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An MINLP model for the minimization of installation and operational costs in water distribution networks

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ABSTRACT. Water Distribution Networks (WDN) are important systems for industrial processes and urban centers. WDN can be formed by reservoirs, pipes, nodes, loops, and pumps and its complete design can be formulated as an optimization problem. The majority of published papers in the open literature use meta-heuristics for problem solution, as well as hydraulic simulators to calculate pressures and velocities. In the present study, a Mixed Integer Non-Linear Programming (MINLP) model was developed to the synthesis of WDN considering the minimization of the WDN total cost, given by the sum of installation and operational costs, which is the novelty in the paper. All the hydraulic calculations were included in the model (mass and energy balances and velocity and pressure upper and lower bounds), avoiding the use of additional software. Reformulation techniques are applied to the model considering the use of logarithms and disjunctive programming. Two case studies extracted from real WDN were used to test the model and global optimization techniques were employed to achieve the results. The results obtained show that the operational costs play an important role in the WDN system design.

Keywords: water distribution networks; optimization; mathematical programming; disjunctive programming; MINLP.

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Introduction

Water supply is essential in the chemical and petrochemical industries as well as in urban centers. Water must be rationally explored and distributed at an adequate pressure and velocity, considering the design of piping and additional equipment. Water pumping stations are responsible for water pressuring with the aid of elevated reservoirs. The main components of a WDN are reservoirs (tanks), pipes, demand nodes, pumps, and valves. Demand nodes can form loops and looped networks are complex systems. Generally, two distinct approaches are used for the synthesis of WDN. The first one is known as Single and considered single pipes, in which each pipe has only one diameter. The second one is known as Split-pipe and each pipeline branch can have one or more different diameters. For the optimization of WDN, the Single approach avoids solutions with a large number of diameters per pipe branch, where additional pressure drops can occur in pipe junctions.

The majority of published papers in WDN optimization consider the minimization of the network installation cost (pipes diameter and cost) subjected to mass balances in demand nodes, energy balances in network loops and pressure and velocity limits. Tube diameters are generally selected from a set of available commercial diameters with different costs. In this way, the optimization problem can consider discrete variables to identify the more suitable diameter from a set of available ones. In general, this optimization problem has non-convexities and nonlinearities and, when integer variables are used, the problem has an MINLP formulation, and stochastic and deterministic approaches have been used to solve the problem. If the problem is the minimization of a cost objective function and if the problem is non-convex, global optimality cannot be ensured. Due to difficulties in solving MINLP models for optimization of WDN using deterministic approaches to large scale problems, meta-heuristic based methods have been used. Moreover, to avoid problems with nonlinear equations used to calculate pressure and velocity, hydraulic simulators are used jointly with the optimization model. The most used software to check pressures and velocities is EPANET (Rossman, 2000).

Genetic Algorithms (GA), used by Savic and Walters (1997) and Kadu, Gupta, and Bhave (2008), Ant Colony Optimization (ACO), used by Zecchin et al. (2006), Honey Bee Mating Optimization (HBMO), used by Mohan and Babu (2009), Harmony Search (HS), developed by Geem (2006), Particle Swarm Optimization (PSO), used in studies of Ezzeldin, Djebedjian, and Saafan (2014), Surco, Vecchi, and Ravagnani (2017) and Surco, Macowski, Cardoso, Vecchi, and Ravagnani (2021) and Simulated Annealing (SA), in Cunha and Sousa (1999) are some metaheuristic methods applied to solve the optimization of WDN.

