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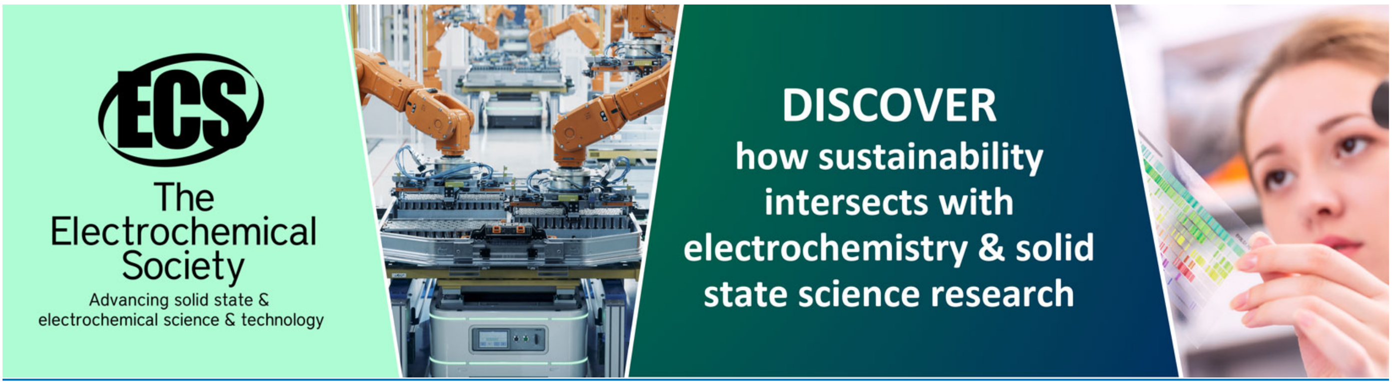


Hydraulic optimization of the physical parameters of a drinking water distribution system

C A Bonilla-Granados[1], **N J Cely-Calixto**[2], **and G A Carrillo Soto**[2]
[1] Grupo de Investigación Etenoha, Universidad de Pamplona, Pamplona, Colombia
[2] Grupo de Investigación en Hidrología y Recursos Hídricos, Universidad Francisco de Paula Santander, San José de Cúcuta, Colombia

E-mail: carlos.bonilla@unipamplona.edu.co

Abstract. Drinking-water distribution systems are generally designed with methodologies based on trial-and-error tests, which generate feasible results. However, these trials are not the most economical and reliable solution since they do not consider the optimization of the network. For the present work, the hydraulic model of the drinking water distribution network of San José de Cúcuta, Colombia, was optimized by applying the concept of resilience rate and minimum cost. The development of the work consisted of the hydraulic modeling of the physical components of the network in EPANET software, as well as the application of calculations of the connectivity coefficient and the unitary power of each section. With the data obtained from the modeling and calculations, the physical parameters were optimized, and the cost-benefit ratio was estimated. It was found that the current drinking water distribution system does not have a power surplus to overcome a system failure. The optimization increased the total energy surplus of the network (261%) and the resilience rate (585%). Also, the connectivity coefficient was improved with an average value of 0.95. The hydraulic optimization methodology applied resulted in a network resilient to system failures.

1. Introduction

Water is considered one of the most important natural resources in the life of human beings since it supplies basic needs and is a fundamental element in domestic and industrial activities [1]; a drinking water distribution system (DWDS) captures and supplies water for a community [2]. However, when the system does not comply with its function, either due to the increase in population or the inefficiency of its structures, it becomes necessary to search for different alternatives that can optimize the system and achieve the objective for which it was planned [3].

Hydraulic optimization of the physical parameters of a DWDS is a practice associated with the solution of several problems, such as deteriorated infrastructures that cause losses due to leaks, decreased water transport capacity, various failures in system components (pumps, valves, pipes, etc.); also, increased maintenance and operating costs, poor fluid quality due to constant service interruptions, and decreased reliability of the system, generating problems to meet the required demand and pressure [4].

