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Gradual transition from intermittent to continuous water supply based on multi-criteria optimization for network sector selection

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Abstract

Piped intermittent water supply bears numerous population health problems and may damage the network infrastructure. Thus, a transition to continuous supply is an option that must be studied. Nevertheless, many water companies have not enough resources to produce the big investments necessary for a direct transition. Consequently, we propose a gradual transition process based on optimal sector selection at the various network upgrading stages of the process, while considering the possibility of simultaneously having continuous and intermittent supplied sectors. We ultimately seek every sector to have continuous supply at the end of the process. Sector selection takes into account qualitative and quantitative criteria, which guarantees equity for still intermittent sectors, benefiting the highest number of users, and facilitating water company operation tasks. Thereby, it is possible to achieve a planned transition that meets water company economical limitations. The problem of optimal sector selection is a computational complex task, since it deals with a non-linear problem with mixed decision variables and is affected by uncertainty and qualitative criteria.

Keywords: Intermittent water supply, multi-criteria analysis, optimization

1. Introduction

Piped water supply for few hours a day, or intermittent water supply, is a common form of access to water in developing countries [1], where water facilities increasingly operate based on crisis management criteria and commonly use water rationing measures, instead of implementing better planning on their systems [2]. Intermittent water supply exists due to various reasons; Totsuka et al [3] indicate three types of problems that can cause or perpetuate intermittent supply: poor technical management, which increases leakage and reduces water availability [4]; economic scarcity, when there are not enough economic resources to enlarge the supply infrastructure; and absolute scarcity of water resources. These conditions, together with extreme events caused by climate change and population growth, may lead to a more frequent use of intermittent water supply [5].

Usually, intermittent supply systems use sectors to organize supply hourly [6]. Nevertheless, water in small systems is commonly delivered to the entire network by hours. In this paper, we analyze the transition process for a sectorized network [7]. However; if the network is not sectorized, sectorization must be a first step before the transition process [8].

Many studies have shown that network deficiencies, caused by intermittent water supply, may not guarantee safe and reliable provision of water [9], due to intrusion of contaminated water when pressure is low or negative, and contamination during storage, bacterial growth in stagnant water, etc. [10], while sanitation and safe and reliable provision of water are fundamental components of basic municipal services. The drawbacks associated to intermittent water supply undermine possible improvements in public health in developing countries [11].

One of the best ways to assure water quality in the network, and to reduce health risks for users, is by maintaining a positive and continuous pressure level throughout the network [10], [12], since using continuous supply ensures security of water. Transformation from intermittent to continuous water supply is thus one of the main challenges in developing countries concerning water and health [13].

One of the main problems for this transition is economic scarcity. Water companies are not able to make large investments to achieve twenty-four-hour supply, so that efficient, long-term planned strategies are required. For instance, a gradual transition based on improvement stages is deemed to be a good option.

Moreover, gradually improving the network enable us to learn from each stage over time to perfect the next improvement. The first transitioned sectors to continuous supply serve as guidance for next sectors. Furthermore, huge one-time investment projects may be vulnerable to initial strategic mistakes even before they have started.

Additionally, high leakage rates might often make impossible a transition to continuous supply on an entire network at once. However, it may be possible to continuously supply some sectors and reduce leakage in them, since leakage management is easier performed under continuous supply conditions [14], [15] before conversion of next sectors.

Although no specific references for gradual transition processes may be found in the literature, there are recommendations suggesting the expansion of operation zones that work with continuous supply [16]. Usually, transition processes are performed with large and single investment projects [17], [18], something that is, most of the times, unaffordable. In this paper, we describe a methodology that enables gradual transition. It is mainly useful for water systems' operators that work constrained to an economic scarcity context.

This methodology is based on a balanced temporal coexistence of intermittent and continuous water supply. However, one must consider equity of water supply in intermittently working sectors, so that the limited amount of water is distributed as fairly and equitably as possible [19].

Guaranteeing water supply equity is one of the biggest problems of intermittent supply [20]. The main factors involved in equity supply are: node pressures, delivered flows, line velocities, node elevation differences, size of supplied areas [21], duration of water supply, supply schedules, connection types and locations [2], network configuration, and location of supply sources [20]. If a system with intermittent water supply is designed considering supply equity, the problematic consequences of water scarcity can be reduced [22]. Hence, a water supply equity index is proposed in this paper that controls equity. It is used to evaluate each sector to prioritize its conversion from intermittent to continuous supply.

Equity in the network can be improved through planning staged hourly supply [20]. As a prerequisite, a network division into sectors is essential to achieve water delivery per hours [6]; we assume the existence of such a division of the network into sectors to achieve gradual transition.

Our paper is based on a process of gradually increasing the network capacity by stages [23]. It helps improve the hydraulic behavior of the network at every stage, and it thus leads to new scenarios with increased capacity that allows higher pressure level in all sectors. Following these stages, we claim that it is possible to perform a gradual transition, where sectors selected to start with continuous supply are those better meeting certain criteria. The transition process is complete when all sectors in the network have continuous water supply.

Thus, in each stage some sectors change to continuous supply while others still continue with intermittent water supply. Selection of sectors that would work with continuous supply must: benefit as many consumers as possible, ensure water supply equity in sectors that still work with intermittent supply, and assure suitability of operation and maintenance tasks for the water company.

The problem of optimal sector selection is addressed by using multi-criteria analysis and genetic algorithms. Using binary variables that define the intermittent/continuous state of the sectors, mixed quantitative and qualitative criteria, and the non-linear relationships between flow and head loss in the mathematical model of the network, makes the optimization process a complex task [24].

In intermittent supply systems with economic scarcity or poor technical management, monitoring and collecting system data resources are limited. Thus, this improvement proposal must be adapted to basic available information, avoiding excessive model simplification though. Moreover, it is necessary to look for alternatives to complete missing information. Therefore, collecting available quantitative information and qualitative information is important to compensate this deficiency.

The quantitative criteria account for the physical and hydraulic variables of the system through the classical theory-driven hydraulic models, and for some management variables used by the water company. Qualitative aspects are introduced in the optimization process through the water company experts' perception of operating conditions of sectors, using surveys based on the Analytic Hierarchy Process (AHP) methodology [25], [26]. Finally, the network topology is included in this process through the reorganization of the network as a directed graph.

After this introduction, Section 2 addresses the methodological issues by describing the ingredients of the optimization problem. Then Section 3 presents a case study, a real-world water supply network. Section 4 contains a detailed summary of the obtained results and a discussion on them. Finally, Section 5 provides some relevant conclusions of the paper.

