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Social-network-based water supply network sectorization methodology using monte carlo simulation to predict economical and operational benefits

Metodología de sectorización de redes de abastecimiento de agua potable basada en redes sociales y simulación monte carlo

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ABSTRACT

Water Supply Network (WSN) sectorization is a broadly known technique aimed at enhancing water supply management. In general, existing methodologies for sectorization of WSNs are limited to assessment of the impact of its implementation over reduction of background leakage, underestimating increased capacity to detect new leakage events and undermining appropriate investment substantiation. In this work, we raise this issue and put in place a methodology to optimize sectors' design. To this end, we carry out a novel combination of the Short Run Economic Leakage Level concept (SRELL- corresponding to leakage level that can occur in a WSN in a certain period of time and whose reparation would be more costly than the benefits that can be obtained). With a non-deterministic optimization method based on Genetic Algorithms (GAs) in combination with Monte Carlo simulation. As an example of application, methodology is implemented over a 246 km pipe-long WSN, reporting 72 397 $/year as net profit.

RESUMEN

La sectorización de redes de abastecimiento de agua potable (RDAP) es una de las técnicas más empleadas para mejorar la gestión en las mismas. Las metodologías de sectorización disponibles, por lo general, se han limitado al estudio del impacto de su implementación sobre la reducción de fugas de fondo. Esto conduce al problema de ignorar la valoración de la capacidad aumentada para detectar nuevas fugas y no permitir justificar adecuadamente la inversión necesaria. En este trabajo se aborda este problema y se presenta una metodología para optimizar el diseño de sectores. Para tal fin, se realiza una innovadora combinación del concepto del nivel económico de fugas a corto plazo (NEFCP, correspondiente al nivel de fugas que pueden ocurrir en una RDAP en un periodo dado, y cuya reparación sería más costosa que el beneficio que se podría obtener), con un método de optimización no-determinístico, basado en algoritmos genéticos (AG) en combinación con simulación Monte Carlo. A manera de ejemplo, la metodología se implementa sobre una red de 246 km de longitud de tubería, reportando un beneficio económico neto de 72 397 $/año.

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Palabras clave:
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INTRODUCTION

Water Supply Network (WSN) sectorization can be described as a technique aimed at improving WSN operational control, including pressure, leakage and water quality management. Sectorization entails partial isolation of areas within networks by closing pipes and setting flowmeters in a single (or few) feed lines. This allows constant follow-up at the inlet flow of each sector. However, sectorization implementation has some drawbacks, such as economic investment for purchase and installation of both, boundary valves and flowmeters. Moreover, by closing some pipes, the area throughout which flow circulates is diminished, increasing head loss and thus reducing pressure

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with which water is delivered to consumers. Whilst pressure reduction may have a positive effect over operation of WSN, given the fact that lower pressures mean lower leakage flow, pressure reduction can also lead to partial supply outages.

A good sectorization layout must offset negative and positive aspects described above. To this end, an optimal distribution of boundary valves and flowmeters must be defined. As it can be figured out, the number of possible layouts might be considerably large, depending on number of pipes and looped configuration of the network. Hence, use of mathematical and computational techniques is very important to appropriately address this problem.

Depending on network topology, sectorization implementation can be twofold: (1) when network has many sources, and these are located within network, sectors can be established around sources; (2) when number of sources is limited and/or are located in outskirt of network, it is expected network to rely on a supply trunk (main conduction network). In this case, sectors should be established from aforementioned supply trunk. This work is aimed at the latter case. To identify trunk network, a method proposed by Campbell *et al.* (2016) is implemented. This method combines Shortest Path concept, from the domain of the Graph Theory, along with hydraulic simulations in EPANET.

Once trunk network is defined, it is decoupled from distribution network, to avoid including pipes constituting trunk network into the sectorization layout. This step is important for two reasons: firstly, to preserve flexibility of the entire supply system, since pipes in charge of distributing main-critical flows are protected, allowing future network extensions if required; secondly, to reduce budget required for acquisition of flowmeters and boundary valves, since costs of valves or flowmeters for typical diameters of pipes in trunk network are higher than costs of same elements in distribution network.

Over distribution network, a community detection algorithm (CDA), called Multilevel CDA (Blondel, Guillaume, Lambiotte & Lefebvre, 2008) is implemented. Through this approach, a partition of distribution network in modules is unveiled, and then, such modules are successively merged based on a series of topological criteria.

