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OPTIMIZATION OF THE OPERATION OF PUMPING SYSTEMS AND RESERVOIRS OF WATER DISTRIBUTION SYSTEMS WITH EMPHASIS IN ENERGY EFFICIENCY

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Abstract

Electricity costs for pumping account for the majority of operating expenses for water distribution systems. Therefore, researchers and technicians in the water sector have sought to develop techniques that minimize the consumption of electricity in these systems. The large number of elements, which can change state at any time, generates a range of possibilities that makes it difficult to determine which operational scheme is most efficient. Defining the best operating rules for pumping systems is often a complex activity. In this context, the present work presents an optimization model for water distribution systems that combines the efficient use of reservoirs with the best operational rule for activating pumping systems. Using a genetic algorithm, the developed model aims to minimize the operating costs of electrical energy in the systems. The results obtained indicated that, with a better use of the water storage infrastructure, it is possible to reduce the electricity costs of the system as a whole.

Keywords: water supply, operational rules, genetic algorithm, optimization.

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Introduction

The increase in water demand in large urban centers and the scarcity of energy resources have demanded more expensive and complex water supply systems from water utilities. Pumping stations play a key role in meeting these demands, so they are responsible for a significant portion of electricity costs in the water sector (Turci *et al*., 2019) (Chen *et al*., 2021).

The systems that operate only by gravity are rare, and many times there is a need for the use of pump stations to discharge water to various points in the network, resulting in high electricity costs. About 20% of the world's energy is consumed in pumping systems (Dadar *et al*., 2021). Therefore, the quest to improve energy efficiency has a significant impact on the sector's operations and, consequently, the reduction in energy costs (Jafari-Asl *et al*., 2021).

The energy consumption of the worldwide water sector accounted for 120 Mtoe in 2014, mainly in the form of electricity, corresponding to 4% of the total global electricity consumption (Luna *et al.*, 2019). Therefore, the search for methodologies and techniques which provide the increase in energy efficiency in the pumping systems and, consequently, the reduction in the costs with energy, has been paramount for water utilities. Nevertheless, it is important to highlight that the combat to excessive energy consumption must not compromise the quality of the supply service.

In Brazil, according to the Brazilian National System of Sanitation Information, base year 2020, the consumption of electricity in the water utilities was of 12.4 TWh, which originates a significant expense in their management and operation. On average, there is a consumption of 0.72 kWh for each cube meter provided by the Brazilian water utilities. Therefore, the efficient use of electricity allows cost reduction, better use of the existing civil and electromechanical infrastructure, in addition to postponing the application of resources to expand the systems.

The operationalization of the water distribution systems is often a complex activity. The great number of elements, which can have their states changed at any given time, generates a range of operational possibilities that hinders the efficient operation of these systems. In many cases, operational decisions are exclusively linked to the experience of technicians, who rarely have specific knowledge about hydraulic and energy efficiency. Among the various operating possibilities, there is the pumping routine (ideal solution) which results in the lowest operating cost and meets the demands and pressures established for the system.

The reduction in operational costs and energy losses in pumping systems, and the use of smart management strategies such as Optimal Pump Scheduling (OPS), are attractive options for water companies and managing authorities (Helmbrecht *et al.*, 2017; Cimorelli *et al.*, 2020b).

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Given the complexibility, the employment of optimization methods appears as an important and appropriate tool to increase energy efficiency and, thus, reduce the costs with electricity and human interference in the decisions. Finding the ideal solution for this type of non-linear problem, with various constraint, by traditional deterministic methods, is limited to relatively small systems, which have reduced search spaces (Abkenar *et al.*, 2015). For problems in large scale, several studies demonstrate that the metaheuristic algorithms provide a more efficient approach for the search of optimal solutions.

Abdallah and Kapelan (2017) ensure that the minimization of energy costs in water distribution systems is not obtained only operating the pumps during the periods of low electric tariff, but also close to their best efficiency points, in other words, a pump may cost less to work if it operates during a period of high electric tariff, but with high efficiency, instead of working during a period of low tariff, but with low efficiency.

Despite the countless publications in the past 20-30 years, the operational optimization problems in water distribution systems are far from being solved (Abdallah and Kapelan, 2019). This is due to the complexity of the problem, the lack of precision in the mathematical formulations of the problem, the number of variables involved, and the specificities of each system. Abdallah and Kapelan (2019) also affirm that there is still no consensus on the best optimization method that can provide the global optimal solution in a short computational time.