Multi-objectives approaches were also proposed to solve the problem. Czajkowska and Tanyimbo (2013) presented a maximum entropy-based multi-objective GA approach for the optimal design of WDN in multiple operation conditions. The hydraulic simulator EPANET was used jointly with a subroutine that calculates the entropy for the WDN configuration. A multi-objective optimization model considering the minimization of the WDN costs and environmental impacts and the maximization the WDN hydraulic reliability was proposed by Wu, Maier, and Simpson (2013) considering the environmental impacts in pumping into storages of water transmission. EPANET was used for the network simulation. Yazdi (2016) proposed decomposition-based multi-objective evolutionary algorithms for the design of large-scale WDN, by integrating the concepts of Harmony Search (HS) and Genetic Algorithms (GA), to avoid the use of Pareto dominance.

Balekelayi and Tesfamariam (2017) presented a review of three approaches to the WDN, deterministic, non-gradient and real time optimization. Authors presented also a comparison among population-based algorithms solutions for a case study. A very detailed review of all methods used and types of WDN problems, involving design of a new WDN, strengthening, expansion and rehabilitation of existing water distribution systems, considering design timing, parameters uncertainty, water quality and operational considerations was presented by Mala-Jetmarova, Sultanova, and Savic (2018).

The number of studies using deterministic approaches for solving the WDN optimization problem is smaller than the previous ones. Bragalli, D'Ambrosio, Lee, Lodi, and Toth (2012) used a nonconvex continuous Non-Linear Programming (NLP) relaxation and an MINLP search approach for optimization of WDN with fixed topology. Raghunathan (2013) applied linearization and global optimization techniques with tailored cuts for the optimal design of nonlinear netwoks with MINLP formulation. Mathematical Programming approaches in the optimization of WDN were reviewed by D'Ambrosio, Lodi, Wiese, and Bragalli (2015), focusing on two different problem classes, the notion of the network design and the network operation. Caballero and Ravagnani (2019) presented an MINLP model to solve the WDN optimization problem considering unknown flow directions in pipeline loops. Global optimization techniques were used. Generalized Disjunctive Programming was used by Cassiolato, Carvalho, Caballero, and Ravagnani (2019) to reformulate the MINLP model, based on Surco et al. (2017), using the Big M approach. A similar approach was proposed but Cassiolato, Carvalho, Caballero, and Ravagnani (2020), but the hull reformulation was used to solve the optimization problem, in that way the relaxation gap is reduced and the overall numerical performance improved.

All the mentioned studies using deterministic approaches use as the objective function the minimization of the network installation costs and operational costs are not considered in the problem. In the present study, an optimization model was developed, being the objective function to be minimized the WDN total cost, considering the installation and the operating network pump costs, which is our main contribution. An MINLP model using the Single approach is proposed for the optimal synthesis of WDN without using hydraulic simulators to calculate pressure and velocity. These calculations are included as constraints in the model and reformulation techniques are used to linearize the nonlinear hydraulic equations, employing logarithms and disjunctions and global optimization deterministic methods can be used to solve the problem. Two case studies were used to test the model, considering real-world water distribution systems. The problems were solved in GAMS, using the BARON (global) and SBB optimization solvers.

In the deterministic approach proposed in the present study, two kinds of costs are considered; the operational cost is not usual in the literature. Also, the pressure calculation evolves a procedure depending on the water flow direction in the pipes, from the reservoir to the demand nodes, not usual in the literature. The computational effort is high, considering that a complex nonlinear system with discrete and continuous variables is solved.

Material and methods

The WDN synthesis can be treated as an optimization problem described as: Given a set of demand points interconnected by pipes, with the possible presence of loops, with fixed elevations and distances and a set of available commercial diameters, the network total cost to be minimized is the sum of the product of the diameters cost and their length (installation cost) and the operational cost, given by the cost of water pressurization and the head height of the pumping system. Optimization variables are the diameters and velocities in the pipes, the pressure in demand nodes and the head height of reservoir. The problem constraints are the mass balance in the nodes, the energy balance in the loops, and the pressure and velocity limits. To each one of the available commercial diameters is associated a rugosity coefficient and a cost. The optimization model is based on Cassiolato et al. (2020).