Distribution network research has the priority to optimize the design of a DWDS, to ensure the development and proper functioning of a society. In recent years, the design of distribution networks has raised different optimization methodologies and from the perspective of minimum cost, which allows finding an optimal point (where costs are minimal). Saldarriaga used the specific power [5], Prasad, Park, Creaco, Franchini, and Todini used the resilience index [6,7], and Creaco, Fortunato, Franchini, and Mazzola used the uniformity of network diameters and the demand satisfaction rate [8].

In addition, that meets the required demand and pressure conditions, *i.e.*, finding economic designs, but with an acceptable degree of reliability. The methodology based on the resilience index and minimum cost allow optimizing a DWDS by creating energy surpluses, defined as the total surplus energy in each network, which allows guaranteeing the demand required by a community in adverse events such as increased demand, pipeline closures, or pipeline failures [9].

The optimal design of the distribution network is conditioned by a good performance of the implemented system, generating the concept of hydraulic reliability. Reliability is related to factors such as the redundancy of the routes by which the fluid can reach the consumption nodes [10], the probability that the fluid reaches the demand points of the network [11], the ability to ensure the minimum required pressure at the nodes, the overpressure available to the consumption nodes [12], among others. To achieve reliability in a DWDS it is necessary to implement an optimal hydraulic design methodology from a minimum cost perspective [13].

This study aims to optimize the physical parameters of the DWDS matrix network of the city of San José de Cúcuta, Colombia, to improve the efficiency of a hydraulic model based on the concept of resilience index and minimum cost. The analysis of the optimization allows knowing the state of the distribution network in terms of resilience to possible failures.

2. Methodology

The concept of the resilience of a DWDS is defined as the ability of a network to overcome a failure and can be estimated by a design methodology that includes minimum cost analysis and resilience index, important reliability parameters [14]. Therefore, it is necessary to provide more power to each of the nodes so that there is a power surplus that can be dissipated internally in the event of a pipe failure or an increase in demand; mathematically it is given by the ratio between the power surplus per unit weight that could be dissipated internally by the network without failing to satisfy the minimum required pressure (15 mWC - meters water column) [14,15].

The distribution network is supplied with a power per unit weight, represented by Equation (1) [14], called power per unit weight input, quantified in terms of flow rate and pressure supplied by energy sources such as reservoirs, tanks, and pumps.

$$P_{inp} = \sum_{i=1}^{ne}(Q_e H_e)i + \sum_{i=1}^{npu}\frac{P_i}{\gamma}, \quad (1)$$

where P_{inp} is power per unit weight input, Q_e is the flow rate and H_e is the piezometric head delivered by the reservoir, ne the number of reservoirs, P_i is the power delivered by the pump, i and npu the number of pumps in the network. At each consumption node, a power per unit weight is delivered, and the sum of this across the nodes is called power per unit weight output (P_{out}). Two types are considered: a minimum power per unit weight output ($P_{min/out}$) corresponding to a minimum pressure at all consumption nodes and a real power per unit weight output corresponding to the real pressure present at the nodes, as shown in Equation (2) [14].

$$P_{min/out} = \sum_{j=1}^{n_n} Q_j H_{*j}, \quad (2)$$

where Q_j is the flow rate supplied to node j, H_{*j} is the minimum piezometric head, and H_j is the actual piezometric head for that node; in its passage through the distribution network the flow loses energy, this power that is consumed by the network is called P_{int} of system operation, the presence of leaks in the network increases the power per unit weight. From the above it can be deduced that the power per unit weight input (P_{inp}) must be equal to the sum of the power per unit weight operation and the P_{out}, shown in Equation (3) [14].

$$\mathrm{P_{inp}} = \mathrm{P_{int}} + \mathrm{P_{out}}. \tag{3}$$

Therefore, the real internal power ($\mathrm{P_{real-int}}$) represents the power per unit weight, consumed by the network and the maximum internal power ($\mathrm{P_{max-int}}$) represents the maximum power per unit weight, that could be consumed internally by the network without failing to satisfy the minimum pressure. The equation defining the resilience index ($\mathrm{I_R}$) is stated in Equation (4) [14].