Given this problem, optimization in supply systems should not be restricted to the operation of pumps. A punctual energy efficiency plan can bring promising results, although incomplete, so it is important to have a macro view of the entire system, considering all the elements that compose it. The selection of optimal tank firing levels to control pump operation has been successful in minimizing energy costs. Research shows that using optimized tank levels saved 20% of energy consumption when compared to fixed tank levels (Luna *et al*., 2019).

The evaluation of the optimized use of the water storage reservoirs has been raised by several researchers. Chang *et al.* (2018) state that previous studies have verified the use of the reservoirs and their hydraulic characteristics, and observed that only 37.6% of the total storage capacity is used. Reservoirs are usually designed to maintain their operation at their maximum level, forcing the pumping systems to be activated several times, providing high electricity consumption.

Hence, it is important to raise that, for a better efficiency of a water supply system, not only the operational optimization of pump performance must be considered, but also a better use of the whole useful volume of the reservoirs, in order to obtain a higher economy in the electricity consumption of the whole system.

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Therefore, the main purpose of this research is to guarantee that the whole useful volume of the reservoirs be properly provided to the system, so that the pumping systems can be less required, minimizing operating costs (energy cost). In a first moment, the optimum politics of storage is determined for each tank, which will be imposed by a constraint to the problem and, subsequently, the optimal scaling of the pumps is performed by the application of the genetic algorithm (GA). GA are frequently used to approximate the solution of optimal pump scheduling problems (Cimorelli *et al.*, 2020b). Recent research demonstrates that a well-implemented GA is able to provide excellent solutions (e.g., Luna *et al.*, 2019; Cimorelli *et al.*, 2020a, 2020b; Chen *et al.*, 2021).

Materials and methods

The problem of this research is characterized by the use of resources from the Operational Research, with the help of a hydraulic simulation model, aiming at optimizing a nonlinear objective function with constraints. The optimization model determines the best operational rules for the activation of pumps in water distribution systems, by the optimization of the use of reservoirs and using the Genetic Algorithm. Thus, it is possible to reduce the costs with electricity, guaranteeing the continuity in the supply.

To obtain efficient operational strategies for water distribution systems, López-Ibáñez *et al.* (2008), Maier *et al.* (2014), De Paola *et al.* (2017), and Abdallah and Kapelan (2017) claim that the use of hydraulic simulators coupled to optimization algorithms brings positive results to locate the best solutions to operationalize the system. The hydraulic simulator evaluates the solutions indicated by the algorithm, respecting the hydraulic viability of the system and energy cost.

The proposal of this work is to use the genetic algorithm (GA), together with the hydraulic simulator EPANET, to define optimum operational routines of water pumping systems, considering the most efficient use of the water storage tanks, and thus minimizing the costs with electricity.

The genetic algorithm minimizes a nonlinear objective function, determining the best operating rule to be applied to the water distribution system, considering the consumption demands; the initial boundary conditions; and the hydraulic, physical and operational constraints of the system. Among the constraints, there is one which is defined determining that the pump be activated only when the maximum volume is used, guaranteeing its better use.

Mathematical Formulation

The objective function considers the pumps' total power consumption, which is the hydraulic power divided by the pumping system efficiency; the value of the energy tariff; the number of

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pumps in the pump station; the number of pumping systems; and operation time, which, for this work, will be in the planning horizon of 24 hours.

The decision variable considered will be the operational state of the pumps, in other words, at each time interval, an analysis will be performed regarding the need for activating the pumps to maintain the system working without interruptions, but with its optimized consumption.

Therefore, the objective function can be expressed as the sum of energy consumption of the pumping systems, within the operational horizon of 24 hours, by the energy consumed by each pump within the interval of one hour if it is activated or not, according to Equation (1):

$$\text{Min } C_t = \sum_{n=1}^{N} \sum_{t=1}^{24} \frac{9.8 \times Q \times H}{\eta} \times TF \times \Delta t$$

Equation (1)

Where:
C_t: Cost with electricity ($);
Q: pumped water flow (m^3/s);
H: Pump head (m);
η: Pumping system efficiency;
TF: Energy tariff ($/kWh);
Δt: Number of hours in which the pump is activated.