2. Methodology

We use the following procedure to select sectors:

- We collect information from intermittent supply sectors to know the inlet volume for every sector.
- Since this is a gradual sector selection procedure, and is based on upgrading network capacity stages, there are some sectors with intermittent supply and some others with continuous supply.
- We choose the process transition criteria. In this paper, the following normalized criteria are used for every sector: number of users, service pressure, water supply equity, and operation difficulty.
- Thus, each criterion weight is calculated by using the AHP method to determine total weight of every sector. We additionally include the network topology and the pressure calculated for each sector to make the transition process organized and efficient.
- Since the optimization process looks for a maximum number of continuous supply sectors at each stage based on the previously mentioned criteria; we use complementary binary vectors that show the supply behavior, continuous or intermittent, in each sector.

The transition process involves changing supply patterns throughout the entire network, from intermittent supply patterns to continuous supply patterns. Gradual selection allows gradual change of supply patterns until all sectors have continuous supply. Intermittent supply sector patterns show rectangular block shapes (see figures 1 and 2, left insets), which are defined by constant flow rates during delivery times [6], [27], while continuous supply is characterized by continuous shapes.

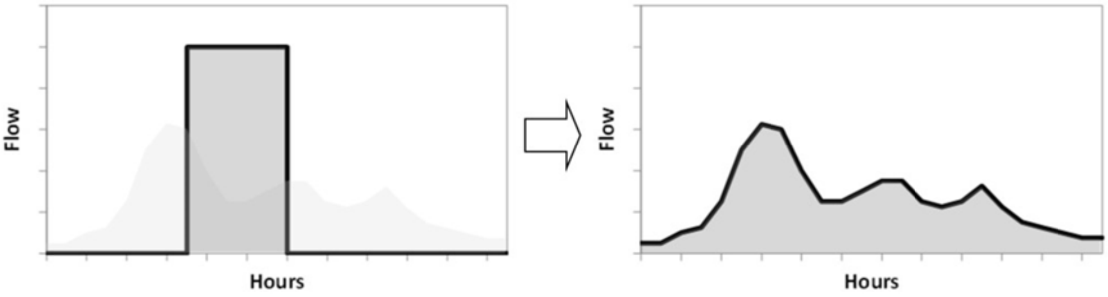


Fig. 1. Supply pattern change in a sector, from intermittent (left) to continuous (right)

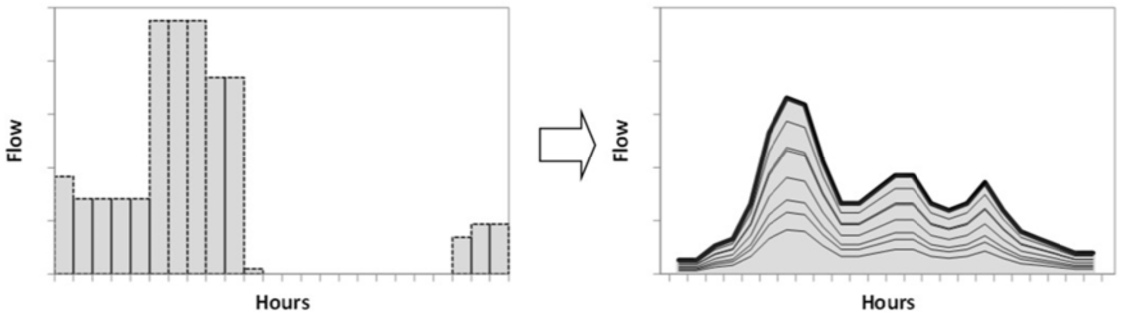


Fig. 2. Supply pattern change in the network, from intermittent (left) to continuous (right)

Fig. 1 shows the transition process from intermittent to continuous water supply in a single network sector. In Fig. 2 we show this process for all the sectors with intermittent and differentiated supply schedules that set an intermittent supply pattern. Furthermore, it shows a new continuous supply pattern after each sector transition.

Obviously, the volume per hour Vs_i of a sector i is calculated by dividing the daily volume, Vd_i, supplied to this sector by the number of supply hours, h_i:

$$Vs_i = \frac{Vd_i}{h_i}. \tag{1}$$

Usually, water companies that manage intermittent supply systems choose to deliver water only during high demand hours, i.e. in the morning, before work activities. These decisions establish simultaneous supply schedules in many sectors. Thus, a very large peak flow is generated, which even can be higher than the peak flow in continuous supply [6]. In this scenario, there is a generalized reduction in pressure and, as a result, consumers' complaints are increased due to lack of water, especially in unfavorable areas [23]. When this type of pattern of supply occurs, it is necessary to reduce the peak flow in the transition.

2.1. Criteria for sector selection

As said, sector selection criteria include quantitative and qualitative criteria.

The quantitative criteria considered in each sector are: number of users (C1), current service pressure (C2), distance from supply source (C3), and water supply equity (C4). The qualitative criterion is the operation difficulty in the sector (C5).

Two additional aspects to be considered are: the network topological configuration (C6), in order to organize the sectors in a gradual transition process; and the pressure calculated at each stage of upgrading (C7), which guarantees equity in water supply for those sectors that still keep intermittent supply.

Next we give a detailed description of these criteria and the associated variables.

C1: It is based on improving the service conditions for as much users as possible. We first calculate the normalized values, u_i, of the number of users of each sector, nu_i, that is, the fraction of users of sector i These u_i, summing up 1, constitute an n-vector $U = (u_i)$, where n is the number of sectors of the network, with components

$$u_i = \frac{nu_i}{\sum_{i=1}^{n} nu_i}. \tag{2}$$

C2: Sectors that still work with intermittent water supply must have good pressure level to ensure equity in water provision. Therefore, low pressure sectors are primarily selected to work with continuous supply. Normalized pressure values, p_i, will be the components of the n-vector P, which are defined, for each sector, by the difference between a maximum inlet pressure, K, and the sector inlet pressure, sp_i:

$$p'_i = K - sp_i \; ; \quad K = \max\left(sp_1, sp_2, \ldots, sp_n\right), \tag{3}$$

$$p_i = \frac{p'_i}{\sum_{i=1}^{n} p'_i}. \tag{4}$$

C3: The distance from the entrance of the selected sector to the supply source, ds_i, is an important element in the decision-making process. When this distance for a sector with continuous supply is short, the pipe is less likely to have water leaks during the transition process. Avoiding leakage is crucial in water operation. We use the inverse values of those distances, d'_i, to obtain the n-vector D of normalized values:

$$d'_i = \frac{1}{ds_i}, \tag{5}$$

$$d_i = \frac{d'_i}{\sum_{i=1}^{n} d'_i}. \tag{6}$$

If there is more than one path to the selected sector, the shortest path is used to determine this distance.

