Analysis of a Town's Water Distribution System

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Abstract

The analysis of an existing water distribution system is presented. The constraint satisfaction model for the study of the network is evaluated using Epanet software. According to the analysis, possible solutions are proposed to improve the distribution of water in the community. One of the recommendations is to add new storage tanks and valves to increase the flow and regulate the pressure without changing the current design of the network. It is not possible to change pipes and diameters because the system is in operation.

1. Introduction

Water distribution systems are a problem of great interest for society. The poor design of the existing distribution networks is due to a lack of methods to optimize their main parameters. It is necessary to implement improvements that do not involve high economic loss, yet meet the needs of consumers. Over more than three decades, researchers have proposed several theoretical models and optimization methods. In practice, however, they have treated only small instances due to the enormous complexity of the problem.

The water distribution network problem can be approached in its different stages: design, operation, rehabilitation and maintenance. Currently, several researchers have conducted studies focused on the stage of the problem design [1].

The problem has been studied by several researchers using different optimization methods, such as genetic algorithms [2, 3, 4, 5 and 6], local search [7], simulated annealing [8, 9], and ant colony [10, 11]. These methods have been implemented to find a suitable configuration of diameters for each pipe as well as the minimum cost of the design network. The optimal design of water distribution networks has important implications for reducing energy consumption and improving the economic and social benefits [12].

Other researchers have reported algorithms [13, 14, 15] to improve the operation stage of a water distribution system.

The problem presented in this paper is the existing water distribution system in the community "Fraccionamiento Real Montecasino," in Huitzilac, Morelos, Mexico. The system is currently operating, but not distributing water efficiently. For this reason, it is important to find possible solutions to improve distribution. To improve the distribution of water in the system, use of a local search algorithm is proposed. The intention is to find a good solution through cost optimization, where costs are related to the balance of pressures in the system, bound by a defined interval.

This article is divided into the following sections: section two defines the water distribution network problem, section three presents the analysis and results of the existing water distribution system, and section four presents the conclusions obtained in this research.

2. Water Distribution Network Problem

The problem description is the following: a network contains pipes, pumps, valves and supply sources. Pipes carry water from supply sources to consumers. At given points, valves limit pressure or flow and pumps help to regulate the flow. The supply sources are the main elements in the water distribution system. They are wells, rivers, streams and storage tanks. [16].

The network presented in this paper is a real instance that exists in the community "Fraccionamiento Real Montecasino," Huitzilac, Morelos, Mexico. This network consists of five geographical sections: "Ensueños," "Piamontes," and "Montecasino," section 1 and 2. Currently the water distribution system is in operation, but it is not optimal due to poor network design. For this reason, it is important to study and analyze the network. The aim is to propose possible solutions without changing the current design (see Figure 1).

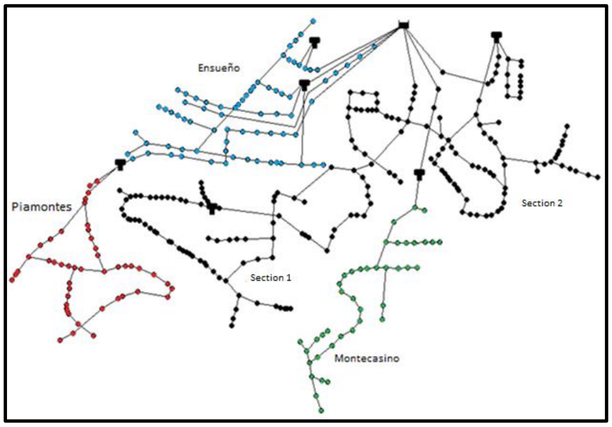

Figure 1. **Water distribution network of Fraccionamiento Real Montecasino, Huitzilac, Morelos, Mexico.**

The water distribution system problem can be represented by graph theory. In a graph, nodes or vertices represent supply sources and consumers. The arcs or edges represent the connection elements such as pipes, valves, and pumps [1]. Therefore, the problem can be resolved using a mathematical model.

