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Sectorization of intermittent water supply networks based on graph theory and clustering techniques

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Abstract: Intermittent water supply is the form of access to water in many countries around the world. It is very common that design, operation, maintenance and, in general, decision-making in these systems are performed using tools originally developed for systems with continuous supply, which are not adequate. However, these tools can be reasonably applied to network sectorization of intermittent supply networks. We propose a sectorization methodology for networks that do not have the possibility of working with continuous supply. In addition, to ensure sufficient pressure, sector design must guarantee equity in the supply. Furthermore, it is not enough to establish sector delimitation as part of the design, but also to define the supply time of each sector based on its hydraulic characteristics. Graph theory, clustering techniques, multi-attribute decision-making and the concept of network capacity are the basis for achieving this methodology.

***Keywords**:* Sectorization, intermittent water supply, clustering techniques, decision-making

1 INTRODUCTION

Continuous water supply (CWS) is threatened by increased demand due to population growth, reduction in availability of water resources due to pollution and effects of climate change, which increase the severity of extreme events, and some deficiencies in the management of water supply systems (Totsuka et al., 2004). As a result, water companies may be forced to adopt a supply for few hours a day, which is known as intermittent water supply (IWS). IWS causes damage to the system infrastructure (Central Public Health and Environmental Engineering Organisation, 2005), health risk (Kumpel & Nelson, 2014), and equity problems in water supply (Vairavamoorthy et al., 2008). Although IWS should be the last action to take, it still remains the form of access to water for millions of people in developing countries mainly.

Design of water supply systems is usually based on the assumption that water supply is continuous. However, hydraulic and operating conditions change in an intermittent supply. IWS generates pressure losses and high inequity in water distribution (Vairavamoorthy et al., 2001); e.g. when water demand is high, users further away from the supply points are the most affected because they cannot be supplied with a sufficient amount of water during the early delivery hours. If IWS is not well planned, it results in supply water inequity for users (Vairavamoorthy et al., 2008).

In CWS systems, the use of sectors is a common practice for leak detection. In contrast, sectorization is common for supply schedule organization in IWS systems (Ilaya-Ayza et al., 2015). When an IWS network is not sectorized, the peak flow produced during supply hours is very large because of simultaneity in water consumption. High flows reduce service quality, and can generate areas with low pressures. When the network works under IWS, it must withstand a load above its capacity. Sectorization of the network in IWS systems is one of the first steps to achieve a more efficient system management, and ensure supply equity. The presence of sectors in the network, each one with a different supply time, can reduce the peak flow and thus improve pressure. Therefore, sectorization is a very useful tool in IWS systems management.

There is abundant literature for the design, management, operation, and maintenance of CWS systems. In contrast, there are few tools for IWS systems that allow proper management and operation. Thus, these tasks are usually performed manually, and based simply on workers experience of water companies (Manohar & Kumar, 2014).

This paper proposes a methodology for sector configuration of an IWS network. Sector size and delivery time are set using graph theory, clustering techniques, multi-attribute decision-making, the network capacity concept, and equity criteria. However, this proposal does not seek to promote intermittent water supply, but to present solutions to improve service in systems in which supply for twenty four hours a day is simply unfeasible.

2 METHODOLOGY

A sector is a discrete area of a water distribution network, hydraulically isolated, temporarily or permanently (Di Nardo et al., 2013). Sectors can be created by installing isolation valves on pipes that connect with other contiguous sectors. In some cases, these pipes can be permanently disconnected.

Usually, the implementation and configuration of sectors is an empirical task based on technical expertise of water companies or trial and error simulations (Di Nardo et al., 2013). The complexity of sector development to reduce leakage and ensure an adequate quality service requires the use of efficient techniques. There is a general tendency to use optimization techniques to achieve an adequate level of service (Izquierdo et al., 2011), and several authors suggest the use of graph theory for sectorization processes as well (Di Nardo et al., 2013), (Campbell et al., 2015).