C4: A sector (network) works with equity in supply, when not only water delivered to every single node is similar, but also the sector (network) has an acceptable hydraulic capacity [23]. Thus, the sector selection process has to consider equity in sectors that continue with intermittent supply. To this purpose, we propose the water supply equity index $I_{eq,i}$, which measures water supply equity through the uniformity coefficient UC_i, associated to the values s_p that relate the supplied flow $Q_{s,p}$ and the demand flow $Q_{d,p}$ for each network node p. Analysis is made for all the n_e nodes in the sector. Calculations must be based on the Pressure Dependent Demand (PDD) concept [28], [29], [30], [31]. Additionally, we considered the theoretical maximum flow, $Q_{maxt,i}$, which is the maximum demand that can be satisfied in the sector given available head at the entrance and hydraulic capacity [23]; and the required maximum flow of the intermittent supply sector $Q_{maxr,i}$:

$$s_p = \frac{Q_{s,p}}{Q_{d,p}}. \tag{7}$$

$$UC = 1 - \frac{\sum \left| s_p - s_{average} \right|}{s_{average} \cdot n_e}, \tag{8}$$

$$I_{eq,i} = \frac{Q_{maxt,i}}{Q_{maxr,i}} \cdot UC_i \,, \tag{9}$$

The relation between the theoretical maximum flow and the required maximum flow enables us to evaluate the capacity of the sector when it works for certain number of hours: the lower the number of supply hours the higher the required maximum flow. A proper performance of the sector provides a ratio above 1. Thus, it ensures that the sector has enough capacity for working with intermittent water supply. On the contrary, when this ratio is less than 1, the sector is deficient in capacity, which can undoubtedly impair water supply equity.

Moreover, the uniformity coefficient enables us to measure the homogeneity between network nodes. A value of 1 ensures supply uniformity, and lower values mean greater differences in node supply.

Therefore, this index is a very useful tool for evaluating water supply equity. When values greater than 1 are reached, equitable supply is possible. On the contrary, values below 1 mean that these sectors have supply deficiencies.

For sector selection in the transition process, sectors with lower water supply equity index should be prioritized. Therefore, the maximum sector equity index, K_{eq}, of the entire network is calculated, which is used for the conversion to a direct variable, e'_i, and its subsequent normalization, e_i. These values are the components of the *n*-vector *E*:

$$e'_i = K_{eq} - I_{eq,i} \;; \quad K_{eq} = \max\left(I_{eq,1}, I_{eq,2}, \ldots, I_{eq,n}\right), \tag{10}$$

$$e_i = \frac{e'_i}{\sum_{i=1}^{n} e'_i} . \tag{11}$$

C5: We consider operation difficulty in the sector as a qualitative criterion, since its assessment depends on several elements tough to quantify. For instance, the subjectivity of manual operation works difficulties, the uncertain presence of available valves, and the sector users' complaints that need some filtering or discrimination procedures. However, this uncertain situation is perceived by the experts of the water company. Thus, it is necessary their experience to evaluate this criterion. Easier-to-operate sectors are considered to more likely keep on working with intermittent supply. And sectors, whose operation is not that easy, should be changed first to continuous supply, since continuous supply does not need operation actions.

Quantification of the operation difficulty is carried out by surveys on water company experts. Prioritization is worked through the AHP method, by building a sector pairwise comparison matrix; its Perron eigenvector [32] will rank sectors according to their operation difficulty. The AHP method was performed based on a 1-9 scale [26], together with their inverse values to make a pairwise importance comparison of sectors. The geometric mean of the eigenvectors obtained for each expert is then normalized and grouped into a new *n*-vector *O*.

Next, we compile vectors *U*, *P*, *D*, *E* and *O* by columns in matrix *C*:

$$C = \left(U; P; D; E; O\right). \tag{12}$$

To define relevant criteria weights, the opinion of the water company experts is also taken into account again using the AHP methodology. The response of the experts gives individual eigenvector results for the importance of the criteria. The geometric mean of these values is used to determine the weight of each criterion, namely, number of users (*wu'*), service pressure (*wp'*), distance to supply source (*wd'*), water supply equity (*we'*), and difficulty in operation (*wo'*). Let us build the diagonal weight matrix *W'*

$$W' = \mathrm{diag}\left(wu', wp', wd', we', wo'\right). \tag{13}$$

The product of matrices *C* and *W'* results in the total weight matrix *W* = *CW'*, which can be organized by columns:

$$W = \left(wu; wp; wd; we; wo\right). \tag{14}$$

These weights will be used in the objective function detailed below.

C6: When some sectors begin to have continuous supply, pressure in several network pipes will be continuous and higher, what tends to increase water leakage [33]. Thus, selected sectors should be interconnected. Therefore, sector selection has to be based on the configuration and topology of the network.

To include the topology in the optimization problem, we consider the adjacency matrix *R* of the simplified network directed graph, which includes the supply source. In this graph, adjacent sectors are linked with edges. Thus, each edge represents the path that water must follow to reach one sector after another from a given feed point.

We define a binary variable vector *S*, which includes the sector state (vector *X*), and includes the supply sources. For the sources, topology-specific components of *S* are used with a constant value of 1. As an example, supposed only one source, the first component of *S* would always equal 1. Specifically,

$$S = \left(1, x_1, . x_2, .., x_n\right), \tag{15}$$

where

$$x_i \text{ is binary, } \forall i = 1,2,\ldots,n$$

and

$$x_i = \begin{cases} 1 & \text{sector with continuous water supply} \\ 0 & \text{sector with intermittent water supply} \end{cases}.$$

The product of the transposed of matrix *R* and the selection vector *S* results in the vector *G*, which establishes the indegree and the possibility of selection of nodes in the following iterations. When the calculated g_i value, *i* = 1, …, *n*, is equal or greater than 1, its selection is possible as an adjacent node or sector:

$$R^T \times S = G, \tag{16}$$

$$G = \left(g_0, g_1, ..., g_n\right). \tag{17}$$

C7: Each stage of the network improvement and the change of some sectors to continuous supply imply changes in incoming pressure to sectors. So that supply is still feasible in the sectors that will continue to be supplied intermittently, the type of supply should not change if the minimum pressure required, P_{req}, is not guaranteed at every single network node.

Calculation of sector pressure, Ps_{ik}, is performed by EPANET 2.0 [34] for each supply hour k, $k = 1, \ldots, m$, in all sectors $i = 1, \ldots, n$, using sector demand either in continuous or intermittent supply. Its minimum value in the entire network during the k-th hour is Pc_k:

$$Pc_k = \min\left(Ps_{1k}, Ps_{2k}, \ldots, Ps_{nk}\right). \tag{18}$$

The m calculated values for every hour are grouped in the m-vector $Pc = (Pc_k)$.

One of the main constraints of the optimization problem is to guarantee at every network node a pressure greater than the minimum.