The following sets, parameters and variables are defined (Table 1):

Table 1. Optimization model sets, parameters and variables

Sets:	
Pipes	j pipes in the WDN
Nodes	k nodes in the WDN
FI_k	Pipes with flow entering node k
FO_k	Pipes with leaving node k
Loops	γ loops in the WDN
PPD_γ	Pipes in which flow is in the loop γ direction
NPD_γ	Pipes in which flow is in the contrary loop γ direction
Pumps	μ pumps in the WDN
τ_k	Pipes in which a flow path is defined, beginning in the reservoir and finishing in node k
Parameters:	
L_j	j pipe length (m)
$dmd\,(j)$	k node demand (L/s)
$E_P^\mu(\gamma)$	Pump μ energy in loop γ (m)
C_j	Hazen-Williams rugosity coefficient in pipe j
α, β and ω	Hazen-Williams equation parameters (depend on the unity system used)
ε_j	Absolute rugosity in pipe j (m)
ν	Water kinematic viscosity (m^2/s)
$pr_{min}\,(k)$	Minimum allowed pressure in node k (m)
$elv\,(k)$	k node elevation (m)
$elv\,(re)$	Reservoir elevation (m)
v_{min}	Minimum allowed velocity (m/s)
v_{max}	Maximum allowed velocity (m/s)
l_2	Natural logarithm of C_j
l_4	Natural logarithm of L_j
Q	Total volumetric flowrate (m^3/s)
η	Pump efficiency
N_{op}	Number of pumping operation hours per year (h/year)
E_c	Energy cost ($/kWh)
F_a	Annualization factor for the operational cost
E_h	Updated pressurization cost per meter of elevation ($/m)
e_1	Interest rate
e_2	Annual energy increase rate
n_a	Installation lifetime
Z_{ter}	Head height (m)
n_d	Number of available diameters
D_i	i available diameter (m)
$Costd\,(D_i)$	Cost per length associated with the pipe with diameter D_i ($/m)
R_i	Rugosity coefficient per length associated with the pipe with diameter D_i
Variables	
x_j	j pipe diameter (m)
$Cost\,(x_j)$	Cost per length of pipe j with diameter x_j ($/m)
IC	WDN installation cost ($)
q_j	Volumetric flowrate in pipe j (m^3/s)
$h_f(j)$	Pressure loss in pipe j
f_j	Darcy-Weisbach friction factor for pipe j
$Re\,(j)$	Reynolds number of pipe j
$pr\,(k)$	Pressure in node k (m)
v_j	Water velocity in pipe j (m/s)
l_1	Natural logarithm of $h_f(j)$
l_3	Natural logarithm of x_j
l_5	Natural logarithm of q_j
l_6	Natural logarithm of v_j
l_7	Natural logarithm of f_j
H_{otm}	Pumping system head height (m)
OC	Operational cost ($)
TC	WDN total cost ($)

$Y_{i,j}$	Boolean variable (true, if in pipe *j* diameter D_i is selected, false otherwise)
λ_j	Pipe *j* cost ($)
σ_j	Pipe *j* rugosity coefficient
$y_{i,j}$	Binary variable (1 if in pipe *j* diameter D_i is selected, 0 otherwise)

The mass balance in demand nodes and the energy balance in WDN loops are given by Equations (1) and (2):

$$\sum_{j \in FI_k} q_j - \sum_{j \in FO_k} q_j = dmd(k), \qquad \forall\, k \in Nodes \tag{1}$$

$$\sum_{j \in PPD_\gamma} h_f(j) - \sum_{j \in NPD_\gamma} h_f(j) = \sum_{\mu \in Pumps} E_P^{\mu}(\gamma), \qquad \forall\, \gamma \in Loops \tag{2}$$