The technical feasibility of the optimal solution is ensured by the inclusion of method constraints, which guarantee the satisfaction of water demands at adequate pressure levels and the maintenance of suitable water tank levels. The system constraints can be expressed as follows:

a) *Maximum level and minimum level of the reservoirs*: the levels of the reservoirs must fit within the minimum and maximum limits during the whole simulation period, guaranteeing the continuity of supply to the system. Equation (2) shows the interval that must be respected for the constraint to be met.

$$H_j(min) \leq H_j(t) \leq H_j(max)$$

Equation (2)

Where:
$H_j(min)$: minimum level of reservoir j (meters);
$H_j(t)$: level of reservoir j at time t (meters);
$H_j(max)$: maximum level of reservoir j (meters).

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b) *Pressures on the network*: the pressures on all nodes have to respect the maximum and minimum limits for each time limit analyzed. This parameter guarantees the continuity of water supply to the system, as shows Equation (3).

$$P_i(min) \leq P_i(t) \leq P_i(max) \quad \text{Equation (3)}$$

Where:
$P_i(min)$: minimum pressure required in node i;
$P_i(t)$: pressure on node i at the time interval t;
$P_i(max)$: maximum pressure required in node i.

c) *Maximum use of the reservoirs:* This constraint determines that the maximum volumes of the reservoirs be used, aiming at optimizing the operation and, thus, at the contribution to a higher efficiency in the costs with energy. Equation (4) expresses mathematically this system constraint:

$$Er = \frac{\sum_{r=1}^{nr} V(cons)}{V(cap)} \quad \text{Equation (4)}$$

Where:
E_r: Efficiency index of reservoir r (%);
$V(cons)$: Volume used in reservoir r (m^3);
$V(cap)$: Volumetric capacity of reservoir r (m^3);

d) *Status of initial recovery of the reservoirs:* for an operational horizon of 24 hours, it is established that the final operating levels of the reservoirs must be equal or superior to the pre-established initial levels. This constraint guarantees the continuity of the operation in the subsequent periods (Equation 5):

$$L_r(fin) \geq L_r(ini) \quad \text{Equation (5)}$$

Where:
$L_r(fin)$: Level of the reservoir at the end of the schedule of 24h.
$L_r(ini)$: Level of the reservoir in the beginning of the schedule.

Hydraulic simulation

Hydraulic simulation using computational tools is the most effective way to analyze the behavior of real water distribution systems. These tools used mathematical models that are capable of satisfactorily representing the processes of these systems.

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The hydraulic simulator used in this study was EPANET (developed by the US Environmental Protection Agency), which is the commonly used open-source software for hydraulic and quality simulations of supply networks (Khatavkar and Mays, 2019). EPANET uses a hybrid node-loop approach to hydraulically balance the system, solving the flow continuity (mass conservation) and headloss (energy conservation) equations of the network at a given point in time (Bonthuys *et al.*, 2020). It was chosen because it is widely adopted by researchers (e.g. Bonthuys *et al.*, 2020; Naidu *et al.*, 2020; Naserizade *et al.*, 2021; Macêdo *et al.*, 2021) and water technicians. As it is open software package, it has already been widely evaluated and tested by the scientific community. EPANET is especially used in optimization problems because it allows for iteration between algorithms developed in different programming languages (Basic 6.0, Basic .NET, MATLAB, C #, Python and C ++) with the calculation routines of the simulator itself (Vegas Niño *et al*., 2018).

To apply the computational model, it was necessary to develop an auxiliary software for the iteration between EPANET and the optimization algorithm. This software was written in the Python 3.8 language by the Water Network Tool for Resilience – WNTR (Klise *et al.*, 2018). WNTR is a Python package designed to simulate and analyze the resilience of water distribution systems. Here, a network refers to the collection of pipes, pumps, valves, junctions, tanks and reservoirs that make up a water distribution system. WNTR has an application programming interface that is flexible and allows changes in the system structure and operations, along with the simulation of disruptive incidents and recovery actions (Klise *et al.*, 2018).

WNTR is accessible at EPANET by a plug-in, improving the resources of hydraulic analysis of the US EPA simulator. In this configuration, EPANET acts as a WNTR input-output interpreter (Sela and Housh, 2019). US EPA, in partnership with the Sandia National Laboratories, has developed this tool to explore the capacity of their systems to handle disruptive incidents and guide the planning necessary to make systems more resilient over time in a single software framework (Klise *et al.*, 2018).