2.2. Supply pattern change

The sector selection process is based on the change of supply pattern. Therefore, we define the supply pattern of each sector in conditions of intermittency and continuity.

At the beginning, every sector has its own water delivery schedule because the network has intermittent water supply. A value of $h_{ji} = 1$ in the binary vector $H = (H_i)$, $i = 1,\ldots, n$, indicates that sector i has water supply during the hour j.

By multiplying vector H and the volume per hour, Vs_i, of sector i, we determine a vector B_i which represents the intermittent water supply pattern of sector i:

$$B_i = Vs_i \cdot \left(h_{1i}, h_{2i}, \ldots, h_{mi}\right) = \left(b_{1i}, b_{2i}, \ldots, b_{mi}\right). \tag{19}$$

To determine the continuous supply pattern of each sector, A_i, the average volume Vd_i/m must be multiplied by each consumption factor per hour k_j, which shows the variations in consumption throughout the day:

$$K = \left(k_1, k_2, \ldots, k_m\right), \tag{20}$$

$$A_i = \frac{Vd_i}{m} \cdot \left(k_1, k_2, \ldots, k_m\right) = \left(a_{1i}, a_{2i}, \ldots, a_{mi}\right). \tag{21}$$

For the sector selection, we propose using two binary vectors.

The first vector, Y, defines the intermittency condition of sectors. For sectors having intermittent water supply, we adopt a value of $y_i = 1$; and for sectors that achieve continuous water supply, we assume a value of $y_i = 0$. At the beginning of the transition process, all components of the Y vector take the value of 1, because all the sectors have intermittent supply.

The second vector is X, already introduced, which is complementary to vector Y, and it is related to continuous water supply. As observed above, the sectors that achieve continuous supply are identified by the value $x_i = 1$, and those that still have intermittent supply keep $x_i = 0$. Consequently, when starting the transition process all of its elements are 0.

This vector defines which sectors will be changed to continuous supply in each of the stages of the network upgrading.

Binary vectors X and Y are complementary, since a sector can only have intermittent or continuous supply, but not both; consequently, the sum of any component of both vectors must equal 1.

The curve that defines the transition process is made up of the sum of volumes in each supply hour. It includes sectors that continue with intermittent supply and sectors that already have continuous supply. This curve adopts the consumption pattern of a system with continuous supply at the end of the process. The transition curve is defined by vector $T = (t_j)$:

$$t_j = \sum_{i=1}^{n} \left(a_{ji} \cdot x_i + b_{ji} \cdot y_i \right), \tag{22}$$

The element with the maximum value is called peak flow of the transition process (Q_t):

$$Q_t = \max \left(t_1, t_2, ..., t_m \right). \tag{23}$$

2.3. Optimization problem

The optimization problem aims to maximize the number of continuous supplied sectors at each stage by benefiting more users, achieving better operating pressures in the remaining intermittent supply sectors, reducing the network pipe distance that can cause leakage, prioritizing water supply equity in sectors with intermittent supply, and facilitating water company operation tasks (24). Furthermore, it also intends to reduce the peak flow of the intermittent water supply.

Therefore, the optimization problem is:

Maximize:
$$\sum_{j=1}^{n} \left(wu_j + wp_j + wd_j + we_j + wo_j \right) \cdot x_j \tag{24}$$

Subject to:

$$x_i + y_i = 1, \tag{25}$$

$$t_j \le Q_t, \tag{26}$$

$$Pc_j \ge P_{ref}, \tag{27}$$

$$x_i \le g_i. \tag{28}$$

The first constraint (25) implies that a sector cannot have both types of supply simultaneously.

Constraint (26) is related to the peak flow limitation in each improvement stage.

Sector transition is possible, only if the inlet sector pressure exceeds the minimum reference pressure, P_{ref}, (27). Sectors, in which the minimum reference pressure is satisfied during transition, should be chosen.

To include the network topology, sectors' indegree must be taken into account in the selection process. The selection binary value x_i of a sector must be equal or smaller than its indegree to be selected. Thus, as implied by constraint (28), we avoid selecting nodes with 0 indegree, which are isolated from the previously selected nodes, since binary value x_i of a selected sector is 1.

3. Case study

The drinking water system of Oruro (Bolivia) has several subsystems. Some of them have intermittent water supply and others have continuous water supply. The studied subsystem in this paper is located in the southern part of the city. It currently has intermittent water supply, and it is composed of 15 sectors which supply water to 37700 inhabitants.

Ilaya-Ayza *et al.* [23] define a process of gradual capacity increase in the southern part of Oruro‘s water supply network. Three stages are defined, and are shown in Table 1. In this process, pipes will be substituted by bigger diameter ones and, consequently, the hydraulic condition will be improved.

Table 1. Stages of the increasing capacity process of southern water subsystem of Oruro [23]

Stage	**Modified pipe**	**New diameter (mm)**	**Cost per stage (BOB)**
First	P-12	350	562303.90
Second	P-17	200	581264.92
Third	P-11, P-2, P-13	350, 350, 300	532875.95

After defining these three stages, we select, at each stage, sectors that will change to continuous supply.

First, we analyze water supply equity (7) in each sector. For example, the S01-05 sector reaches a low uniformity coefficient of 0.851 (see (29) and Table 2). However, the ratio between the theoretical maximum flow (for a minimum pressure of 10 m) and the water requirement of users in intermittent supply is 1.423, which enables the sector to achieve a water supply equity index higher than 1 (see equation (30) below).

Table 2. Uniformity coefficient calculation in sector S01-05

Node	**Supplied flow at node, $Q_{s,p}$ (l/s)**	**Demanded flow at node, $Q_{d,p}$ (l/s)**	**Supplied and demanded flow ratio at node, s_p**	$\lvert s_p - s_{average} \rvert$
1	0.229	0.242	0.946	0.092
2	0.158	0.172	0.920	0.067
3	0.188	0.302	0.624	0.230
4	0.026	0.046	0.570	0.283
5	0.194	0.213	0.911	0.057
6	0.042	0.051	0.834	0.019
7	0.201	0.236	0.853	0.001
8	0.221	0.278	0.795	0.058
9	0.045	0.063	0.720	0.134
10	0.037	0.066	0.555	0.298
11	0.057	0.069	0.825	0.029
12	0.067	0.074	0.916	0.063
13	0.552	0.552	1.000	0.147

14	0.311	0.311	1.000	0.147
15	0.076	0.080	0.952	0.098
16	0.047	0.082	0.570	0.283
17	0.305	0.305	1.000	0.147
18	0.528	0.528	1.000	0.147
19	0.102	0.106	0.962	0.109
20	0.114	0.118	0.969	0.115
21	0.329	0.329	1.000	0.147
			Total:	**2.668**

$$CU = 1 - \frac{\sum \left| s_p - s_{average} \right|}{s_{average} \cdot n_e} = 1 - \frac{2.668}{0.853 \cdot 21} = 0.851 \tag{29}$$

$$I_{eq,S01-05} = \frac{Q_{maxt,S01-05}}{Q_{maxr,S01-05}} \cdot CU_{S01-05} = 1.423 \cdot 0.851 = 1.211 \tag{30}$$

In Table 3, water supply equity indices are summarized and calculated for each of the network sectors.