Pressure loss is calculated by the Darcy-Weisbach equation. If water is the fluid used in the pipeline, pressure loss can be calculated using the Hazen-Williams equation, with satisfactory results. In the WDN literature, the equation of Hazen-Williams is currently used and is given by:

$$h_f(j) = \frac{\omega\, L_j\, q_j^{\alpha}}{C_j^{\alpha}\, x_j^{\beta}}, \ \forall\, j \in Pipes \tag{3}$$

The equation of Darcy-Weisbach is:

$$h_f(j) = \frac{0.0827\, f_j\, q_j^2\, L_j}{x_j^5}, \ \forall\, j \in Pipes \tag{4}$$

The friction factor can be calculated as proposed by Swanee and Janin (1976):

$$f_j = \frac{1.325}{\left[\ln\left(\frac{\varepsilon_j}{3.7\, x_j} + \frac{5.74}{Re(j)^{0.9}}\right)\right]^2}, \ \forall\, j \in Pipes \tag{5}$$

where

$Re(j) = v_j\, x_j / \nu$, for all $j \in Pipes$.

The reservoir elevation $elv(re) = Z_{ter} + H_{otm}$ will influence the pressure of each one of the nodes calculations. If node $k = k_r$ corresponds to the reservoir, the pressure is given by:

$$pr(k_r) = elv(k_r) = elv(re) \tag{6}$$

If not:

$$pr_{min}(k) \le pr(k) = -\sum_{j \in \tau_k} h_f(j) + [elv(re) - elv(k)], \ \forall\, k \in Nodes, k \neq k_r \tag{7}$$

Water velocity in each pipe is given by:

$$v_{min} \le v_j = \frac{4\, q_j}{\pi\, x_j^2} \le v_{max}, \ \forall\, j \in Pipes \tag{8}$$

Equations for pressure loss and velocity calculation are nonlinear. So, logarithms are applied to linearize these nonlinear terms. Defining

$l_1 = \ln h_f(j), \qquad l_2 = \ln C_j, l_3 = \ln x_j, l_4 = \ln L_j, l_5 = \ln q_j, l_6 = \ln v_j$

and

$l_7 = \ln f_j$, for all $j \in Pipes$.

The nonlinear equations of Hazen-Williams, velocity and Darcy-Weisbach, after the application of logarithms are:

$$l_1 + \alpha\, l_2 + \beta\, l_3 = \ln \omega + l_4 + \alpha\, l_5 \tag{9}$$

$$\ln \pi + l_6 + 2\, l_3 = \ln 4 + l_5 \tag{10}$$

$$l_1 + 5\, l_3 = \ln 0.0827 + l_7 + 2\, l_5 + l_4 \tag{11}$$

The WDN installation cost is given by:

$$IC = \sum_{j \in Pipes} L_j\, Cost(x_j) \tag{12}$$

The updated cost of water pressurization per meter of elevation ($/m), and the actualization factor are given by:

$$E_h = \frac{9.81\,Q}{\eta} E_c\, N_{op}\, F_a \tag{13}$$

$$F_a = \frac{(1+e_2)^{n_a} - (1+e_1)^{n_a}}{(e_2 - e_1)(1+e_1)^{n_a}} \tag{14}$$

The WDN operational cost is:

$$OC = E_h\, H_{otm} \tag{15}$$

Each pipe has associated a diameter, a rugosity coefficient and a cost. The following disjunction can be used to represent the choice for a specific diameter:

$$\underset{i \in \{1,\ldots,n_d\}}{\veebar} \begin{bmatrix} Y_{i,j} \\ x_j = D_i \\ \lambda_j = L_j\, Costd(D_i) \\ \sigma_j = R_i \end{bmatrix}, \ \forall\, j \in Pipes \tag{16}$$