Although the importance of structured sectorization in IWS networks is recognized (McIntosh, 2003), there are no specific references in the literature related to design of IWS network division into sectors.

In the following paragraph, we detail the concept of network capacity, which is useful for calculating the supply time; the network sectorization process is described next.

2.1 Setting curve and theoretical maximum flow

By regulating head or inlet pressure in the supply source to supply demand points with at least the minimum pressure required, P_{min}, it is possible to reduce the energy loss produced when users do not require water. Moreover, continuous regulation does not define a head or setpoint pressure, but a setting curve that ensures, for each network load condition, the strictly necessary minimum pressure at the demand points (Martínez et al., 2009).

For calculation of the setting curve, it is necessary to adjust the demand factor (k_j) on all nodes of the network. We define thereby a load condition (j) and thus the new demanded flows (Q_i) in each node (i). Consequently, the hydraulic behaviour of the network responds to this new load condition, and new head at the supply source (H_j) and flow injected to the network (Q_j) are obtained. A set of load states defines a set of ordered pairs (H_j, Q_j), which form the setting curve. When this head equals the head at the supply source (H_s), we obtain the *theoretical maximum flow* (Q_{maxt}) of the network (Ilaya-Ayza et al., 2016).

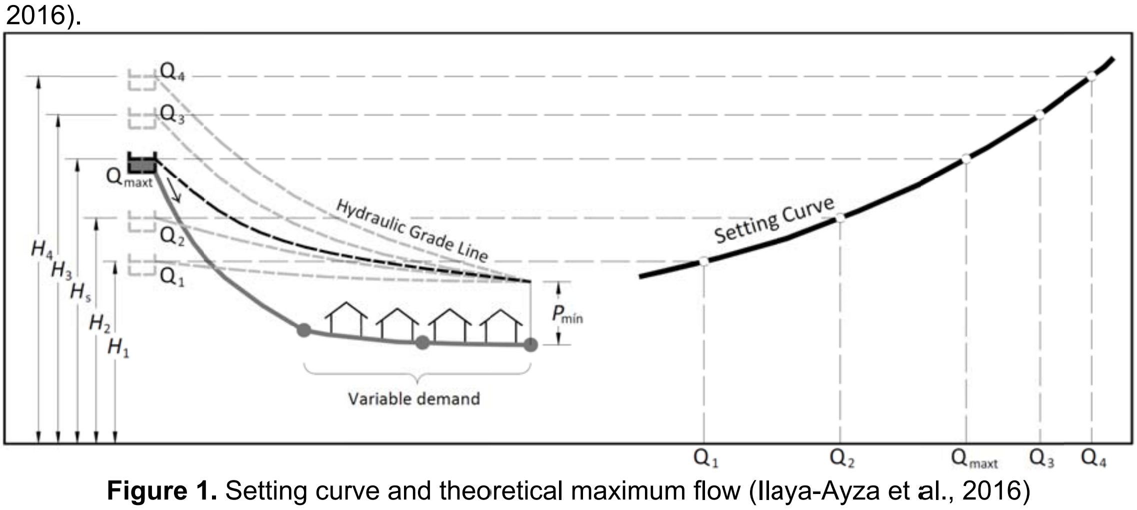

Figure 1. Setting curve and theoretical maximum flow (Ilaya-Ayza et al., 2016)

2.2. Sectorization network process

Sectorizing an IWS network is a different task from sectorizing a CWS network. We must first consider that the supply must have sufficient pressure and be equitable. To ensure these two objectives, a good sectorization of an IWS network has to be able to define the number of supply hours and the ideal size of each sector. A procedure for IWS network sectorization is shown in Figure 2.