Table 3. Water supply equity index calculation for each network sector

Sector	**Q_{maxt} (l/s)**	**Q_{maxr} (l/s)**	**Q_{maxt}/Q_{maxr}**	**CU**	**I_{eq}**
S01-05	6.007	4.222	1.423	0.851	1.211
S01-06	4.694	12.803	0.367	0.723	0.265
S01-07	10.779	19.048	0.566	0.895	0.506
S01-08	14.715	10.116	1.455	0.959	1.395
S01-10	2.939	7.758	0.379	0.800	0.303
S01-11	2.494	6.117	0.408	0.761	0.311
S01-09	5.458	6.807	0.802	0.830	0.665
S01-13	-	11.851	0	-	0
S01-14	-	3.184	0	-	0
S01-15	-	3.109	0	-	0
S01-16	-	4.658	0	-	0
S02	9.740	6.780	1.437	0.910	1.307
M02	4.230	2.821	1.499	0.890	1.335
S01-12	-	32.832	0	-	0
S01-18	9.942	11.710	0.849	0.912	0.775

If a network sector does not reach the minimum pressure for calculating the theoretical maximum flow, we adopt a sector capacity equal to zero. In these conditions, there is no need to calculate the uniformity coefficient.

Based on the water supply equity index, number of users, inlet sector pressures, and distance from supply source to each sector, we calculate the respective normalized values (Table 4).

Table 4. Normalization of quantitative variables

Sector	nu_i	u_i	vp_i (m)	p_i	ds_i (m)	d_i	I_{eq}	e
S01-05	147	0.019	40.03	0.005	239.84	0.251	1,211	0.0143
S01-06	467	0.062	16.83	0.075	436.27	0.138	0.265	0.0879
S01-07	593	0.079	19.44	0.067	386.98	0.1556	0.506	0.0691
S01-08	437	0.058	22.1	0.059	1096.06	0.0549	1,395	0
S01-10	385	0.051	20.06	0.065	1596.22	0.0377	0.303	0.085
S01-11	244	0.032	11.95	0.089	1690.14	0.0356	0.311	0.0844
S01-09	515	0.068	30.02	0.035	1211.49	0.0497	0.665	0.0568
S01-13	1065	0.141	4.44	0.112	1852.27	0.0325	0	0.1086
S01-14	276	0.037	15.56	0.079	1958.56	0.0307	0	0.1086
S01-15	211	0.028	15.67	0.078	2100.25	0.0287	0	0.1086
S01-16	918	0.122	0	0.125	2226.05	0.027	0	0.1086
S02	575	0.076	41.7	0	902.92	0.0667	1,307	0.0068
M02	237	0.031	26.12	0.047	986.51	0.061	1,335	0.0047
S01-12	1085	0.144	2.01	0.119	3618.26	0.0166	0	0.1086
S01-18	385	0.051	26.77	0.045	4284.83	0.0141	0.775	0.0483
Total:		**1**		**1**		**1**		**1**

Sector operation difficulty criteria quantification is obtained through interviews with three water company experts. After this process, pairwise comparison matrices and their respective eigenvector are set (Table 5 shows the case of expert 1).

Table 5. Pairwise comparison matrix of operation difficulty criterion in the sector, expert 1

	S01-05	**S01-06**	**S01-07**	**S01-08**	**S01-10**	**S01-11**	**S01-09**	**S01-13**	**S01-14**	**S01-15**	**S01-16**	**S02**	**M02**	**S01-12**	**S01-18**	**Eigen-vector**
S01-05	**1**	1/5	1/3	1	1/3	1	1	1	1	1	1	1/3	1/7	1	1	0.0310
S01-06	**5**	**1**	3	3	3	3	5	3	3	3	3	1/5	1/5	3	3	0.1125
S01-07	**3**	**1/3**	**1**	3	3	3	3	3	3	3	3	3	1/7	3	3	0.1033
S01-08	**1**	**1/3**	**1/3**	**1**	1	1	1	1	1	1	1	1/3	1/7	1	1	0.0337
S01-10	**3**	**1/3**	**1/3**	**1**	**1**	1	1	1	1	1	1	1	1/7	1	1	0.0415
S01-11	**1**	**1/3**	**1/3**	**1**	**1**	**1**	1	1	1	1	1	1	1/7	1	1	0.0377
S01-09	**1**	**1/5**	**1/3**	**1**	**1**	**1**	**1**	1	1	1	1	1/3	1/7	1/3	1	0.0304
S01-13	**1**	**1/3**	**1/3**	**1**	**1**	**1**	**1**	**1**	1	1	1/3	1/3	1/7	1/3	1	0.0292
S01-14	**1**	**1/3**	**1/3**	**1**	**1**	**1**	**1**	**1**	**1**	1	1/3	1/3	1/7	1/3	1	0.0292
S01-15	**1**	**1/3**	**1/3**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	1/3	1/3	1/7	1/3	1	0.0292
S01-16	**1**	**1/3**	**1/3**	**1**	**1**	**1**	**1**	**3**	**3**	**3**	**1**	1	1/5	1	3	0.0531
S02	**3**	**5**	**1/3**	**3**	**1**	**1**	**3**	**3**	**3**	**3**	**1**	**1**	1/5	1	3	0.0972
M02	**7**	**5**	**7**	**7**	**7**	**7**	**7**	**7**	**7**	**7**	**5**	**5**	**1**	5	7	0.2863
S01-12	**1**	**1/3**	**1/3**	**1**	**1**	**1**	**3**	**3**	**3**	**3**	**1**	**1**	**1/5**	**1**	3	0.0568
S01-18	**1**	**1/3**	**1/3**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1/3**	**1/3**	**1/7**	**1/3**	**1**	0.0292

The consistence ratio (*CR*) of this matrix is 5.7%, lower than 10% [26], [35], [36], shows sufficient consistency for this matrix. Eigenvectors of pairwise comparison matrices of each expert represent the weight given to each sector based on the sector operation difficulty criterion. The geometric mean [37] for each sector is subsequently normalized (Table 6).