The model can be reformulated into an MINLP problem, by using the hull reformulation. According to Grossmann and Lee (2003) and Sawaya and Grossmann (2007), this disjunction must satisfy the following equations:

$$x_j = \sum_{i=1}^{n_d} D_i\, y_{i,j}\,,\ \forall\, j \in Pipes \tag{17}$$

$$\lambda_j = L_j \sum_{i=1}^{n_d} Costd(D_i)\, y_{i,j}\,,\ \forall\, j \in Pipes \tag{18}$$

$$\sigma_j = \sum_{i=1}^{n_d} R_i\, y_{i,j}\,,\ \forall\, j \in Pipes \tag{19}$$

$$\sum_{i=1}^{n_d} y_{i,j} = 1,\ \forall\, j \in Pipes \tag{20}$$

Finally, the optimization model can be described as (Table 2):

Table 2. Optimization model

$$
\begin{aligned}
&\min && \sum_{j \in Pipes} \lambda_j + OC \\
&\text{subject to} && \sum_{j \in FI_k} q_j - \sum_{j \in FO_k} q_j = dmd(k), \qquad \forall\, k \in Nodes \\
& && \sum_{j \in PPD_\gamma} h_f(j) - \sum_{j \in NPD_\gamma} h_f(j) = \sum_{\mu \in Pumps} E_P^{\mu}(\gamma), \qquad \forall\, \gamma \in Loops \\
& && pr_{min}(k) \le pr, \qquad \forall\, k \in Nodes \\
& && v_{min} \le v_j \le v_{max}, \qquad \forall\, j \in Pipes \\
& && \sum_{i=1}^{n_d} y_{i,j} = 1, \qquad \forall\, j \in Pipes \\
& && x_j = \sum_{i=1}^{n_d} D_i\, y_{i,j}\,, \qquad \forall\, j \in Pipes \\
& && \lambda_j = L_j \sum_{i=1}^{n_d} Costd(D_i)\, y_{i,j}\,, \qquad \forall\, j \in Pipes \\
& && \sigma_j = \sum_{i=1}^{n_d} R_i\, y_{i,j}\,, \qquad \forall\, j \in Pipes \\
& && l_1 + \alpha\, l_2 + \beta\, l_3 = \ln \omega + l_4 + \alpha\, l_5 \\
& && \ln \pi + l_6 + 2\, l_3 = \ln 4 + l_5 \\
& && l_1 + 5\, l_3 = \ln 0.0827 + l_7 + 2\, l_5 + l_4 \\
& && E_h = \frac{9.81\,Q}{\eta} E_c\, N_{op}\, F_a \\
& && F_a = \frac{(1+e_2)^{n_a} - (1+e_1)^{n_a}}{(e_2 - e_1)(1+e_1)^{n_a}} \\
& && OC = E_h\, H_{otm} \\
& && \exp(l_1) = h_f(j)
\end{aligned} \tag{21}
$$

$\exp(l_2) = C_j$

$\exp(l_3) = x_j$

$\exp(l_4) = L_j$

$\exp(l_5) = q_j$

$\exp(l_6) = v_j$

$\exp(l_7) = f_j$

Results and discussion

To demonstrate the model applicability for optimization of WDN, two case studies were chosen. In both problems, the optimal network pipe design and the reservoir elevation must be calculated considering the installation cost of the pipes and diameters and the energy pumping cost. Problems were solved in GAMS using the BARON (global) and SBB optimization solvers in a computer with a 1.70 GHz Intel® Core™ i5-3317 processor and 6.00 GB of RAM.

Case study 1

This case is known in the literature as Grande Setor (Surco et al., 2021). The water catchment level is 30 m, which is coincident with altitude elevation, i.e., Z_{ter} = 30 m. Figure 1 illustrates the network topology, with fixed flow directions and pipes length, the existing two loops and the nodes demand and elevation. Table 3 lists the set of available commercial diameters with the respective costs and rugosity coefficients. Velocity limits are v_{min} = 0.2 m s^{-1} and v_{max} = 3 m s^{-1} and the minimum pressure is 25 m. Table 4 presents the parameters used to calculate pumping costs. The Hazen-Williams equation was used in this case study.

