Comparison between Optimal and Real Design in Water Distribution Systems (WDS). Effect of Population Growth during the Project Lifespan.

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ABSTRACT

Urban processes affect Water Distribution Systems (WDS) and cause unsatisfactory operation, which violates the minimum pressure limit. For this reason, stablishing a valid rehabilitation criteria based on previous studies is necessary. In this paper a methodology to verify the results obtained by Specific Power and Resilience Index criteria is presented. The results obtained for six study cases in Colombia were analyzed in terms of costs, parameters and number of changes showing a reduction in costs and a reduced number of changes in the algorithm based on the second index.

Keywords: WDS rehabilitation, optimum design, population growth

1   BACKGROUND

Population growth generates an increase in potable water demand over time, and it reaches values above the range considered during the original design. Specifically, developing countries have experienced during the last decades a displacement from rural areas to cities causing enormous pressure on public infrastructure. As a result, several problems appear at a WDS as low pressure conditions, reduced hydraulic capacity, water losses, and service disruptions [1]. In most cases, nodes pressures and hydraulic capacity are increased affecting the pressure at the entrance but this leads to frequent pipe bursts, more water losses and disruptions. It is clear that rehabilitation processes are vital for this infrastructure in order to fulfill standards but it should be treated gradually and not as a complete design with resemblance to reality.

With these problems in mind, several approaches have been developed to improve the WDS hydraulic capacity as increasing some pipe diameters or installing parallel pipes, using methodologies based on hydraulic indicators as network resilience, Specific Power [2], and a deterministic algorithm to maximize the uniformity of the pressure service level [3], among others. The algorithms of rehabilitations has been improved and the results obtained show a difference in costs for each criteria and a decrease in computing time.

Water Distribution System optimal design is a highly indeterminate problem considered as NP-HARD due to the large number of possible pipe configurations [4]. An optimal hydraulic design determines the pipe diameters with an adequate pressure and a minimum capital cost [5][6], but in some cases it has a low resilience [7][8]. Although the WDS were constructed with an appropriate time horizon, rapid growth increase lead to an inadequate network expansion without the proper planning. Thereby, the research here presented proposes a comparison between rehabilitated and designed networks for different periods of time regarding water demand for the service projected population in order to quantify the differences in terms of costs
And hydraulic parameters.

2   METHODOLOGY

During the present investigation, six WDS from Colombia were analyzed with the aim of comparing a gradually rehabilitated network in which the demand was increased and the optimum design of the same network with the final demand regarding costs and Resilience Index. The main steps are described below:

1. The original networks, developed 10 years ago, were modified. Specifically, the water demand at every node was increased taking into account the population growth for the respective location.

2. Afterwards, the system was designed using a specialized software developed at Universidad de los Andes, REDES. For that purpose, the Optimal Power Use Surface methodology (OPUS) was implemented, comparable with other methodologies as Genetic Algorithms [11], Harmony Search [12], among others, with very similar results.

3. Based on the optimum design, some models violated the minimum pressure (15 m) even though they were designed for a 30 years period or more. In that case, a rehabilitation process was made with a selection of pipes based on two main criteria: Specific Power and Resilience Index.

4. Results obtained from both rehabilitation criteria were compared with the optimum design in terms of two parameters (Resilience Index and Dissipated Power), costs, pressure distribution and number of changes per criteria.

The process was repeated 6 times per network, increasing the water demand 5 years at a time during 30 years. Every network was first designed using OPUS methodology with the purpose of comparing under the same circumstances.

2.1   Resilience Index

The Resilience Index is an indicator of a network's vulnerability to failure. It is calculated with the following equation where n_r refers to the number of reservoirs, n_p is the number of pumps, Q_i is the flow transported by the pipe, q_i correspond to the node water demand, H_i is the pressure and H_i^* is the minimum pressure required.

$$I_r = \frac{\sum_{i=1}^{n_n} q_i(H_i - H_i^*)}{[\sum_{i=1}^{n_r} Q_i H_i^* + \sum_{i=1}^{n_p} P_{Pi}] - \sum_{i=1}^{n_n} q_i H_i^*} \qquad (1)$$

The algorithm for the election criteria starts with analyzing the hydraulics and stablishing the original I_r of the network. Afterwards, the diameter of a specific pipe is increased to the next available diameter and the new value of I_r is calculated. The difference between the new and the original I_r is estimated and the original conditions are restored, including the replaced pipe. Therefore, the previous steps are repeated until the every pipe of the network is analyzed, taking into account the variation caused in I_r by every change. The biggest difference corresponds to the pipe which has to be replaced permanently and it is necessary to analyze again the model hydraulics in order to verify the pressure restriction. Additionally, the costs of pipeline replacement is

calculated with the corresponding changes and in case every node fulfill the requirements the process stops. However, if it does not, the methodology must be repeated until all nodes satisfy the limit.