Optimization by the Genetic Algorithm
Optimal pump scheduling (OPS) problem consists of seeking a sequence of pump actuations (ON/OFF) able to achieve the minimum energy consumption during an operating cycle (Figure 1). OPS problem is classified as a large combinatorial discrete nonlinear nondeterministic polynomial-hard (NP-hard) optimization problem. Such problems are nonlinear and non-convex, and deterministic optimization techniques cannot usually solve them. Therefore, several evolutionary algorithms have been developed and are available to solve OPS problems. The traditional algorithm is the genetic algorithm (GA) that has been widely applied and developed during years showing very good performance (Niccolai *et al*., 2021).

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In this research, GA determines the best solution from the systematic evaluation of a random group of solutions (initial population). It was chosen because it is a widespread algorithm in the scientific community, easily adaptable to optimization problems and water distribution networks. The parameters used were based on recent studies, Abkenar *et al.* (2015), Bi *et al.* (2015), Chang *et al.* (2018) and Luna *et al.* (2019), where they have already been tested and evaluated, proving its efficiency for this type of research.

Pump	Pump 1						Pump 2						Pump 3					
Chromosome	1	1	0	1	...	1	0	0	0	1	...	0	0	1	1	1	...	0
Hour	1	2	3	4	...	24	1	2	3	4	...	24	1	2	3	4	...	24

0 = ON
1 = OFF

Figure 1. Binary representation of a chromosome for 3 pumps and 24 intervals.

GA is a heuristic inspired by Darwin's theory of natural evolution, reproducing the process of natural selection, in which the most fit individuals in a population are selected for breeding to produce offspring for the subsequent generation (Bagloee *et al.*, 2018; Luna *et al.*, 2019). The analogy consists in maintaining and developing the solutions that are closer to the optimum, whereas population diversity is used to search for more solutions.

As in Genetics, the solutions are described as a group of chromosomes which contain a chain of genes that corresponds to the controls (condition on and off) of a pump during the operating period (for instance, 24 h) (Abkenar *et al.*, 2015). After assembling the chromosomes of all pumps in the network, a solution is generated. From a group of random solutions (initial generation – parents) GA optimization starts. To update the current population, the algorithm selects a parent chromosome based on its fitness function and by crossing and mutation operators, descending chromosomes result, which will be used to form the population for the subsequent generation with better solutions. After repeating this process several times, GA advances towards an optimal solution, until the stopping criterion is reached, and the last generation will contain a group of optimum solutions.

The parameters used in the stopping criteria of the algorithm, such as: population size, mutation rate, breeding rate, number of iterations; are extremely important items and which can directly interfere in optimization. Increasing the number of solutions, that is, population size, will cover a larger search space, increasing the probability of finding a larger number of optimum solutions, and consequently the processing of data will take more time and computational expenditure. Nevertheless, for problems regarding supply network optimization, the hydraulic analysis requires a little more of the algorithm. To have a notion, in a problem of pump

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activation, the dimension of the search space for the solution of the problem is defined as $2^{(N \times T)}$, where N is the number of pumps and T, the time of analysis. In this sense, the choice of parameters which may help finding better solutions needs to be careful.

Results and Discussions

The proposed model was applied to the test network presented by Van Zyl *et al.* (2004). It is a network with simple layout; nonetheless, it has complex operation, which is appropriate for the application of the optimization, besides presenting several pieces of information which enhance the hydraulic analysis. Another motivation for the use of this system is that it has been adopted as reference for countless works in the field of optimization (Van Zyl *et al.*, 2004; López-Ibáñez *et al.*, 2008; Makaremi *et al.*, 2017; De Paola *et al.*, 2017; Cimorelli *et al.*, 2020a, 2020b; Karami *et al.*, 2020), demonstrating it is a good model for the study.

More detailed information on this system, such as energy price, consumption pattern, pump curves, efficiency curves, are found in Van Zyl *et al.* (2004). Figure 2 shows the network's layout. It contains all main elements of a typical water distribution system: a source of drinking water, three pumps, two tanks, and a retention valve.