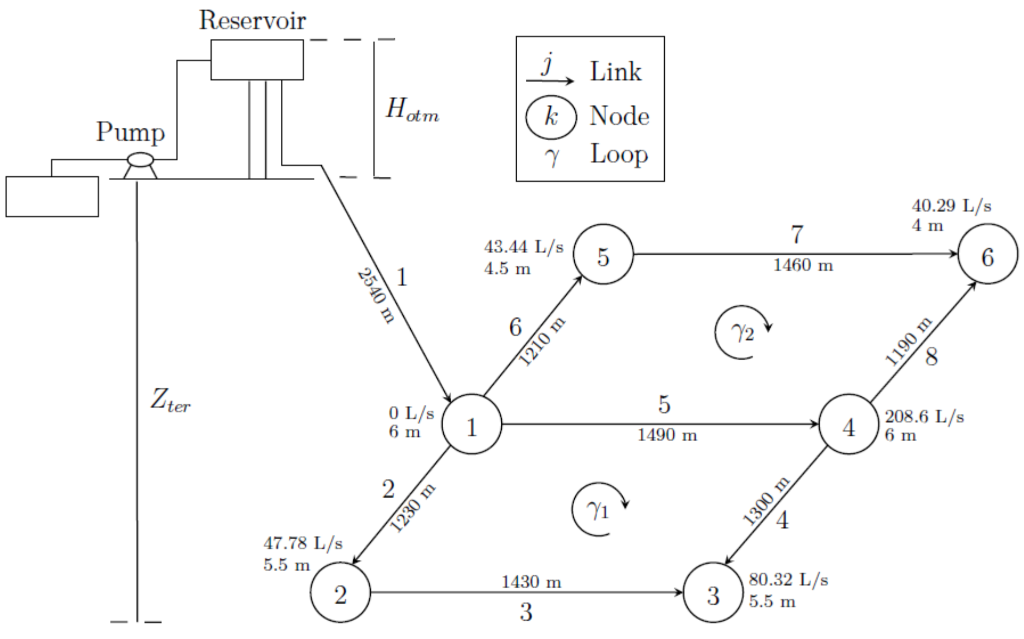

Figure 1. Grande Setor WDN

Table 3. Set of commercial available diameters for the Grande Setor WDN.

Diameter (m)	Cost ($ m^{-1})	Hazen-Williams rugosity coefficient	Diameter (m)	Cost ($ m^{-1})	Hazen-Williams rugosity coefficient
0.1084	23.55	145	0.3662	158.93	130
0.1564	31.90	145	0.4164	187.50	130
0.2042	43.81	145	0.4666	218.12	130
0.2520	59.30	145	0.5180	257.80	130
0.2998	76.12	145	0.6196	320.15	130

Table 4. Data for the pumping energy cost calculation for the Grande Setor WDN.

Parameter	Value
Q	0.42043 m^3 s^{-1}
η	75%
N_{op}	7300 h $year^{-1}$
E_c	0.1 $ kWh^{-1}
e_1	12%
e_2	6%
n_a	20 years
F_a	11.12544401
E_h	44,657.389 $ m^{-1}

Table 5 lists the problem solution, with optimal diameters and head height. Tables 6 and 7 present velocity and pressure for the optimized diameters. Table 8 presents the costs comparison.

Table 5. Diameter and head height for the Grande Setor WDN.

Pipe	Surco et al. (2021)	Present study
1	0.6196	0.6196
2	0.2998	0.2998
3	0.2520	0.2520
4	0.2998	0.2998
5	0.5180	0.5180
6	0.2520	0.2520
7	0.2042	0.2042
8	0.2042	0.2042
H_{otm} (m)	13.655	13.655

Table 6. Velocity for the Grande Setor WDN.

Pipe	Velocity (m s^{-1})	Pipe	Velocity (m s^{-1})
1	1.39	5	1.33
2	1.13	6	1.20
3	0.64	7	0.50
4	0.69	8	0.73

Table 7. Node pressure for the Grande Setor WDN.

