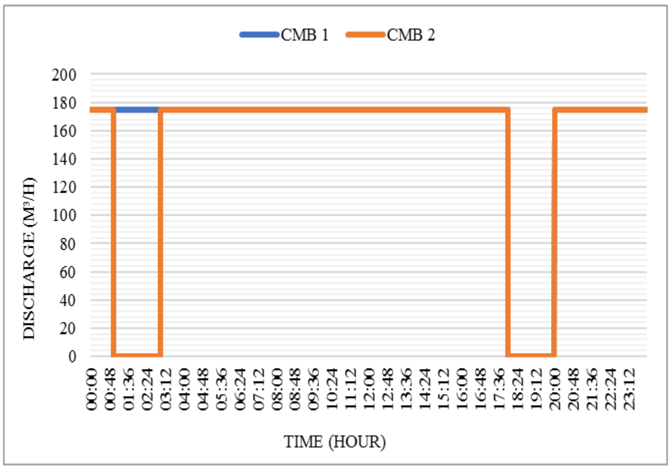

Fig. 3. Number of operations for Calculation 1 - CMBs 1, 2 and 3 (2,043 m³).

Table 2. Number of operations.

Calculation		CMBs	Operation levels			Number of operations/day			Functioning hours/day		
nº	ER (m³)		Min	Med	Max	H.F.P	H.P	Total	H.F.P	H.P	Total
1	838	CMB 1	0	3	7	1	1	2	19	2	21
		CMB 2	0	3	7	1	1	2	19	2	21
		CMB 3	0	3	-	2	1	3	3	2	5
2	2.043	CMB 1	0	3	7	2	-	2	15	-	15
		CMB 2	0	3	-	2	-	2	15	-	15

*H. F. P: peak hour for the electric sector.

Table 3. Consumption of Electric Energy (kWh)

Calculation		CMBs	Operations level			Eletric energy					
						kWh/day				kWh/month	kWh//year
n°	ER (m³)		Min	Med	Max	H.F.P.	H.P.	Total (CMB)	Total	Total	Total
1	838	CMB 1	0	3	7	478	5	483	987	29609	355311
		CMB 2	0	3	7	394	5	399			
		CMB 3	0	3	7	100	5	105			
2	2043	CMB 1	0	3	7	440	5	440	818	24542	294503
		CMB 2	0	3	7	378	5	378			

*H.F.P: peak hour in the electric sector.

Simulation with ER's greatest useful volume (2,043 m³) provided a 17% decrease (169 kWh) in daily consumption of electricity, with 818 kWh/day in TWS. Furthermore, water was not pumped during peak hours; CMB 3 was not operating and 43 kWh/day and 21 kWh/day were respectively saved in CMB 1 and in CMB 2, when compared to data from the previous simulation, as Table 3 shows.

Electric energy costs with the simulated routes were R$ 398.00/day and R$ 298.00/day for useful storage volumes of 838 m³ and 2,043 m³. It is relevant to underline that costs of the smallest volume are the sum of peak and non-peak hours. Cost forecast of electric energy provides a saving of R$ 35,903.00/year and R$ 359,030.00/10 years, with the use of ER's greatest useful volume (2,043 m³), or rather, a 26% decrease of total TWS costs, as **Table 4** demonstrates. Since the two simulations were undertaken with CMBs of similar capacity and at maximum water level in ER prior to the start of peak hour, the greatest water storage capacity favored the best operation route with ER's useful volume of 2,043 m³, featuring only two CMBs functioning per day and with less operation time, less kWh consumption and less electric energy costs.

In spite of a simpler calculation procedure, without employing the water consumption curve during 24 h, ER calculation by NBR 12,217 (1994) provided better hydropower rates when compared to the two simulations. This was due to greater operational flexibility, ceasing of water pumping in peak hours and less electric energy consumption and cost rates. However, NBR 12,217 (1994) should be updated to optimize the calculation of the reservoir's useful volume according to operation performance and hydroelectric efficiency.

CONCLUSION

Calculation alternatives provided different rates for ER's useful volume, namely 838 m3 and 2.043 m3. The former directly impacted rates to be invested in construction, whilst the latter on the operational costs with electricity.

The calculation of useful volume of 838 m3 occurred with consumption curve and is more compatible with the users' hourly water demand. Although it best represents facts, it has the lowest operational flexibility to avoid CMB's operation during peak hours.

Calculation by daily discharge equation provided ER's useful volume of 2,043 m3, which directly depended on the coefficient per capita (150 l/inhab.day), which, in our case, was the closest to mean rate for Brazilian municipalities.

Best applicability of calculation alternatives should be analyzed by the planner. When assessing construction costs, the planner frequently decides for the ER's lowest volume. However, when electricity costs are underscored, a greater volume is indicated for the Sector Guanabara since it has the best adjustments in the number and period of operations of CMBs of TWS.

When consumption rates and electricity costs are taken into account, 987 kWh and R$ 398 with volume 838 m³ and 818 kWh and R$ 298 with volume 2,043 m³, the later saves R$ 359,030.00 during 10 years. Results show that the best hydropower option is the calculation of useful water with a more simplified calculation recommended by NBR 12,217 (1994) (without consumption curve).

The Norm lacks any calculation procedures for consumption and costs saving in electricity. The criterion may be incorporated in a future upgrading of the NBR 12,217 (1994), specifically with regard to calculation procedures of the ER's useful volume. Current research does not exhaust all discussions on the importance of hydropower efficiency in the calculation of water pumping and storage systems. It must be normatized and undertaken for each situation specifically, following the aims of the responsible person of the ER project. Significant electricity consumption and costs may be reduced with the proper calculations of the useful volume of the reservoir. It is an important contribution for the efficiency and sustainability of water supply service providers.

Table 4. Costs of Electric Energy (R$).

Calculation		CMBs	Day			Eletric energy costs						
						R$/day				R$/month	R$/year	R$/10 years
n°	ER (m³)		Operations	H. Func.	kWh	H.F.P.	H.P.	Total	Total	ToTal	ToTal	ToTal
		CMB 1	2	21	483	168	7	175	398			
1	838	CMB 2	2	21	399	145	7	152		398	143108	1431080
		CMB 3	3	5	105	64	7	71				
2	2043	CMB 1	2	15	440	157	-	157	298	298	107205	1072050
		CMB 2	2	15	378	140	-	140				

*H.F.P: peak hours in the electric sector. Operations: number of operations/day. H. Func.: number of operations/day

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