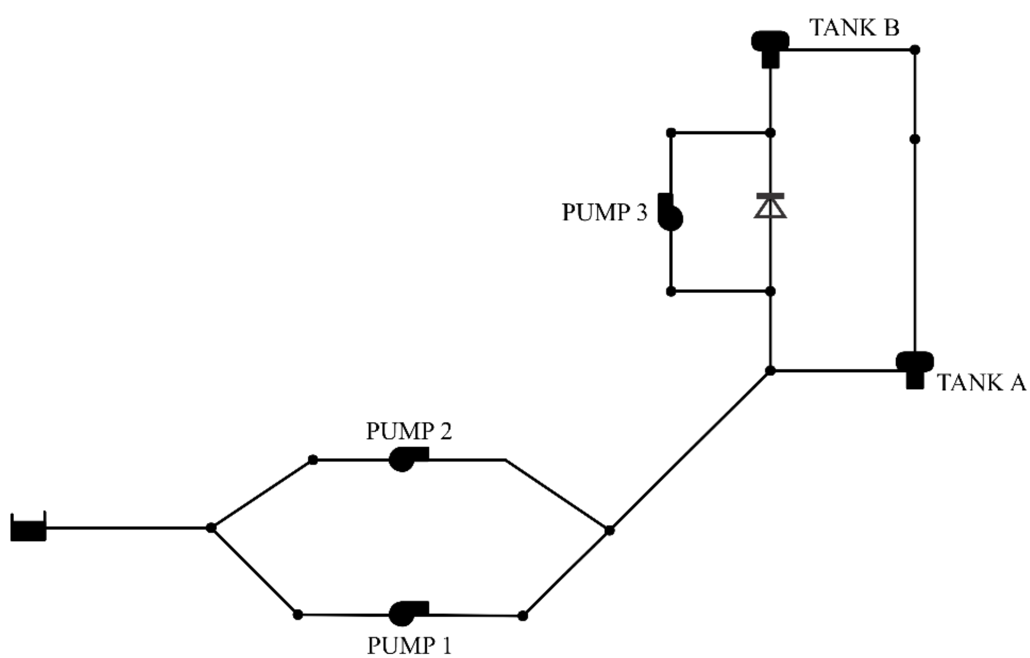

Figure 2. Layout of the test network Van Zyl (2004) in EPANET.

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From the main source (FLR) comes the main pumping station composed of two identical pumps (PUMP 1 and PUMP 2) in parallel, which are responsible for feeding two reservoirs of varying level - RVL (TANK A and TANK B), at different elevations, which are fed by a booster (PUMP 3). PUMP 1 is controlled by the level of reservoir A, whereas PUMP 2 is controlled by the level of TANK B. The efficiency curves of the pumps were selected to define the similar unit pumping costs for the pumps operating alone and in parallel.

PUMP 3 is installed in the section that feeds the tallest of the two reservoirs B. When both pumps in the pumping station are operating, the booster increases the level of TANK B. Nevertheless, when PUMP 1 and PUMP 2 are operating, PUMP 3 transports water from TANK A to TANK B. The two tanks are connected by a pipe, whose drainage is by gravity. The demands vary according to a typical residential demand pattern with the peaks occurring at 7:00 and 18:00 (Figure 3). When the demand is high, the water is extracted from both tanks to supply the demand. Conversely, under conditions of low demand, the water is transported by gravity from TANK B to TANK A (van Zyl *et al*., 2004).

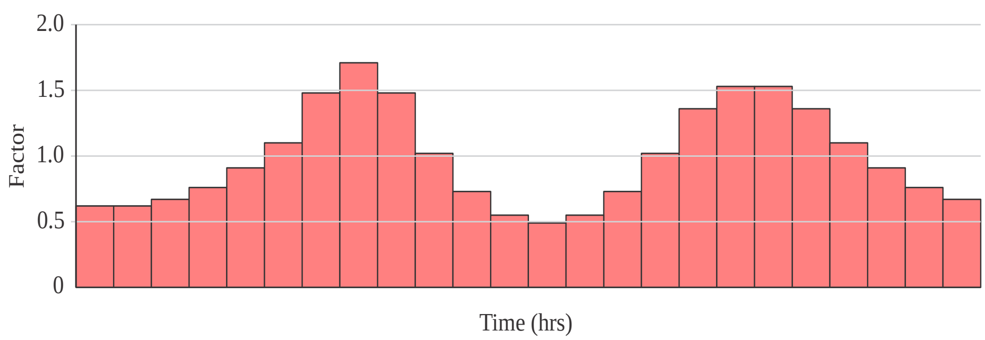

Figure 3. Demand pattern of the test network Van Zyl (2004).

Simulation before optimization

A simulation of the network operation was performed before applying the optimization. For this analysis, the result presented in Table 1 was achieved. The total cost per day was $ 422.17. For this example, the authors have not defined a currency to determine the price of energy; therefore, the values for the costs are expressed in undefined monetary values.