Node	Surco et al. (2021)	Present study
1	30.84	30.84
2	27.10	27.10
3	25.00	25.00
4	26.30	26.30
5	26.62	26.62
6	25.40	25.40

Table 8. Costs comparison for the Grande Setor WDN.

Cost	Surco et al. (2021)	Present study
IC ($)	1,662,535.10	1,662,535.10
OC ($)	609,796.65	609,852.39
TC ($)	2,272,331.75	2,272,387.49

The solution obtained in the present study with the proposed model using $\omega = 10.667$ in the Hazen-Williams equation, for diameter and node pressure, is exactly the same as presented by Surco et al. (2021), having a difference only in the cost of operation due to the numerical approximations the authors made in parameters of the pumping system. It is interesting to comment that the authors used EPANET for hydraulic calculations and a bi-objective optimization approach. To solve the model, a bi-objective PSO was proposed. It is an indicative that Surco et al. (2021) found the global optimum, considering that the global optimization solver BARON was used to solve the problem. As can be seen, in this case study, the pumping cost represented approximately 27% total cost an is very significant.

The reservoir piezometric height is:

$$\omega = 10.667 \Rightarrow elv(re) = Z_{ter} + H_{otm} = 30 \text{ m} + 13.655 \text{ m} = 43.655 \text{ m}$$

Case study 2

This case study refers to the existing WDN in the municipality of Itororó, state of Bahia, Brazil. The water catchment level is 222 m and is coincident with the altitude elevation, i. e., Z_{ter} = 222 m. Figure 2 shows the WDN topology for this example. Table 9 lists the set of available diameters and respective costs. In this case, Darcy-Weisbach equation is used and a rugosity coefficient of 2×10^{-5} m for all diameters is considered. The water kinematic viscosity at 20 °C was considered $\nu = 1.004 \times 10^{-6}$ m²/s, the velocity limits are v_{min} = 0.2 m s^{-1} and v_{max} = 3.5 m s^{-1} and the minimum pressure is 15 m for all nodes. Table 10 presents the parameters necessary to calculate pumping costs.