2.1 Constraint Satisfaction Model

A water distribution system must comply with mass and energy conservation equations through the following constraint satisfaction model.

$$\sum_i Q_{in} - \sum_i Q_{out} = Q_e \qquad (1)$$

$$\sum_m h_f = \sum_m E_p \qquad (2)$$

$$H_{min} \leq H_i \leq H_{max} \qquad (3)$$

$$V_{min} \leq V_{ij} \leq V_{max} \qquad (4)$$

The Law of Conservation of Mass is obeyed in each node (see Eq. 1). Q_{in} is the pipe flow into the node, Q_{out} is the pipe flow out of the node, and Q_e is the external demand or supply at the node.

The Law of Energy Conservation is obeyed in each circuit (see Eq. 2), where h_f is the frictional energy loss and E_p is the pumping energy. This equation is required for each loop in the network. The pressure constraint is Eq. 3, where H_{min} is the minimum pressure required, H_{max} is the maximum pressure required and H_i is the pressure at node *i*. The velocity constraint must be respected as well (see Eq. 4). V_{min} is the minimum velocity required, V_{max} is the maximum velocity, and V_{ij} is the velocity from node *i* to node *j*. The constraint satisfaction model is evaluated by Epanet software.

2.2 Epanet Simulation System

Epanet is free software developed by the Environmental Protection Agency (EPA). Epanet allows analysis of the hydraulic and water quality behavior in water distribution systems [16]. Figure 2 shows an Epanet environmental scheme.

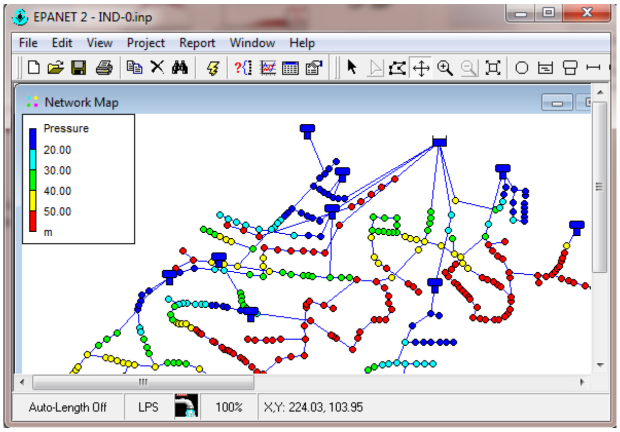

Figure 2. **Epanet scheme**

The simulation of the water distribution network is made by Epanet toolkit. Epanet toolkit is a dynamic link library (DLL) of functions that allows for observation of the flow in each pipe, the pressure at each node, and the height of water in each tank in the network during a simulation of a specific time period [17].

2.3 Local Search Algorithm

The local search procedure requires a neighborhood structure and an objective function that maximizes or minimizes costs.

The local search starts with a start solution *s* and the solution set *N(s)*. From this set, a solution *s'* is selected via an σ movement. The type of movement performed to select a neighbor defines the structure of the neighborhood. The objective function works by means of a stochastic process *C(s', Epanet) <= C(s, Epanet)*. If this is true, the solution *s* is replaced with the solution *s'*. This is repeated until the stop criterion of the local search is reached (see Figure 3).

```
Generate initial solution $s$
  do
    $s' = Nf(s,\sigma)$
    if ($C(s',Epanet) \leq C(s,Epanet)$) then
      $s'$= best solution found
      $s=s'$
    end-if
  while stop criterion
```

Figure 3**. Local Search Algorithm**

In Figure 3, the neighborhood structure, *Nf*, when applied to the neighborhood *N(s)*, provides access to neighbors of solution *s*. Through small movements in the configuration of *s*, the cost of each solution *s* and *s'* can be evaluated with Epanet. In the case of solution *s* in the hydraulic system presented in Figure 1, a neighboring solution, *s'*, is a slight change to *s*. In this work, the movements used in the neighborhood structure *Nf* are changes in the coordinates of tank locations, the dimensions of the tanks, and the exchange valves in the pipes.

The cost of the objective function is a penalty function, based on the range of pressures between 10 and 60 m (where m refers to water column meters). This function must be satisfied for each node of the hydraulic system. It is punishable with a one-unit cost per node that is not in the pressure range. For example, if 10 nodes are not met, the cost added to the objective function would be 10 units. The solution s of the hydraulic system is described as feasible when the pressures in all the nodes are within the established range. There are two stop criterions in the algorithm (Figure 3). The first is when the cost reaches zero, i.e., the best solution is found to comply with the pressure range in all nodes in the system. The second stop criterion is when a certain number of iterations is reached.