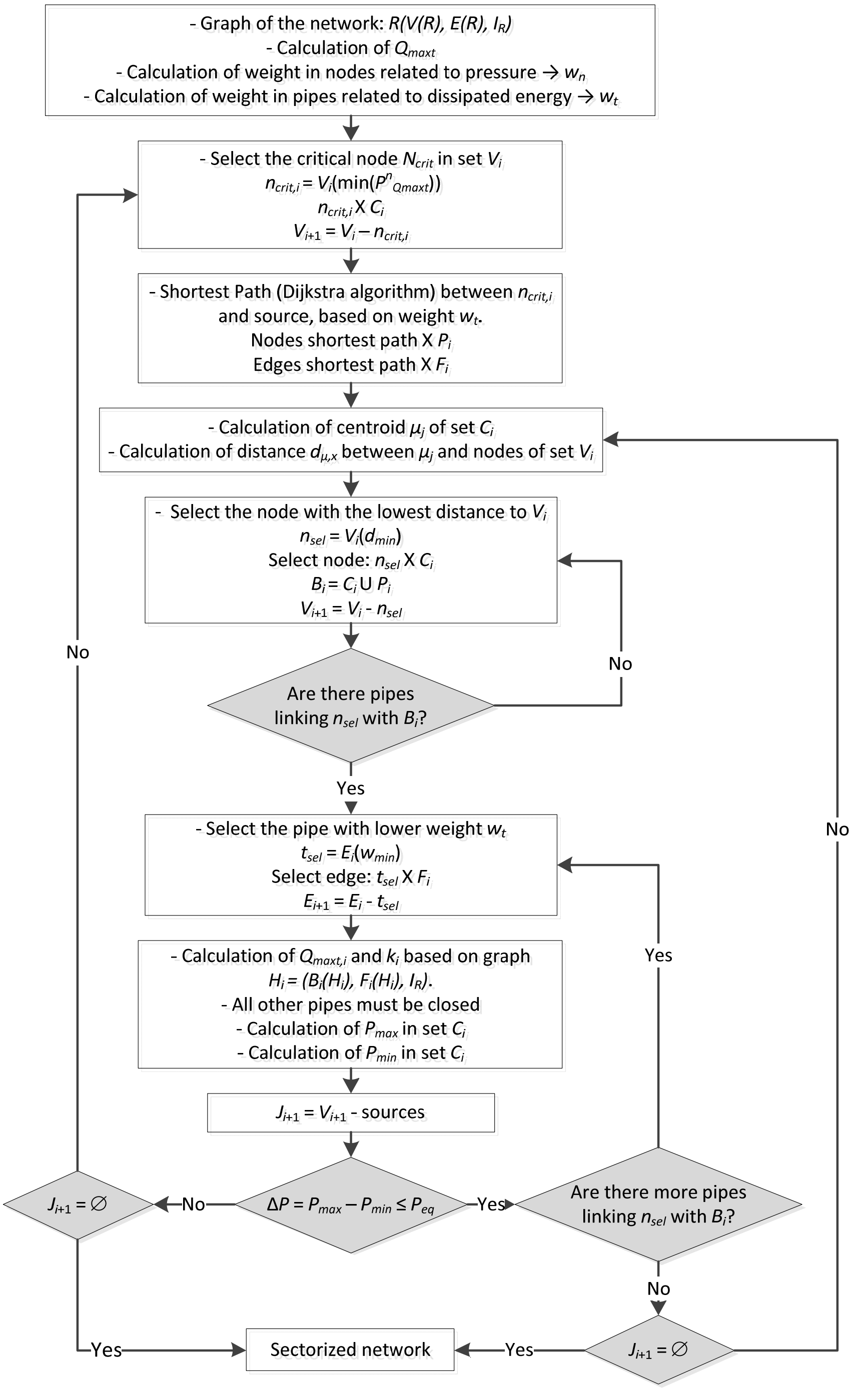

Figure 2. Flowchart for sectorization of IWS networks

First, a water supply network can be modelled as a graph. In this paper, a network or an initial sector is represented by an undirected graph R, defined by the set of network nodes $V(R)$, the set of pipes $E(R)$, and the incidence relation I_R that associates each element $E(R)$ with an unordered pair of $V(R)$:

$$R = (V(R), E(R), I_R). \tag{1}$$

In the first hydraulic simulation, pressures are calculated on all the network nodes when the network works under the theoretical maximum flow. The calculated pressure for node n (P^{n}_{Qmaxt}) is used as the weight of node n (w_n). The node with the lowest weight becomes the critical node. In the same way, flows and head losses in each pipe are calculated with the load condition associated to the theoretical maximum flow. The dissipated power (energy per unit time) (Todini, 2000) in each pipe of the network (P_t) depends on the specific weight of water (γ), the flow that circulates through pipeline t (Q_t), and the head loss in pipeline t (h_t). To identify the pipes exhibiting lower losses, a weight (w_t) related to the energy loss, is calculated for each pipe as the inverse of the power:

$$w_t = \frac{1}{\gamma \cdot |Q_t| \cdot h_t}. \tag{2}$$

The pressures at the nodes are used to identify the critical node of the network. With this origin and the supply source as end point, we calculate the shortest path (Dijkstra, 1959) based on the energy dissipation (w_t). This is essential for sector identification, since each sector is associated with an initial shortest path.

The critical node ($n_{crit,i}$) becomes the initial centroid (μ_{cm}) of a forming cluster or sector C_i. Later, we select the next node (n_{sel}), that is connected to the cluster through an edge (pipe) t_{sel} and has the shortest distance ($d(\mu_c,x_j)$). With this new node, the theoretical maximum flow and corresponding pressures are again calculated. The selection of each node reorganises the cluster, so it is necessary to recalculate the centroid (μ_{cm}) again:

$$d(\mu_c, x_j) = w_{g,j} \cdot \sqrt{\sum_{m=1}^{p} w_m \cdot (\mu_{cm} - x_{jm})^2}, \tag{3}$$

$$w_{g,j} = 1 - \frac{g_j}{M}, \tag{4}$$

$$\mu_{cm} = \frac{1}{N_c} \sum_{q=1}^{N_c} x_{qm}. \tag{5}$$

The distance depends on: the weight related to the degree of connection of node j ($w_{g,j}$), the degree of connection of node j (g_j,), a constant that depends on the importance assigned to the connection degree (M), the normalized value of variable m of node j (x_{jm}), and the variable m in the weight (w_m) where m = 1 for the x coordinate, m = 2 for the y coordinate, m = 3 for the elevation, and m = 4 for the pressure. Observe that p is the total number of variables (p = 4); μ_{cm} is the centroid of cluster C for variable m; and N_c is the number of nodes belonging to the cluster in formation C.

Coordinates x and y enable us to find the horizontal distance to other nodes in the network. Nodes closer to the centroid of the cluster are the most likely to be incorporated. Both, node elevation and pressure are aimed at improving supply equity in the network or sector. It is intended that nodes of a sector have similar elevations and pressures. The configuration of a sector or cluster can leave isolated nodes connected to the sector through a single pipe and leave them without the possibility of being taken into account by other sectors. This situation requires using the node degree in the network as a variable for calculating the distance, so that nodes with a lower connection degree are first prioritized.

The geographically nearest node is not necessarily the one with the shortest distance or greater similarity; since there must also be an edge between the node and the set of nodes previously selected, including the nodes of the shortest path.

The node clustering process concludes when the pressure difference (ΔP) exceeds a limit value (P_{eq}) that guarantees the equity of supply. If there are still nodes without assignment, the algorithm begins the process with another sector. This procedure must be repeated, thus generating multiple clusters C_i, until all nodes are assigned to sectors. In this paper, we use the recommended values of CPHEEO (2005) defined in a range of ΔP = 3 to 5 m.