2.2   Specific Power

This concept developed by Universidad de los Andes, is defined by the equation below where P_{UTi} corresponds to Specific Power of pipe i, Q_i corresponds to the flow transported by the pipe i, and, h_a and h_b are the pressures at the upstream and downstream node of the pipe i, respectively.

$$P_{UTi} = Q_i(h_a - h_b) \qquad (2)$$

Similarly to the Resilience Index criteria, for this methodology the hydraulics of the networks must be analyzed and the P_{UT} is estimated for each pipe. Afterwards, the pipe with the higher P_{UT} value must be replaced for a new one with the next available diameter and the hydraulic simulation is executed. The cost is estimated and the pressure limit is verified. In case the pressure in every node is above the limit the process stops but on the other hand, the P_{UT} must be calculated again and the pipe with higher value is replaced. Consequently, this rehabilitation methodology is repeated only the number of times pipes are replaced while Resilience Index methodology is run NT times per pipe.

2.3   Dissipated Power

According to the power concept introduced by Todini [9], total power of a WDS can be expressed as the sum of the power dissipated by means of friction and leaks plus the delivered power at demand
nodes.

$$P_{tot} = P_{dis} + P_{out} \qquad (3)$$

Then, it is possible to obtain a value for the optimum and real dissipated water where the principal aim is to obtain equal values on both of them.

$$P_{dis}^{obj} = P_{tot} - P_{out}^{obj} \qquad (4)$$

$$P_{dis}^{real} = P_{tot} - P_{out}^{real} \qquad (5)$$

3   STUDY CASES

The networks used are from various departments of Colombia and differ from each other. Cazucá and Sector 35 are part of Bogotá city (Population: 8 million) with a flat topography and a feeding reservoir for each one. On the other hand, Candelaria and Bolívar are WDS of municipalities in Valle del Cauca department with homogenous topography though the last one has several low

nodes. At last, Circuito la 51 and T23 are two hydraulic sectors in Manizales city (Population: 450.000) with only one reservoir in each and a variable topology for the first. The hydraulic characteristics of each WDS are presented in Table 1.

Table 1. WDS study cases characteristics

WDS	Number of Nodes	Number of Pipes	Length of pipes (km)
Cazucá	145	150	13.64
Sector 35	1190	1289	39.47
Candelaria	463	567	23.31
Bolívar	285	333	29.46
Circuito 51	127	134	4.38
T23 Alta Suiza	110	122	4.81

For each city, population was projected based on an expression derived from a linear regression in order to calculate the annual growth rate. As a result, during the study period Bogotá will have a growth between 1% and 1.43%, Manizales among 0.62% and 0.76% and Valle del Cauca from 0.8% to 1.04%.
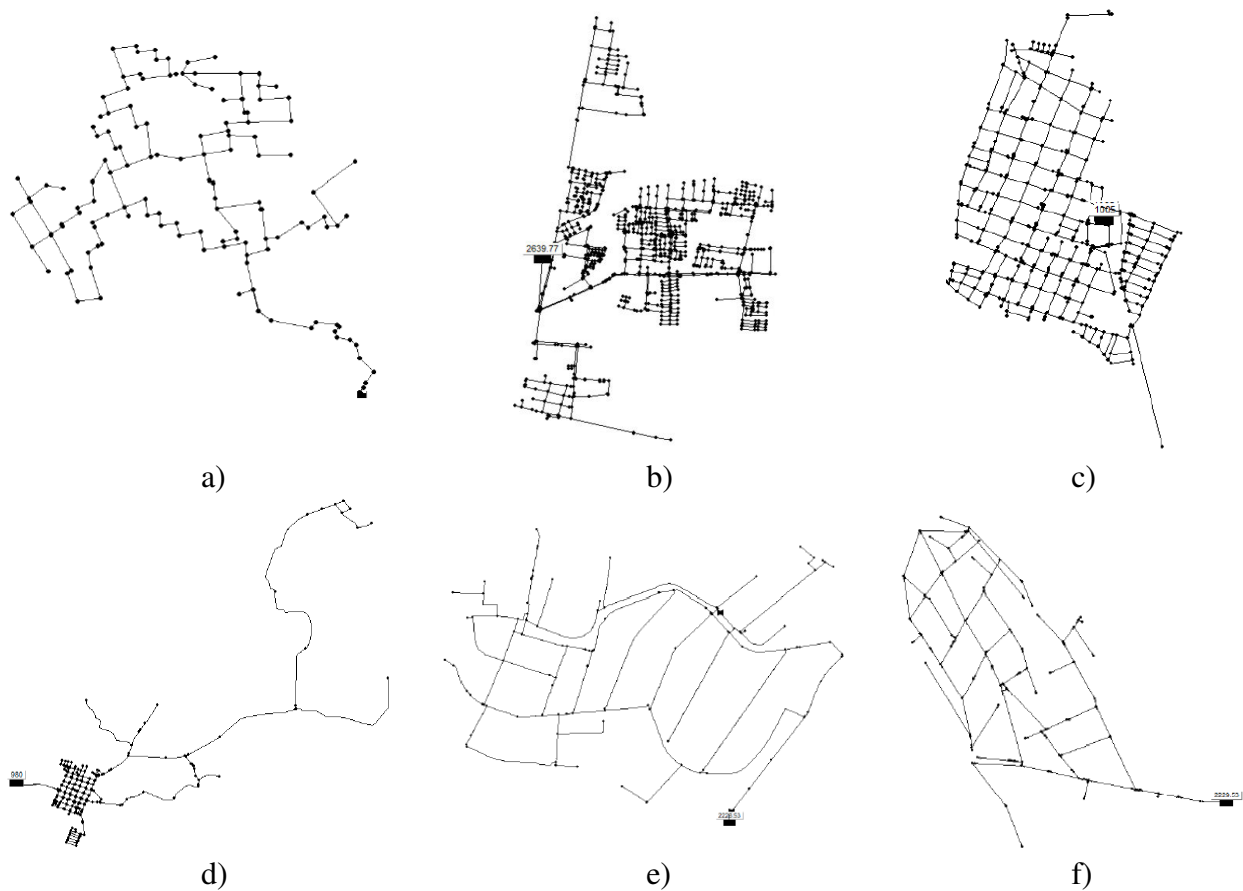