Table 6. Normalization of operation difficulty criteria in the sector

Sector	**Expert 1**	**Expert 2**	**Expert 3**	**Geometric mean**	o_i
S01-05	0.0310	0.0310	0.0332	0.0317	0.0318
S01-06	0.1125	0.1013	0.1132	0.1089	0.1089
S01-07	0.1033	0.1026	0.1058	0.1039	0.1040
S01-08	0.0337	0.0335	0.0349	0.0340	0.0341
S01-10	0.0415	0.0412	0.0426	0.0418	0.0418
S01-11	0.0377	0.0374	0.0385	0.0378	0.0379
S01-09	0.0304	0.0314	0.0318	0.0312	0.0312
S01-13	0.0292	0.0291	0.0299	0.0294	0.0294
S01-14	0.0292	0.0291	0.0290	0.0291	0.0291
S01-15	0.0292	0.0291	0.0299	0.0294	0.0294
S01-16	0.0531	0.0561	0.0589	0.0560	0.0560
S02	0.0972	0.0929	0.0854	0.0917	0.0918
M02	0.2863	0.3011	0.2749	0.2872	0.2874
S01-12	0.0568	0.0530	0.0621	0.0572	0.0572
S01-18	0.0292	0.0312	0.0299	0.0301	0.0301
Total:	**1.000**	**1.000**	**1.000**	**0.999**	**1.000**

After defining the first five criteria, it is necessary to calculate the weights of the criteria for their inclusion in the optimization process. Thus, experts' opinion about each criterion importance for the sectors selection process (Table 7 is for expert 1) is also obtained.

Table 7. Pairwise comparison matrix, expert 1

	Users	**Pressure**	**Distance**	**Equity**	**Operation**
Users	**1**	1	5	1	3
Pressure	**1**	**1**	3	1	1
Distance	**1/5**	**1/3**	**1**	1/5	1/3
Equity	**1**	**1**	**5**	**1**	3
Operation	**1/3**	**1**	**3**	**1/3**	**1**

Eigenvector
0.2931
0.2164
0.0569
0.2931
0.1405

The weight for each criterion is calculated by the geometric mean and then these weights are normalized (Table 8).

Table 8. Normalized weight of each criterion

Criteria	**Expert 1**	**Expert 2**	**Expert 3**	**Geometric mean**	**Weight**
Users	0.2931	0.2754	0.3228	0.2965	wu' = 0.2986
Pressure	0.2164	0.2278	0.1326	0.1870	wp' = 0.1883
Distance	0.0569	0.0487	0.0642	0.0563	wd' = 0.0567
Equity	0.2931	0.3231	0.3478	0.3205	we' = 0.3229

Operation	0.1405	0.1249	0.1326	0.1325	*wo'* = 0.1335
Total:	**1**	**0.875**	**0.867**	**0.993**	**1**

The weight of each sector is calculated by the product of the criterion weight and the weight of the respective sector (14) (see Table 9).

Table 9. Calculation of weights for each criterion

Sector	**C1**	**C2**	**C3**	**C4**	**C5**
	wu	***wp***	***wd***	***we***	***wo***
S01-05	0.0058	0.0009	0.0142	0.0046	0.0042
S01-06	0.0185	0.0141	0.0078	0.0284	0.0145
S01-07	0.0235	0.0126	0.0088	0.0223	0.0139
S01-08	0.0173	0.0111	0.0031	0	0.0045
S01-10	0.0152	0.0122	0.0021	0.0274	0.0056
S01-11	0.0097	0.0168	0.0020	0.0272	0.0051
S01-09	0.0204	0.0066	0.0028	0.0183	0.0042
S01-13	0.0422	0.0211	0.0018	0.0351	0.0039
S01-14	0.0109	0.0148	0.0017	0.0351	0.0039
S01-15	0.0084	0.0147	0.0016	0.0351	0.0039
S01-16	0.0364	0.0236	0.0015	0.0351	0.0075
S02	0.0228	0	0.0038	0.0022	0.0122
M02	0.0094	0.0088	0.0035	0.0015	0.0384
S01-12	0.0430	0.0225	0.0009	0.0351	0.0076
S01-18	0.0152	0.0084	0.0008	0.0156	0.0040

The simplified graph of southern subsystem network of Oruro (figure 3) shows the water path between sectors.

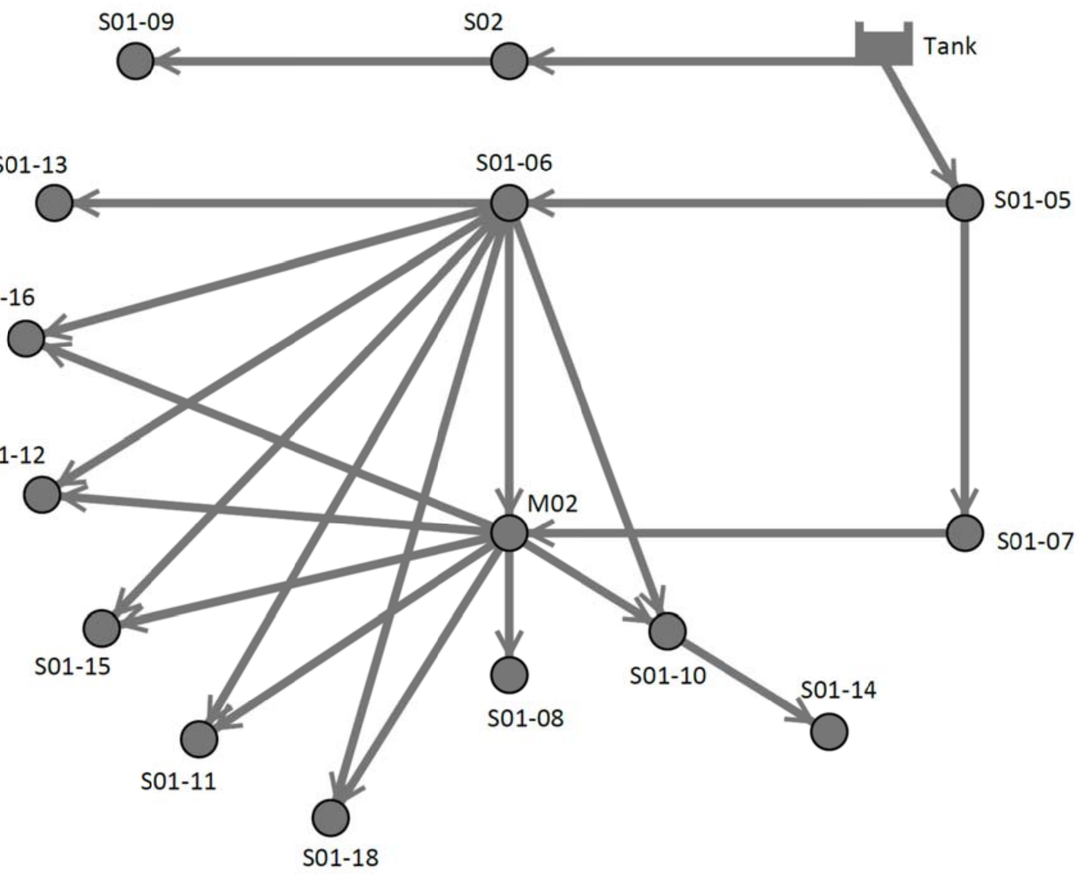


Fig. 3. Directed graph of southern subsystem network of Oruro

Its adjacency matrix (31) is important for the selection process.