$$\mathrm{I_R} = 1 - \frac{\mathrm{P_{real-int}}}{\mathrm{P_{max-int}}}. \tag{4}$$

The most resilient networks are those that represent a lower value of the ratio $\mathrm{P_{real-int}}/\mathrm{P_{max-int}}$ and therefore tend to 1 in the value of the resilience index. The general expression for the resilience index is shown in Equation (5) and is stated below [14].

$$\mathrm{I_R} = \frac{\sum_{j=1}^{nn} Q_j (H_j - H_{*J})}{\left\{\sum_{i=1}^{nn} (Q_e H_e) + \sum_{i=1}^{npu} \frac{P_i}{\gamma}\right\} - \sum_{j=1}^{nn} Q_j H_{*J}}. \tag{5}$$

The analysis and subsequent optimization of the DWDS matrix network of the city of San José de Cúcuta, Colombia, which is supplied by the Pamplonita and Zulia rivers, Colombia, was carried out. The system to be optimized is divided into four large zones, named the South, East, North, and North Valleys. The city's DWDS has a configuration based on the principle of hydraulic sectorization [15]. The matrix network that supplies each sector and subsector is shown in Figure 1.

There are 23 sectors and 43 hydraulic subsectors, supplied by the Pamplonita river, Colombia, basin. In addition, the system has 6 pumping stations and 4 storage tanks. Detailed information on the main network was provided by the city's water system operator. The hydraulic analysis and modeling of the physical components of San José de Cúcuta, Colombia, WPS main network were performed in the EPANET software [16,17]. The physical characteristics of the different components of the network and the demand of each subsector were provided by the operating company, as well as the network's own increase factors, the number of inhabitants per sector, area of each subsector, and the consumption curve. The maximum hourly, maximum daily, and average daily flow rates were calculated and an approximate real representation of the operation of the network was obtained.

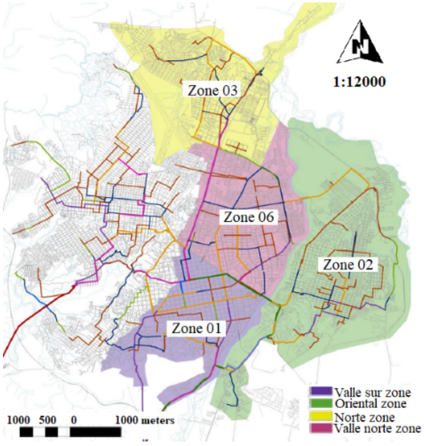


Figure 1. Diagram of the hydraulic zoning of San José de Cúcuta, Colombia, DWDS.

The optimization of the distribution network was carried out, considering the minimum cost method versus the resilience index, looking for an optimal combination of the most relevant physical parameters, the diameters of each pipe, which would minimize the construction cost of the system and at the same time provide acceptable reliability levels. The cost function can generally be expressed by means of an exponential relationship of the diameter, for this project the construction cost was considered to include the commercial value of the pipes plus their installation cost, and it was determined to replace the existing sections with ductile iron pipes.

The connectivity coefficient ($\mathrm{C_j}$) measures the variability of diameters connected to the same node in a network, that is, it measures the uniformity of diameter sizes in a node. The value of $\mathrm{C_j}$ is equal to one ($\mathrm{C_j} = 1$) when the pipes connected to a node have the same diameter or there is only one pipe connected to it, and it will be less than one ($\mathrm{C_j} < 1$) when the pipes connected to a node present different diameter, the connectivity coefficient is obtained by Equation (6) [18]. Where NT is the number of pipes connected to node j and $\mathrm{D_1}$ is the diameter of each pipe.

$$\mathrm{C_j} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{NT}} \mathrm{D_1}}{\mathrm{NT}\max\{\mathrm{D_1}\}}. \tag{6}$$