3. Analysis and Results of the Huitzilac Water Distribution System

The Huitzilac water distribution network consists of 350 nodes (consumers), 365 pipes, 6 tanks, and one reservoir. The network requires use of the Hazen–Williams equation with a roughness coefficient C = 120 to solve the hydraulic simulation in Epanet. The roughness coefficient value depends on pipe material [18].

Epanet indicates the pressures on nodes using color ranges. Red has a pressure range of >50m. Pressure range <20 m is navy blue (see Figure 4).

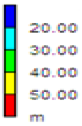

Figure 4. **Pressure ranges in Epanet.**

3.1 Operation of the Original System

3.1.1 Input Data System

Tables 1-3 show the general characteristics of the system installed in the village of Huitzilac. These data cannot be modified because the network already exists. The only possible additions would be new tanks and valves. Here MSL indicates the height of a node with respect to sea level.

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Table 1. **Properties of nodes in the network**

Node	MSL(m)	Demand(l/s)
1	2238	0.003
2	2243	0.003
3	2244	0.003
4	2246	0.003
5	2248	0.003
..		..
350	2252	0.003

Table 2. **Properties of pipes in the network.**

Pipe	Length(m)	Diameter(mm)	Roughness
1	238	38.1	120
2	991	19.05	120
3	299	38.1	120
4	991	19.05	120
..	..	..	..
..	..	..	..
364	572.1	50.8	120

Table 3 shows the properties of the six tanks in the original Huitzilac network. Initial level indicates the beginning of the simulation.

Table 3. **Properties of tanks in the network.**

Tank	MSL (m)	Initial level (m)	Maximum level (m)	Minimum level(m)	Diameter (m)
1	2308	2	1	4	8.67
2	2334	2	0	4	5.86
3	2337	2	0	5	4.72
4	2364	2	0	4	5.93
5	2373	2	1	6	8.41
6	2398	2	1	7	10.16

Figure 5 shows the Huitzilac water distribution system. The simulation indicates that there is low pressure at some points.

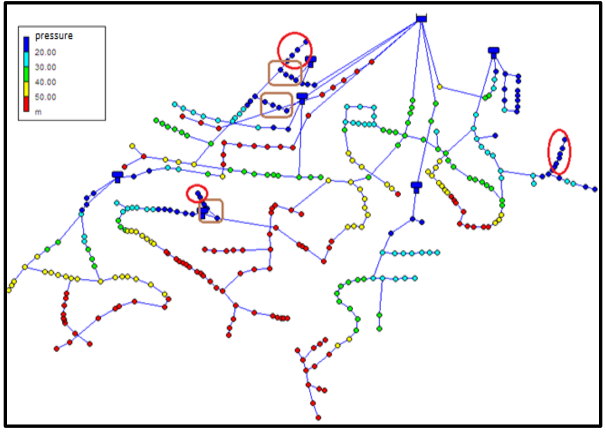

Figure 5. **Huitzilac water distribution network simulation.**

Figure 6 shows the pressure results in the Huitzilac network. It can be seen that there are very low, even negative pressures. Therefore, the distribution system does not work optimally for the network.

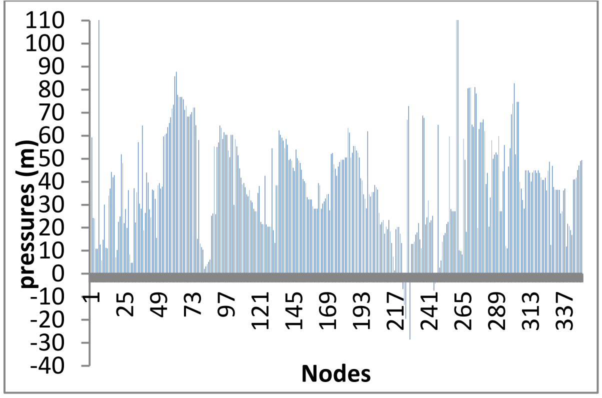

Figure 6. **Huitzilac water distribution network pressures.**

Figure 6 shows that between nodes 217 and 241, negative pressures are present in a total of 24 nodes. The load of negative pressure is about -10 to -25 m; this indicates that at these points there is no water. It can also be observed that there are nodes with pressures over 100 m; the water is received at a high pressure at these nodes.