$$R = \left(\begin{array}{c|cccccccccccccccc} & Tank & 05 & 06 & 07 & 08 & 10 & 11 & 09 & 13 & 14 & 15 & 16 & S02 & M02 & 12 & 18 \\ Tank & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ S01-05 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ S01-06 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 1 & 1 \\ S01-07 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ S01-08 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ S01-10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ S01-11 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ S01-09 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ S01-13 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ S01-14 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ S01-15 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ S01-16 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ S02 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ M02 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ S01-12 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ S01-18 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array} \right). \qquad (31)$$

To define the supply curves, we first need to know the incoming water volume of each network sector and the number of supply hours (Table 10).

Table 10. Water volume that enters each sector

Sector	Vd_i (m^3/d)	h_i (h)	Vs_i (m^3/h)
S01-05	75.99	5	15.20
S01-06	230.46	5	46.09
S01-07	342.86	5	68.57
S01-08	182.08	5	36.42
S01-10	139.65	5	27.93
S01-11	110.10	5	22.02
S01-09	196.03	8	24.50
S01-13	341.32	8	42.67
S01-14	91.70	8	11.46
S01-15	89.54	8	11.19
S01-16	184.46	11	16.77
S02	292.88	12	24.41
M02	142.18	14	10.16
S01-12	590.97	5	118.19
S01-18	168.62	4	42.16

The intermittent supply pattern (Table 11) must change to a continuous supply pattern.

Table 11. Intermittent supply pattern in each network sector

Hour	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8	H_9	H_{10}	H_{11}	H_{12}	H_{13}	H_{14}	H_{15}
	S01-05	**S01-06**	**S01-07**	**S01-08**	**S01-10**	**S01-11**	**S01-09**	**S01-13**	**S01-14**	**S01-15**	**S01-16**	**S02**	**M02**	**S01-12**	**S01-18**
1	0	0	0	0	0	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**	0	0
2	0	0	0	0	0	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**	0	0
3	0	0	0	0	0	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**	0	0
4	0	0	0	0	0	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**	0	0
5	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	0
6	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	0
7	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	0
8	**1**	**1**	**1**	**1**	**1**	**1**	0	0	0	0	0	**1**	**1**	**1**	0
9	**1**	**1**	**1**	**1**	**1**	**1**	0	0	0	0	0	**1**	**1**	**1**	0
10	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	**1**	0	**1**	0	**1**

22	0	0	0	0	0	0	0	0	0	0	**1**	**1**	**1**	0	**1**
23	0	0	0	0	0	0	0	0	0	0	**1**	**1**	**1**	0	**1**
24	0	0	0	0	0	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**	0	**1**

To perform the transition process, it is necessary to have a continuous supply pattern (Table 12). In this case study, we adopt a pattern of other areas of Oruro that have drinking water for twenty-four hours.

Table 12. Pattern of continuous supply

Hour	**k_j**
1	0.06
2	0.17
3	0.22
4	0.53
5	1.38
6	2.28
7	2.50
8	1.98
9	1.41
10	1.42
11	1.34
12	1.41
13	1.50
14	1.51
15	0.83
16	0.75
17	0.93
18	1.24
19	1.10
20	0.58
21	0.39
22	0.32
23	0.12
24	0.04

Pressure at every node must be higher than the minimum reference pressure, P_{ref}, in order to consider this new scenario in which some sectors work with continuous supply and others in intermittent supply possible. The reference pressure value for all the process stages is 10 m.

4. Results and discussion

After performing the optimization process in each of the three stages of the transition process, we have the following results:

- In the first stage, no sector can be selected, because none satisfies the constraints in the optimization problem. Furthermore, pressures are very low and continuous water supply is not possible. Network sectors are not enough improved to change to continuous supply.

- In the second stage, the hydraulic capacity of the network has increased. This sets better service conditions. As a result, some sectors can now have continuous supply. The optimization process defines that 13 of the 15 sectors can have continuous supply (Table 13), and manages to reach higher pressures than the 10m minimum constraint. Likewise, the transition curve is closer to the continuous supply curve (Figure 4).
- In the third stage, the remaining intermittent sectors are selected. Eventually, the whole sub-system works with continuous supply, and the incoming pressures for all the sectors are higher than 20 m (Fig. 5).