The analysis of the behavior of tanks A and B was performed for a projection simulation of 10 days (240 hours). The importance of performing this kind of analysis is to evaluate whether the tanks are being used well and whether, for a larger period than one day of schedule (24 hours), their behaviors will remain constant and will not compromise the water supply of the system. Figures 4 and 5 present, respectively, the behavior of reservoirs A and B for a schedule of 240 hours.

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Table 1. Energy report for the simulation before optimization.

Property	Pump1	Pump2	Pump3
Average power (Kw)	141.72	140.11	33.95
Percentage of usage (%)	27.38	57.63	68.21
Specific energy consumption (kWh/m³)	0.24	0.24	0.07
Cost per day ($)*	76.30	189.85	47.38

** Because it is a hypothetical network, the authors who proposed this example chose not to specify a currency for the energy tariff.*

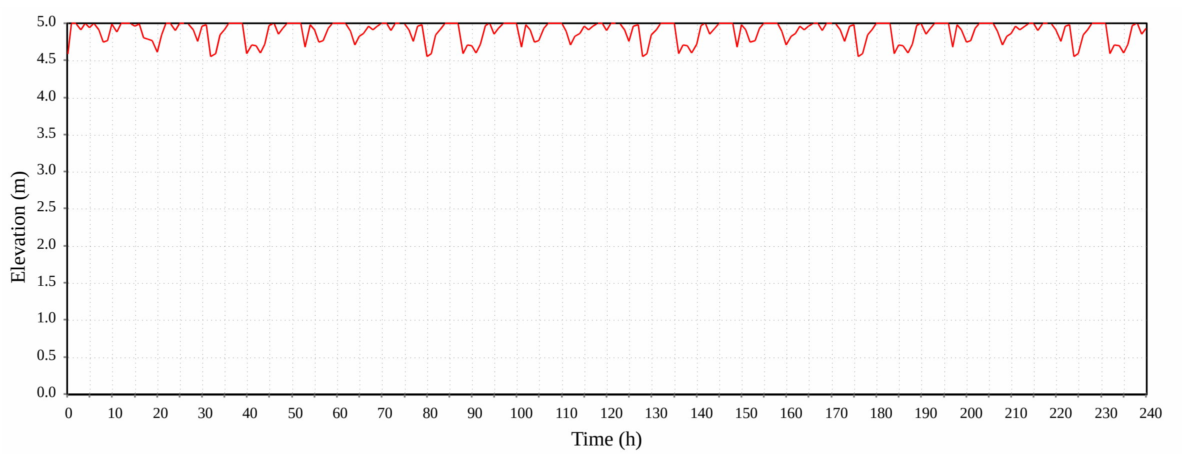

Figure 4. Behavior of TANK A for a simulation of 10 days.

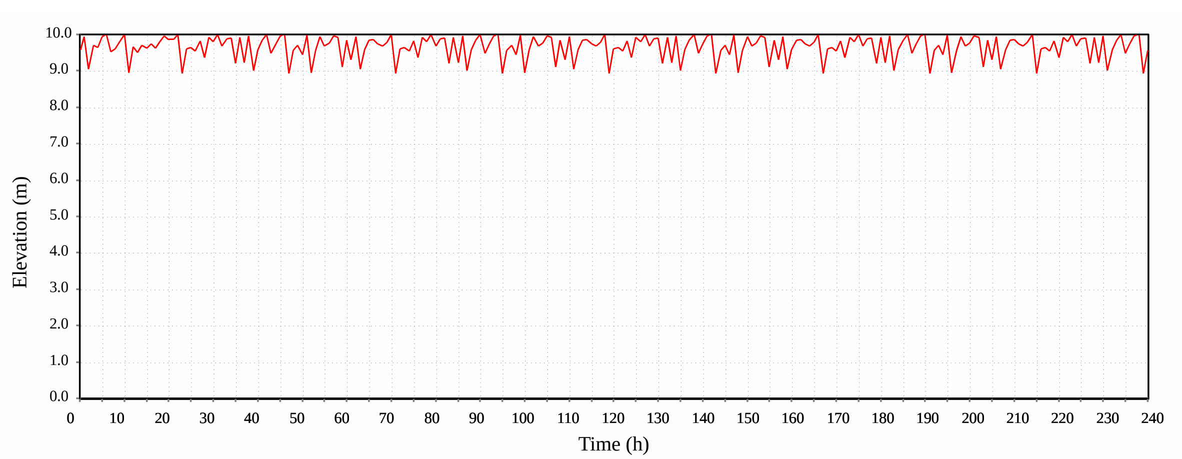

Figure 5. Behavior of TANK B for a simulation of 10 days.