$$P_{\max} = \max_P (C_i) \tag{6}$$

$$P_{\min} = \min_P (C_i) \tag{7}$$

$$\Delta P = P_{\max} - P_{\min} \le P_{eq} \tag{8}$$

Each step or iteration in the formation process of a new sector allows us to calculate the theoretical maximum flow. Using the average consumption or demand (Q_i) of the selected nodes (ns), it is possible to know the peak factor (k_j). This factor is related to the number of supply hours, which is calculated under the following conditions:

$$Q^{j}_{\max t} = k_j \cdot \sum_{i=1}^{ns} Q_i \;\text{ for all } j. \tag{9}$$

To calculate the supply time (t_s), we assume that the volume consumed in continuous supply is equal to the volume consumed in intermittent supply (V_s). Moreover, we assume that the average flow must be distributed along 24 hours a day, and the network capacity (Q_{maxt}) enables us to deliver a higher flow in a shorter supply time.

$$V_s = \sum_{i=1}^{ns} Q_i \cdot 24\,, \tag{10}$$

$$V_s = Q^{j}_{\max t} \cdot t_s\,, \tag{11}$$

$$t_s = \frac{24}{k_j}\,. \tag{12}$$

To introduce the expert opinion of the water company into the sectorization process, we use the Analytic Hierarchy Process (AHP) (Saaty & Vargas, 2012). With this method, we assign a weight (w_m) to each criterion.

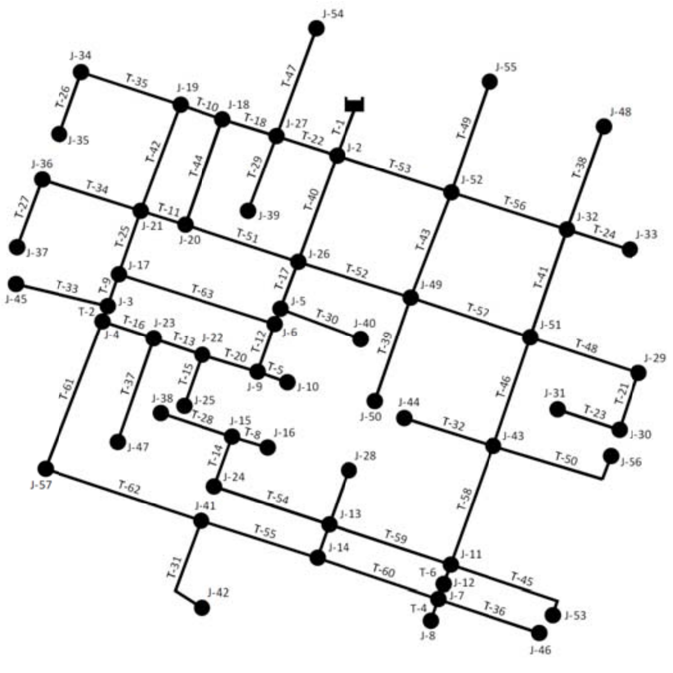

Figure 3. Network model

3. RESULTS AND DISCUSSION

The water supply network presented in Figure 3 is a subsystem of the network of Oruro (Bolivia), which delivers water only for four hours a day. The flow demanded to meet the population needs in this period is 12.64 L/s, and the minimum pressure required is 10 m. The minimum water level in the reservoir that feeds the network is at an altitude of 3737 masl (meters above sea level), and the network has an average elevation of 3718 masl.

The current network has a pressure difference (ΔP) of 11.99 m, and the lowest pressure reaches 5.3 m. As a result, supply is inequitable. We seek equitable supply by defining sectors exhibiting a pressure difference between the maximum and minimum value that does not exceed 5 m.

Interviews to water company experts are used to calculate the weight for each criterion through pairwise comparison matrices (Saaty & Vargas, 2012). As an example, Table1 presents the comparison matrix and the priority vector for expert #1. The consistency ratio (*CR*) is 5.1%.