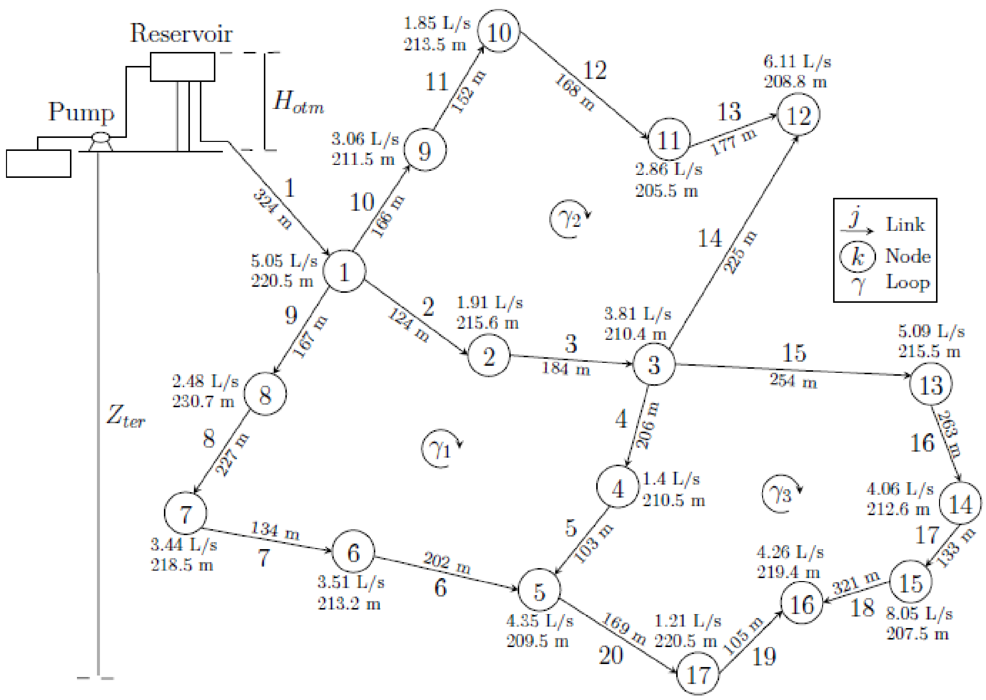

Figure 2. Itororó WDN.

Table 9. Set of available diameters and costs for the Itororó WDN.

Diameter (m)	Cost ($ m^{-1})	Diameter (m)	Cost ($ m^{-1})
0.0534	24.16	0.2042	87.62
0.0756	32.12	0.2520	118.59
0.1084	47.09	0.2998	152.24
0.1564	63.80		

Table 10. Data for the pumping cost calculation for the Itororó WDN.

Parameter	Value
Q	0.0625 m³ s^{-1}
η	75%
N_{op}	7300 h year^{-1}
E_c	0.134 $ kWh^{-1}
e_1	10%
e_2	6%
n_a	25 years
F_a	15.0969377
E_h	12,072.70 $ m^{-1}

Table 11 lists the optimal results for the diameters and the head height. Tables 12 and 13 present velocity and pressure results, for the optimized diameters. Table 14 presents the installation, operational and total costs for the Itororó WDN. In this case study, results showed that the operational cost is greater than the installation cost.

Table 11. Diameter and head height for the Itororó WDN.

Pipe	Diameter (m)	Pipe	Diameter (m)
1	0.2520	11	0.0756
2	0.1564	12	0.0756
3	0.2042	13	0.0534
4	0.1084	14	0.0534
5	0.0756	15	0.1564
6	0.0534	16	0.1084
7	0.0756	17	0.1084
8	0.0756	18	0.0534
9	0.1564	19	0.0756
10	0.0756	20	0.1084
H_{otm} (m)		25.54	

Table 12. Pipe velocity for the Itororó WDN.

Pipe	Velocity (m s^{-1})	Pipe	Velocity (m s^{-1})
1	1.25	11	1.47
2	1.97	12	1.05
3	1.10	13	0.83
4	1.07	14	1.90
5	1.89	15	0.94
6	0.22	16	1.41
7	0.89	17	0.97
8	1.66	18	0.38
9	0.52	19	0.76
10	2.15	20	0.50

Table 13. Node pressure for the Itororó WDN.

Node	Pressure (m)	Node	Pressure (m)
1	25.48	10	18.99
2	27.92	11	24.47
3	32.23	12	18.51
4	30.08	13	25.85
5	26.54	14	24.43
6	23.13	15	28.43
7	19.32	16	15.35
8	15.00	17	15.12
9	25.17		

Table 14. Itororó WDN costs.

Costs	Present study
IC ($)	181,857.23
OC ($)	308,341.00
TC ($)	490,198.23

The problem was solved with the SBB optimizer. The pumping head height is 25.54 m and the total cost is $ 490,198.23.

In this case, the operational cost was responsible for 63% total cost. It means that this cost must be always considered when the minimization of WDN costs is the problem to be studied.

The reservoir piezometric height is:

$$elv(re) = Z_{ter} + H_{otm} = 222 \text{ m} + 25.54 \text{ m} = 247.54 \text{ m}$$

Conclusion

It can be concluded that operational costs play an important role in the WDN system design. In the first case study, the operational cost represents more than a quarter part of the total cost and in the second case study, the operational cost is the most important feature, representing almost 63% total WDN cost. Not only the installation cost must be used as the variable to be minimized in the objective function, and if operational costs are neglected, very nonrealistic results can be achieved in real WDN systems.

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