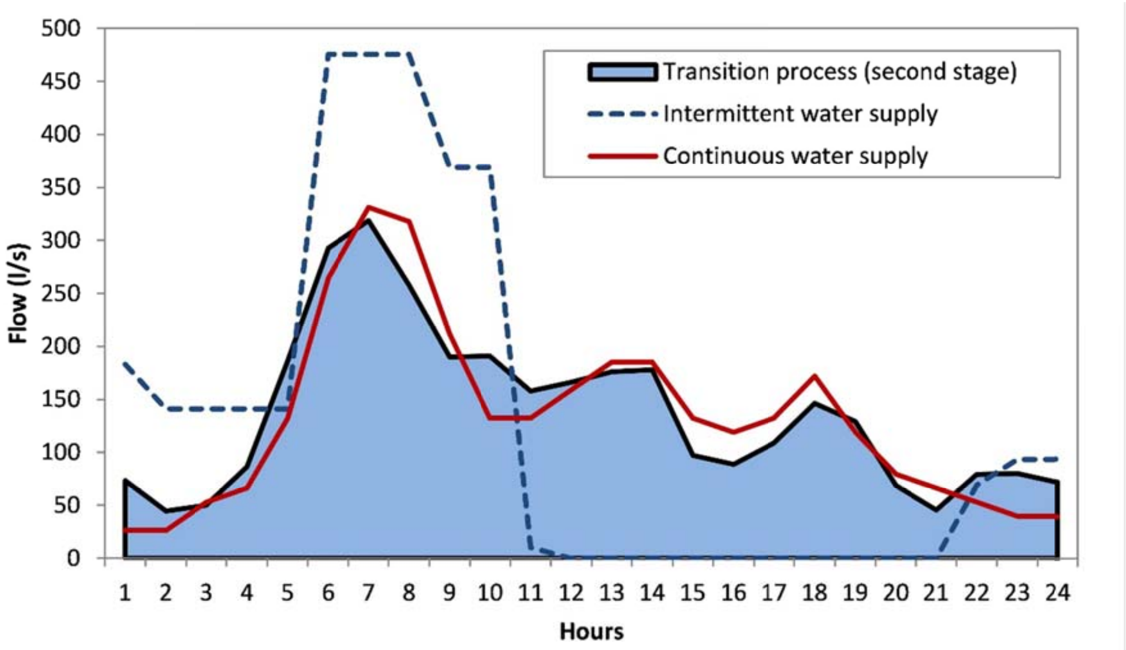


Fig. 4. Change of network supply curve in sector selection process, second stage

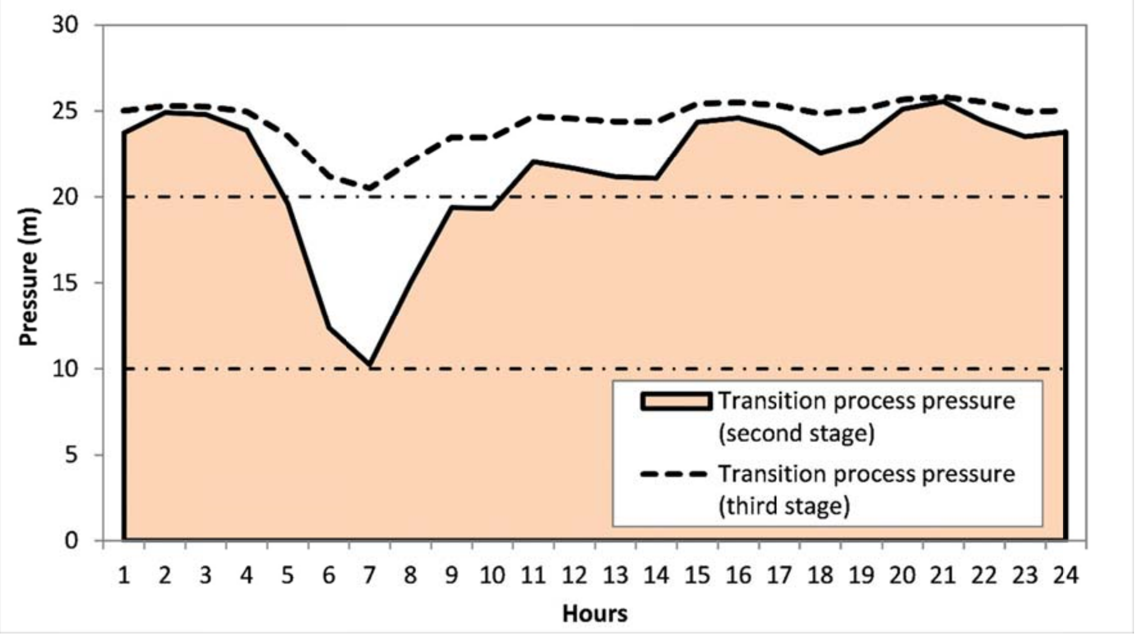
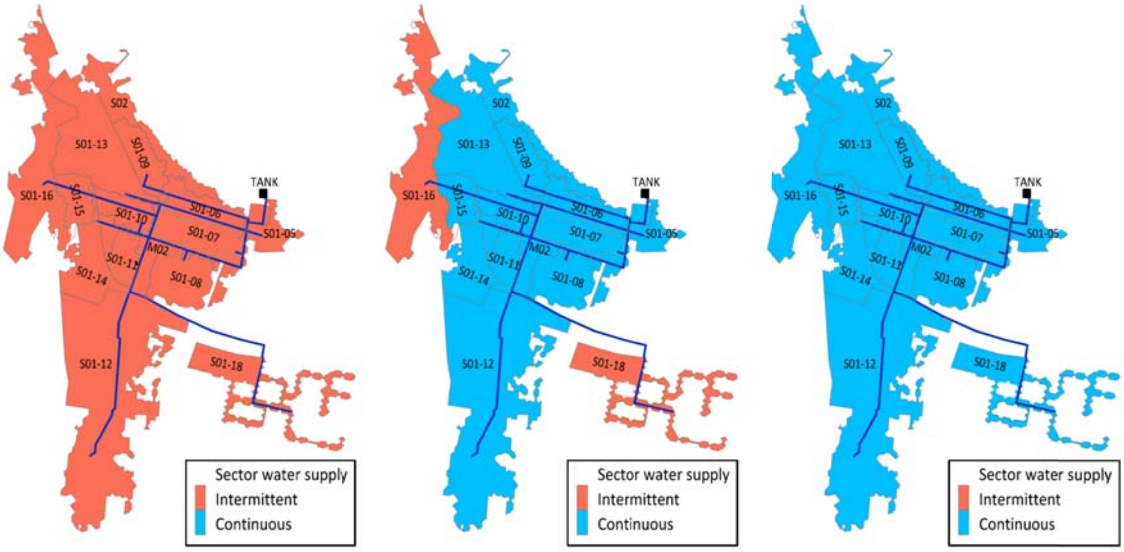


Fig. 5. Network minimum pressures in the second and third stages of the transition process



a) First stage b) Second stage c) Third stage

Fig. 6. Selected sectors with continuous water supply at every stage

Figure 6 summarizes the characteristics of the transition process to continuous supply during the three stages, and details the selected sectors.

5. Conclusions

This study shows that a gradual transition from intermittent to continuous supply is possible based on an optimal sector selection in various network-improvement stages. To improve drinkable water services in systems with economic limitations, a gradual transition is thus an advisable option.

In the first stage of the transition process, no sector adopts continuous supply due to low pressure across the network. Keeping the intermittent supply and household tanks, the minimum conditions are granted for water supply to users at low pressures. In the following two stages, some sectors change to continuous supply due to improved pressure in the network. Under this condition, household tanks are no longer needed.

We propose a water supply equity index that not only measures water supply uniformity, but also takes into account the hydraulic capacity of the sectors to satisfy consumers' demand in the limited supply hours. Therefore, it can be a very useful tool as a performance indicator in intermittent water supply systems.

By including the network topology in the optimization process we obtain more efficient solutions. Likewise, including water-company experts' opinion in the optimization process is very important, since intermittent-supply systems management is usually empirical.

To solve the presented optimization problem use is made of evolutionary algorithms to cope with the hard characteristics of the problem in terms of non-linearities, mixture of various kinds of variables, and mixture of constraints of varied nature, including not only objective, but also subjective and uncertain elements.

The methodology proposed is limited by the available information of water companies that manage intermittent supply systems. Thus, additional criteria can be included in the transition process, for instance, each sector leakage.

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