3.1 System Optimization Results

3.1 Add Storage Tanks

Storage tanks allow regulation of the distribution of flow and prevent failures in the supply.

Benefits:

- Match the supply and demand for water.
- Minimize the pressure variation during periods of high consumption.
- Reduce the size of the pump and the cost of energy.
- Increase the pressure in the distribution system.

Adding storage tanks at the points where the pressure is very low or even negative could increase the pressure. With this addition, it was possible to adjust the pressure on the nodes.

Figure 7 shows three new storage tanks that are added at the points where the pressure is minimal. Each tank has different properties. The simulations were conducted on Epanet and pressure increases were observed.

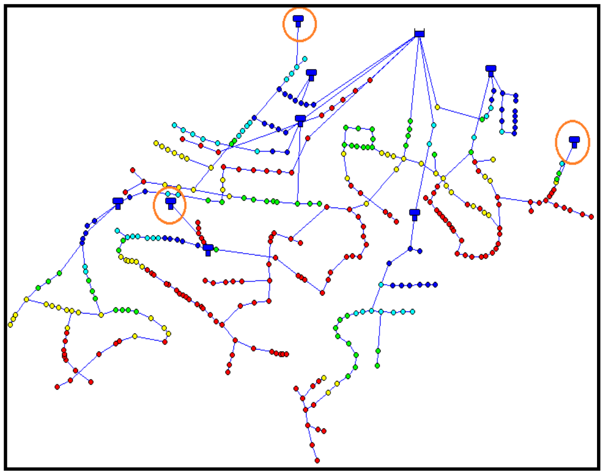

Figure 7. **Addition of tanks to the water distribution network.**

Figure 8 shows the properties of the new tanks. Pressure depends on the properties of the tanks that are generated, such as diameter, height, volume and levels.

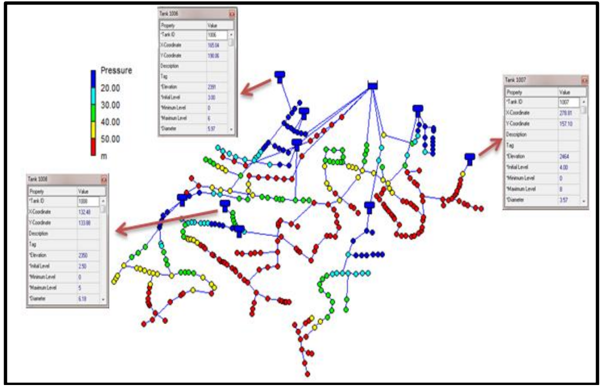

Figure 8. **Properties of the tanks added to the water distribution network.**

Figure 9 shows the pressures of the Huitzilac network after adding new tanks. At the points where the pressure is low, it can be seen that the pressure increases, and therefore, there are no negative pressures. The result improved the water distribution system. Figure 9 presents a solution which improves the pressure at the nodes, obtaining pressures above 10 m. The solution is not considered a feasible solution because there are nodes where the pressure is very high which may cause breaks in the system piping.

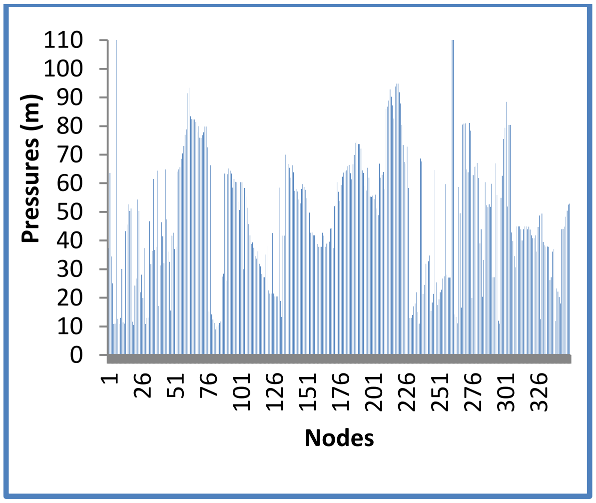

Figure 9. **Huitzilac water distribution network pressures.**

3.2 Valve Addition

The valves help regulate the pressure or the flow at certain points in the water distribution system. Epanet uses various types of valves, such as PRV (pressure reducing valve), PSV (pressure sustaining valve), PBV (pressure breaker valve), FCV (flow control valve), and GPV (general purpose valve) [17]. The valve studied in this paper is the PRV type.