The unit power ($\mathrm{P_{UT}}$) of a pipe i, is defined as the flow rate flowing in this, multiplied by the difference between the piezometric height of the initial and final nodes, where $\mathrm{q_{ij}}$ is the flow rate flowing through the pipe from node i to node j, and the pressures of nodes i and j, are $\mathrm{h_i}$ and $\mathrm{h_j}$ respectively and is obtained by Equation (7) [5].

$$\mathrm{P_{UT}} = \mathrm{q_{ij}}(\mathrm{h_i} - \mathrm{h_j}). \tag{7}$$

3. Results

The resilience index and the connectivity coefficient of the current DWDS network were calculated, to then determine the unit power found in the nodes with the lowest connectivity coefficient and calculate the cost of changing each of the pipes connected to the nodes with the lowest connectivity coefficient, to select the pipe with the highest ratio (PUT/cost) and run the hydraulic model again with the optimized physical parameters. The new cost and the new resilience index of the DWDS were calculated until obtaining a resilience index equal to or higher than 0.5, a value with which a system or network is considered resilient.

The hydraulic optimization of the physical parameters of the DWDS matrix network of the city of San José de Cúcuta, Colombia, was carried out under the concept of resilience index and minimum cost, with 200 iterations. The resilience index was increased from 0.0714 to 0.489, *i.e.*, there was an increase of 585% to the initial value, which allows observing the efficiency of the optimization, going from being an unreliable network to a resilient network capable of overcoming system failures in terms of flow and pressure. The resulting $\mathrm{I_R}$ value is close to what is expected but does not guarantee a minimum for the resilience rating of 0.59 as mentioned in [14]. However, this value allows the preservation of a sufficient degree of resilience in the system to cope with possible failures [8,14].

The process of increasing the $\mathrm{I_R}$ does not involve a large initial increase in cost (low slopes), this initial behavior varies as the iterations of the optimization process increase, with an increase in the $\mathrm{I_R}$ that generates considerable increases in cost; there was an increase in cost concerning the initial value of 30.17 %, as shown in Figure 2. The connectivity coefficient was improved with an average value of 0.95, obtaining practical connectivities, *i.e.*, the pipes connected to the same node do not vary widely in diameter and the evaluation of the energy surplus was performed, where it was obtained that the total energy surplus of the network went from 4849.7 mWC (meters water column) to 17526.4 mWC, showing an increase of 261 %.

Finally, the hydraulic simulation of the current distribution network was carried out and then the simulation of the optimized DWDS was performed under the concept of resilience index and minimum cost. The analysis of the pressures of the two hydraulic models, shown in Figure 3, shows critical zones in the current model at the hour of maximum consumption, 9:00 a.m., where pressure values of less than 20 mWC. are obtained. The situation improved significantly in the optimized model, where uniform pressures are observed in the DWDS, increasing the degree of hydraulic reliability, maximizing the conservation of energy input, and dissipated by the system.

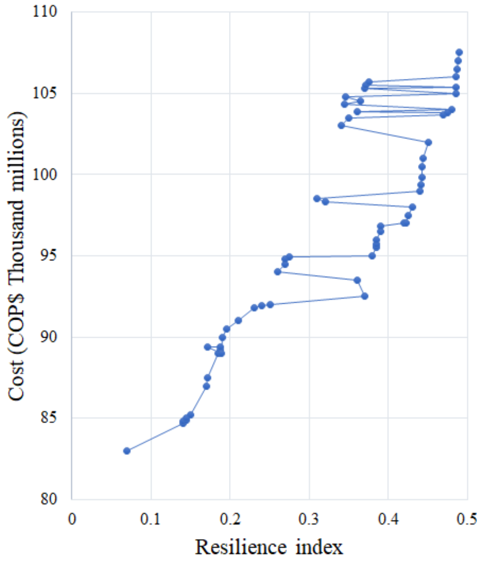
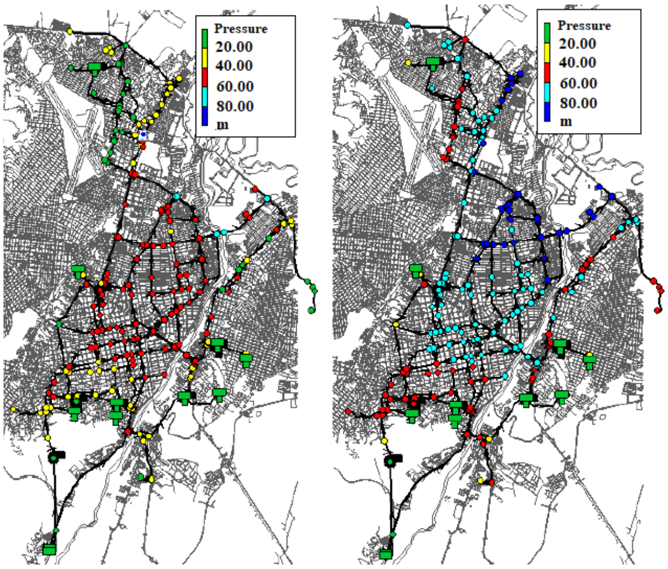