Table 1. Pairwise comparison matrix for expert #1, including priority vector

	x and *y* coordinates	Elevation	Pressure	Eigenvector
***x* and *y* coordinates**	**1**	3	1/2	0.333
Elevation	**1/3**	**1**	1/3	0.140
Pressure	**2**	**3**	**1**	0.528

The weight of each variable is obtained (see Table 2) by calculating the geometric mean of the eigenvectors obtained from the matrix of each expert (Delgado-Galván et al., 2014).

Table 2. Normalized weight of each variable

Criterion	Expert 1	Expert 2	Expert 3	Geometric mean	Normalized weight
***x* and *y* coordinates**	0.333	0.333	0.200	0.281	0.291
Elevation	0.140	0.333	0.200	0.210	0.218
Pressure	0.528	0.333	0.600	0.473	0.490
Total	**1**	**1**	**1**	**0.964**	**1**

From the critical node, we find the shortest path to the supply source, which is used to form the first sector. Once the critical node is defined, the algorithm starts the clustering of nodes based on the distance of similarity. In each iteration, a node is added to the sector. Each step is evaluated until the set of nodes achieve a pressure difference that ensures the desired equity.

As known, a clustering process depends on the distance function and on the used clustering technique. In our case, a sensitivity analysis (see Figure 4) of the clustering quality is performed by including the importance of the node degree (see Equation 4) through factor *M*, which manages to avoid having unlinked nodes. In intermittent water supply networks, it is convenient to obtain greater size sectors under equity criteria. Specifically, in this network we obtained a 26-node sector, #1, with the selected set of nodes not exceeding ΔP = 5 m and, due to its characteristics, we assigned *M* a bigger value or simply $w_{g,j}$ = 1, with minor differences; otherwise a smaller sector is obtained.

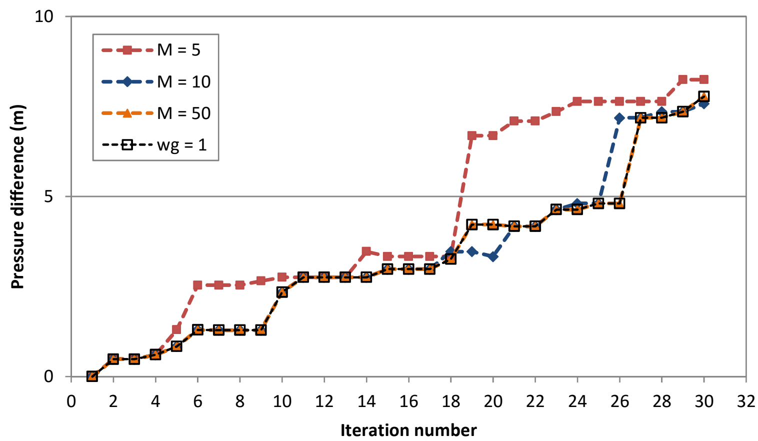

Figure 4. Iterations to configure sector #1

As the critical node of the network has already been selected as part of the first sector, there is a new critical node. The pressure difference between this new node and the supply source is very large, and it makes difficult to fulfil the condition of equity in the supply. Therefore, one can either reduce head at the source (Figure 5), or decide to create more sectors. Operationally, it is better to reduce head at the source, since it also reduces the leakage level.