a)   b)   c)

d)   e)   f)

Figure 1. (a) Cazucá, (b) Sector 35, (c) Candelaria, (d) Bolívar, (e) Circuito 51, (f) T23

4   RESULTS

The results obtained following the proposed methodology were analyzed in terms of Resilience Index, Dissipated Power, costs, number of changes and pressure distribution.

4.1   Number of changes

It was quantified the number of times the diameter of a pipe was changed during the rehabilitation process in the networks for every year of analysis. As presented in Table 3, the specific power criteria causes increased number of changes in order to achieve the same I_r values obtained with the other criteria. By contrast, resilience index caused modifications with a major impact on the pressure, thereby fewer changes.

Table 3. Number of changes per WDS during the analyzed period

Criteria	Cazucá	Sector 35	Candelaria	Bolívar	Circuito 51	T23
Resilience Index	70	40	29	4	1	2
Specific Power	159	54	33	7	1	2

4.2   Resilience Index

In general, OPUS methodology results in low resilience indexes for the optimum designs which implies a vulnerable network. The resilience index and specific power criteria used for rehabilitation were appropriate in order to improve the redundancy of the models, very similar for both of them and superior to the one with optimum design. Furthermore, the growth of the index caused by the resilience index was between 4.03% for Bolívar and 41.4% for Candelaria while for specific power ranged from 4.12% to 41% respectively. Thus, the effect on the index is similar for both criteria although Specific Power requires a larger number of runs compared with Resilience Index.

Table 4. Resilience Index comparison between rehabilitated and OPUS designed WDS

Criteria/WDS	Cazucá	Sector 35	Candelaria	Bolívar	Circuito la 51	T23
Optimum Design OPUS	0.342	0.334	0.288	0.756	0.323	0.283
Rehabilitated with I_r	0.439	0.396	0.514	0.734	0.319	0.285
Rehabilitated with P_{UT}	0.388	0.44	0.533	0.736	0.319	0.303

4.3   Dissipated Power

As shown in Table 3, resulting values of dissipated power for the rehabilitated WDS are similar or lower to those obtained with the OPUS methodology. This is consistent with results of the previous section allowing to conclude that the rehabilitated models are similar to the optimum designed and have, mostly, better hydraulic indicators.

Table 5. Dissipated power comparison between rehabilitated and OPUS designed WDS

Criteria/WDS	Cazucá	Sector 35	Candelaria	Bolívar	Circuito la 51	T23
Optimum Design OPUS	0.021	0.008	0.014	0.012	0.031	0.02
Rehabilitated with I_r	0.017	0.008	0.008	0.011	0.031	0.02
Rehabilitated with P_{UT}	0.019	0.007	0.008	0.010	0.031	0.02

4.4   Costs

The cost function used and takes into account supply and installation, excavation, fill and surplus retirement [10]. It was designed for PVC pipes and is presented in equation 3 where D represents the nominal diameter in millimeters.

$$CU = 80,825D^{1.385} \quad (3)$$

Table 6 and 7 present the costs of the WDS cases after being designed with different criteria. The results suggest that gradual rehabilitation based on Resilience Index criteria generates networks with similar costs than those obtained for the optimum design. While Sector 35, Candelaria and Cazucá had higher prices (2.3%, 6.5% and 13.4% of additional cost, respectively), Bolívar and Circuito la 51 resulted in lower costs.