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Analyzing the behavior of the level of the tanks, it is possible to observe that there is an inconsistency in its use, since in most of the schedule, they do not reach the minimum level, in other words, the reservoirs are being underutilized.

Optimization results

For the optimization, as reported in the previous item, the Genetic Algorithm was applied. The aim is to minimize the value of the objective function related to the daily electricity cost, subjected to system constraints, previously raised.

GA basically is an algorithm for problems without constraints. To insert the constraints to the problem, a fitness function was determined, where all system constraints were added to the objective function as penalties. These values are defined according to the degree of relevance of the constraint. The more important the constraint to maintain the good operation of the system, the higher the value of the penalties. For the problem addressed, the penalty values defined are presented in Table 2.

Table 2. Penalty values for each constraint of the fitness function.

Constraints	Penalties
Maximum and minimum levels of the reservoirs (continuity of the supply)	100,000
Maximum use of the reservoirs	100
State of reservoir recovery	10

In defining the optimal pump scheduling (OPS), a safety margin of 10% of the total capacity of each reservoir was assured, destined to an emergency reserve, that is, the total storage capacity of the tanks was 90%.

The parameters of the GA algorithm were defined based on recent research studies in the field of optimization in water resources, such as Abkenar *et al.* (2015), Reca *et al.* (2017) and Chang *et al.* (2018). After some tests, these values were adjusted to the problem and adopted according to Table 3.

After applying the optimization, a new simulation is performed by EPANET, whose results are arranged in Table 4. They indicate a reduction in the value of the daily electricity cost when compared to the value without the optimization. For the new simulation, the analysis of the behavior of tanks A and B was also performed for the period of 240 hours (10 days). Figures 6 and 7 show these results.

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Table 3. Entry parameters of the Genetic Algorithm.

Parameters	Values
Max iteration	200
Population size	100
Mutation probability	0.5
Elite ration	0.1
Crossover probability	0.9
Parents' portion	0.3
Crossover type	Two points
Type of mutation	Uniform by center
Type of selection	roulette

Table 4. Energy report for the simulation after optimization.

Property	Pump1	Pump2	Pump3
Average power (Kw)	127.58	122.31	27.67
Percentage of usage (%)	66.66	47.64	66.66
Specific energy consumption (kWh/m³)	0.28	0.28	0.06
Cost per day ($)*	185.43	164.16	41.10

** Because it is a hypothetical network, the authors who proposed this example chose not to specify a currency for the energy tariff.*

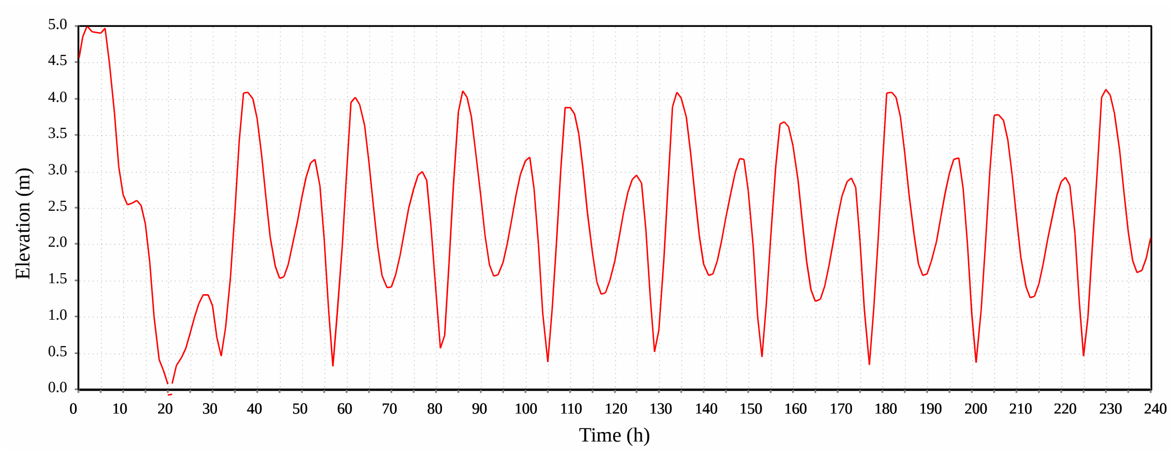

Figure 6. Optimized behavior of TANK A for a simulation of 10 days.