Table 4 shows the properties of the valves added to Huitzilac network. Consign value allows for the control of pressure at the node.

Table 4. **Properties of valves**

Valve	**Start node**	**End node**	**Diameter (mm)**	**Valve type**	**Consign value**
1	307	308	50.8	PRV	30
2	98	366	76.2	PRV	30
3	152	151	50.8	PRV	35
4	211	210	50.8	PRV	40
5	201	202	50.8	PRV	35
6	213	218	50.8	PRV	40

Figure 10 shows the pressures of the Huitzilac network after adding valves in points where the pressure is very high.

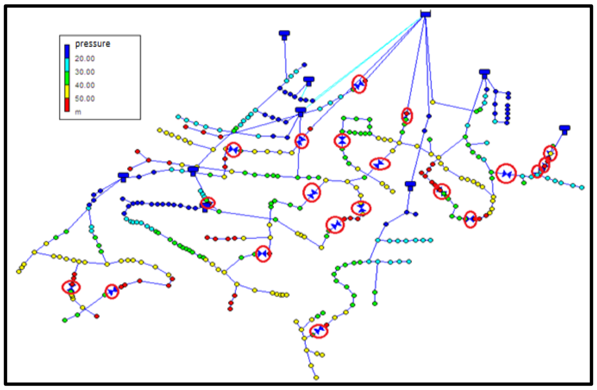

Figure 10. **Addition of valves to the water distribution network.**

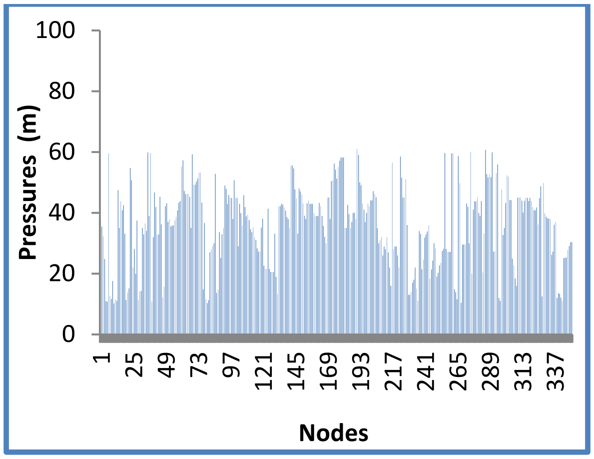

Figure 11. **Pressures after addition of tanks and valves.**

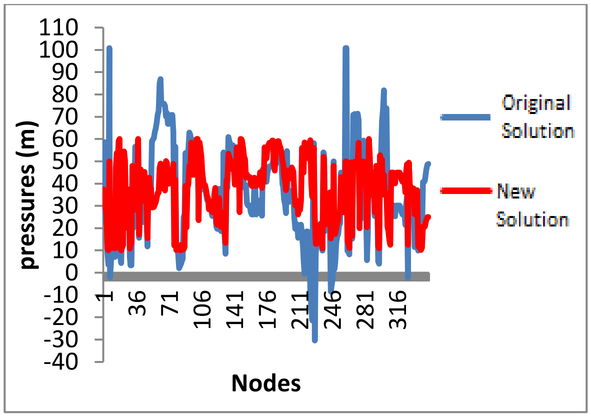

Figure 12. **Pressure results for both cases.**

Figure 11 shows the best solution found with the local search algorithm by adding tanks and valves. In this solution, the cost value in the objective function is zero, because the pressure range of each node is within the range of accepted pressures (10-60m). This solution favors the system because there is a better distribution of the pressures on all network nodes.

Figure 12 shows the comparison of the pressures on the nodes with the initial configuration of the Huitzilac network and after adding storage tanks to increase pressure and valves to regulate the pressure. The proposed possible solution is efficient because it meets the objective of distributing the pressures at the nodes in an equitable manner.

4. Conclusions

It was found that a local search heuristic applied with EPANET software is an effective way to improve water distribution systems that are in operation. The method allows for better water distribution in populations when pressure balancing is done by optimizing the cost function, which cost penalizes any node not within the defined pressure range.

Acknowledgement

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