Figure 2. Resilience index vs. cost, benefit-cost ratio.

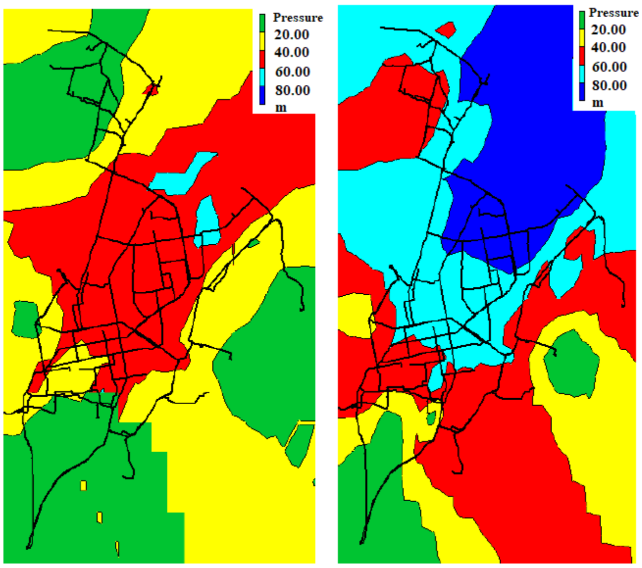


(a) (b)

Figure 3. Hydraulic modeling: (a) current DWDS, and (b) optimized DWDS.

Figure 4 shows the pressure isolines of the network for 9:00 a. m. for the current DWDS model and the optimized DWDS model. This plot shows that at present, the network shows an imbalance in the available power in the northern area of the city, which is reflected in the degree of reliability of the network, which decreases considerably, being the DWDS matrix network of the city, a network susceptible to recurrent damage in this area, contrary to what is observed in the optimized DWDS, where uniformity is observed in the state of pressure at the time of maximum consumption and during the day.

The efficiency allowed by hydraulic optimization is not limited with simplified networks but is also used in the matrix network for more rigorous optimizations, as discussed in [14]. There is a balance in the available power and an acceptable hydraulic behavior, showing improvements in the efficiency of the hydraulic optimization of the physical parameters of the DWDS matrix network of the city of San José de Cúcuta, Colombia.



(a) (b)

Figure 4. Pressure isoline: (a) current DWDS, and (b) optimized DWDS.

4. Conclusions

The resilience index of the network was increased from an initial value of 0.07139 to 0.489, an increase of 585% concerning the initial value, going from being an unreliable network to a resilient network capable of overcoming failures in the system (in terms of flow and pressure). In addition to improving the connectivity coefficient to an average value of 0.95, obtaining practical connectivities, *i.e.*, the pipes connected to the same node do not vary widely in diameter.

The analysis of pressures at the hour of maximum consumption, in the model of the current drinking water distribution system, allows identifying that, at present, the network presents an imbalance in the available power in the north zone of the city, a network susceptible to recurrent damages in this zone. This is contrary, in the optimized drinking water distribution system, in the state of pressure at the hour of maximum consumption and throughout the day.

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