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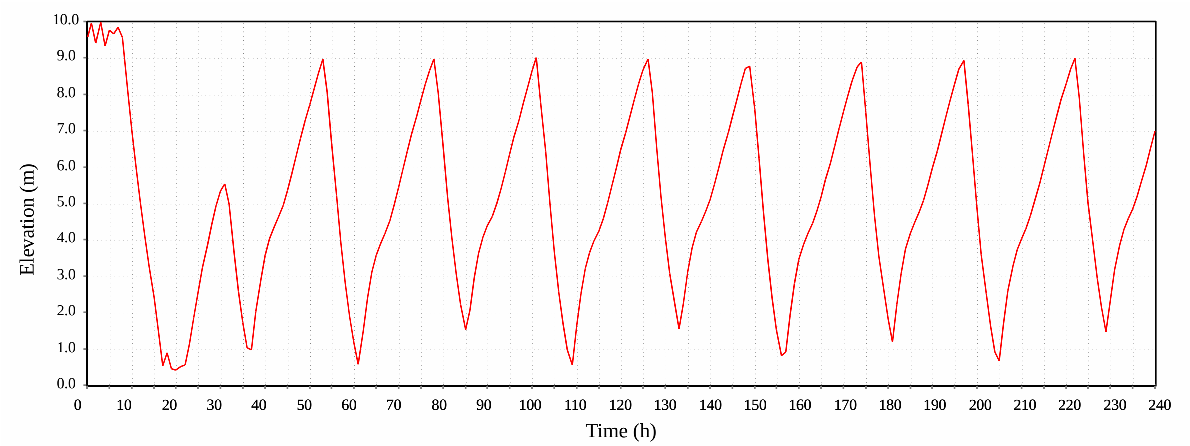

Figure 7. Optimized behavior of TANK B for a simulation of 10 days.

Analyzing the results, after optimization, it is possible to verify a more efficient behavior in the use of the reservoirs. They can operate at their maximum capacity, using (disregarding the emergency reserve) their totality of storage. It is also observed that the exploitation of the use of the reservoirs together with the optimization resulted in the minimum number of pump switches. According to Lansey *et al.* (1994), an operation schedule that turns the pumps on and off several times may increase wear and, consequently, the costs with maintenance. For this reason, authors, such as López-Ibáñez *et al.* (2008) and Costa *et al.* (2010), use this information as a constraint of the problem.

Optimization of pumping systems resulted in a reduction in daily electricity costs of around 26%, which shows that only with a better use of the structure arranged in the supply system is it possible to achieve important results regarding energy efficiency. When the results are compared with other works in the literature, e.g., Van Zyl *et al*. (2004), López-Ibáñez *et al*. (2008), De Paola *et al*. (2017) and Jafari-Asl *et al*. (2021), it is observed that the proposed method presented better results (Table 5).

Table 5. Comparison of total daily energy costs between proposed method and other works

Work	Total daily energy cost ($/day)
Van Zyl *et al*. (2004)	344.2
López-Ibáñez *et al*. (2008)	322.5
De Paola *et al*. (2017)	323.5
Jafari-Asl *et al*. (2021)	327.2
Proposed approach	313.5

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Conclusions

The present article showed the application of a model of optimization, based on the Genetic Algorithm, that aims at finding the best operational strategies for pump activation, to minimize the costs with electricity in the water supply systems. The work demonstrated that the efficient use of the storage capacity of the reservoirs and, in parallel, the application of an optimized schedule for pump activation, make it possible to have a greater use of the system's infrastructure and, consequently, a reduction in the costs with electricity. The comparison of results showed the capability of the proposed method to achieve an optimal solution.

The importance of the number of pump switches during the process of operation schedule optimization was observed. According to recommendations from other studies in the literature, the maximum number of three activations per day was adopted. Despite being a difficult criterion to measure, some authors consider that the number of switches is directly related to pump wear and, therefore, to the costs with maintenance.

Although the proposed method was applied in a test network, the model proved to be acceptable for real problems, since it is easily applicable, with the need of only small adaptations to suit other networks.

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