Similarly, specific power criteria approach generated costlier designs than those obtained with OPUS methodology between 0.9% and 9.7%. However, Cazucá network resulted in an increase of 45.4% of the optimum design cost while Bolívar in a decrease of 3.7%. Altogether, both of the used criteria allow to obtain, mostly, similar WDS than those designed by OPUS methodology in terms of costs.

Table 6. Economic cost of three final WDS for each criteria– Cazucá, Sector 35 and Candelaria

Criteria/WDS	Cazucá	Sector 35	Candelaria
Optimum Design OPUS	$1,051,597,375.19	$1,176,252,502.80	$516,299,269.30
Rehabilitated with I_r	$1,192,236,156.17	$1,202,850,723.72	$550,096,039.97
Rehabilitated with P_{UT}	$1,528,912,337.99	$1,290,010,462.96	$553,409,122.61

Table 7. Economic cost of three final WDS for each criteria– Bolívar, Circuito la 51, T23

Criteria/WDS	Bolívar	Circuito la 51	T23
Optimum Design OPUS	$886,191,016.92	$87,678,094.20	$88,836,809.10
Rehabilitated with I_r	$839,718,261.70	$84,598,193.59	$88,836,809.10
Rehabilitated with P_{UT}	$853,579,580.34	$84,598,193.59	$89,644,778.68

4.5   Pressure distribution

Demand increase had an important impact over some networks generating irregular surfaces including depressions or peaks. Results showed that proposed rehabilitation methodologies including I_r and P_{UT} criteria allowed the homogenization of the hydraulic gradient surface by modifying the pressure.

Additionally, the pressure values obtained by the rehabilitation were similar to those in the base design without generating unnecessary increases. Even more, although the modifications resulting of each criteria may have important differences with each other and the original model, the pressure distributions including minimum, maximum and average are very similar.

Table 8. Pressure distribution comparison between the original and rehabilitated networks for T23WDS

Criteria	Minimum Pressure (m)	Average Pressure (m)	Maximum Pressure (m)
Optimum Design OPUS	13.77	28.33	46.40
Rehabilitated with I_r	21.92	36.49	54.55
Rehabilitated with P_{UT}	21.91	36.47	54.54

a)   b)
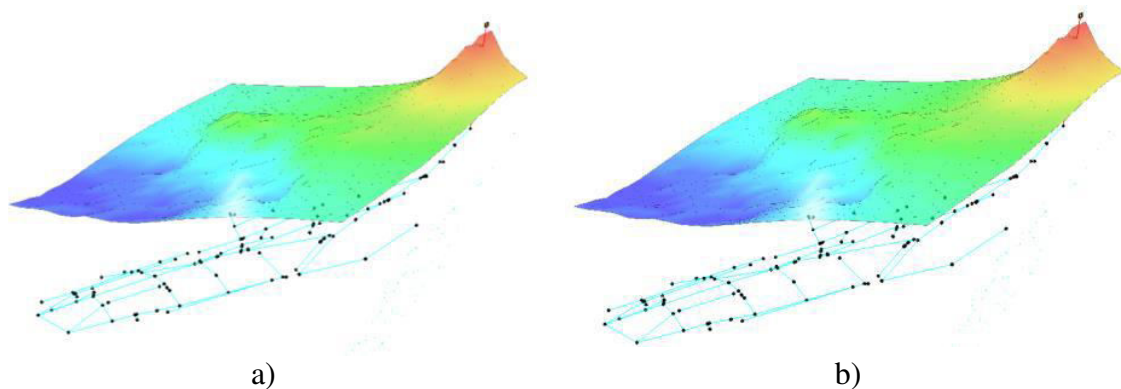
Figure 2. HGS of T23 WDS rehabilitated by (a) Specific Power, (b) Resilience Index criteria

5   CONCLUSIONS

This investigation proposed the use of population growth rates in water demand of WDS in order to analyze the optimum design compared with two different rehabilitation criteria. Each one of the six study cases resulted in pressures below the minimum pressure stablished (15 m) due to the increase of demand. Based on this methodology, it is possible to confirm the need of a rehabilitation criteria to guarantee the correct functioning of a WDS.

The parameters used in the present investigation were Resilience Index and Dissipated Power analyzed in terms of costs, number of changes and pressure distribution. The first one proved to result in WDS costs nearby the optimum one with a limited number of changes in the process. On contrary, the second criteria requires an increased number of modifications with more expensive networks but higher resilience indexes.

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