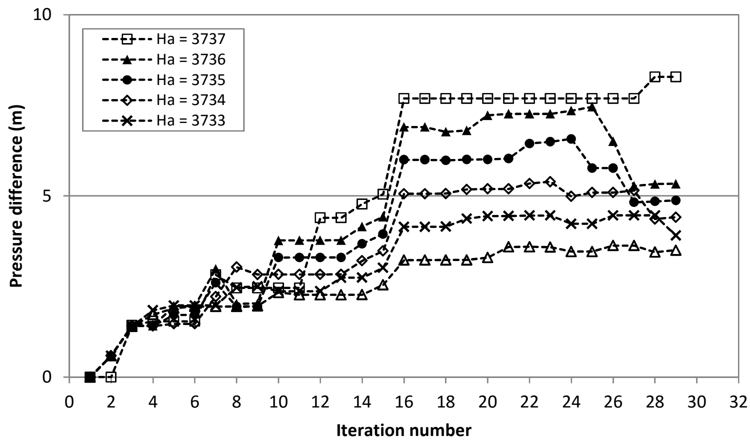

Figure 5. Iterations to configure sector #2

By reducing the network inlet pressure, we obtain a pressure difference lower than 5.0 m from a value of 3735 masl. For lower inlet heads, there are lower pressure difference between the supply source and the critical node; thus greater equity may be achieved. However, reducing the pressure difference means increasing the number of supply hours; the smaller this difference, the more hours of service are required. Reducing the current supply time is not an option, because it would generate consumer complaints. Therefore, we set a minimum limit of 4 hours of supply, and we can therefore reduce the incoming pressure in the second sector to a head H_a = 3732 m. As a result, two sectors are configured (see Figure 6, and summarized results in Table 3).

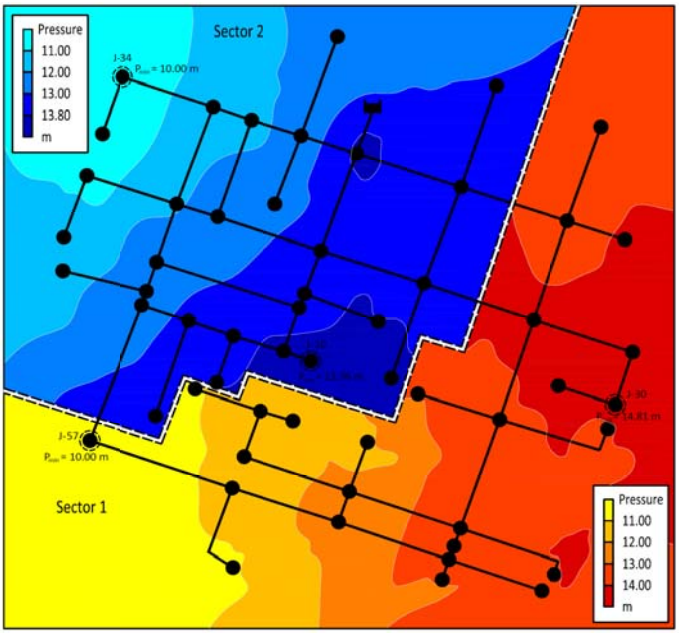

Figure 6. Sectorized network

Table 3. Sectorization process results

Sector	P_{max}	P_{min}	Pressure difference (m)	Q_{maxt} (l/s)	Supply time (h)	H_a (m)	Nodes in sector
Sector 1	14.81	10.00	4.81 < 5	2.76	8.46	3737	26
Sector 2	13.54	10.00	3.54 < 5	6.18	4.41	3732	30

3. CONCLUSIONS

The common use of IWS in many developing countries, consequently generating inequity in the supply due to its characteristics, and the few available tools for planning and managing these systems make it necessary to develop methods to improve the performance of IWS systems. In our method, we propose a tool for sectorization (network clustering) based on hydraulic criteria, equity criteria, and water company experts' opinion. Furthermore, we define the supply hours for every sector. This is a new and useful approach in network sectorization and, by making use of this method, better decision-making, management and performance of IWS systems can be achieved.

The use of the connection degree in the distance function to set the clusters manages to reduce the sector size, thus indirectly helping to avoid having nodes without an assigned sector. At the same time, the use of this parameter enables us to perform a qualitative assessment of the obtained clustering (sectorization).

In the presented case of study, sector #1 included originally the critical node of the entire network, which imposed the most unfavourable conditions on the network: this node reduced the sector capacity and defined longer supply times. However, sector #2 may have, after some iteration, improved capacity, since the critical node of the original network is no longer involved. Thus, a new critical node, which tends to impose greater capacity, is calculated. It can then be concluded that the critical node strongly affects the supply time of the sector.

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