In the following step, arrangement of entrances/boundary valves has to be defined. To this end, benefits derived from implementation of different arrangements are evaluated based on Short Run Economic Leakage Level (SRELL) concept and Economic Unreported Real Losses Level (EURL). Such benefits are included, along cost of boundary valves and flowmeters, in an objective function, which is maximized by means of Genetic Algorithms (GA) and Monte Carlo simulation. Use of Monte Carlo simulation allows considering uncertainties on detection of new leaks for every sectorization layout tested.

Method to define sectors over distribution network is described in detail in the second part of paper. Heuristic method to optimize arrangement entrance/boundary valves is discussed in the third part; and finally, in the fourth part an example of implementation is presented.

Sector definition by means of graphs and social network theory

Graphs are structures topologically formed by nodes and links or edges (hereafter, these last terms are interchangeable). Graph theory is a branch of mathematics devoted to study of these structures. Graphs topology perfectly fits topology of WSNs, and allows representing the latter as graphs and therefore, to implement algorithms derived from graph theory domain. One of these concepts is the Shortest Path concept, which allows finding the most efficient way to reach one node from any other in a graph by means of a search algorithm (Depth First Search, for example). In the method proposed by Campbell *et al.* (2016) to define trunk network, pipes are ranked according to their role in supply of the entire network. The method starts by simulating network in the most critical scenario (the hour of highest demand). From this simulation, flows and directions are obtained for each node. Then, the shortest paths, to all reachable nodes, are calculated by means of algorithm depth first search (Moore, 1959). Result is arranged in a square matrix, where sum of rows corresponds to Accumulated Shortest Path Value (ASPV) of each node.

ASPV in each node is transferred to its corresponding downstream pipe, by summing up ASPV of its upstream node +1 (1 is added, in order to include the last node in case of extreme pipes). This way, pipes connected to sources are expected to have the greatest values of ASPV, whilst extreme pipes are expected to have an ASPV equal to 1. ASPVs are standardized dividing values in all pipes by the greatest value of ASPV in the entire network. This way, pipes connected to sources will have a value very close to 1, and extreme pipes will have a value very close to 0.

Typically, in a WSN, pipes with higher ASPV are less frequent. These pipes correspond to the ones of trunk network, whereas, pipes with lower ASVP, are more frequent and they belong to distribution network. Several strategies can be followed to define scope of trunk network. For example, selection can be limited to those pipes whose closure would lead to supply outages. Also, selection can be based upon a particular urban interest.

After identifying trunk network, it is decoupled from distribution network. Resulting distribution network is treated as a social network, which is a mesh of elements (represented as a graph) mutually intercommunicated. Social network graphs contain several practical advantages; one of them is capacity to topologically represent no tangible interconnected elements (for example, a network of friends in *Facebook*) or tangibly interconnected elements (for example, a network of pipes in a WSN). Other advantage is capacity of defining characteristics on edges or at nodes. For example, diameters, roughness, ages, etc., of pipes in a WSN can be associated to edges of their corresponding social network graph elements, and demand, elevation, consumption of nodes can be associated to nodes of same social network graph. Social network theory-based community detection algorithms detect groups of elements connected by any interaction, which can be subjective (e.g. email communications) or physical (e.g. pipes). Broadly known method *Louvain* (Blondel, Guillaume, Lambiotte & Lefebvre, 2008) is a multilevel algorithm based on a "bottom-up" approximation. Initially, each node *i* is assigned to its own community *C*. Iteratively, algorithm builds up a series of *ij* neighbouring communities, with the aim of increasing the so-called graph quality partition modularity index (Newman, 2006). In the next step, and at a higher level, a new network of aggregated communities is formed. Edges between vertices belonging to the same community are defined as ties (depart and arrive at/to the same vertex), and for the rest of edges, weight is adapted by sum of weights of all edges that act as a bridge between each pair of communities. Then, process is repeated until there is no more gain in modularity index. This algorithm is classified as extremely fast and able to work on networks of up to 10^9 edges, in a reasonable time, with normal computing resources (Fortunato, 2010).

The modularity index, previously mentioned, is calculated by counting fraction of edges in network connecting vertices of the same community minus expected value of this fraction, should the edges be randomly placed. Usually, values of this index are in range 0.0 – 1.0. In real networks, values range between 0.3 and 0.7 (Newman & Girvan, 2004).

By implementing *Louvain* algorithm over a WSN, partition of maximum modularity can generate extremely small communities. Implementing such small communities as sectors would be economically unfeasible and therefore, once partition with highest modularity values is obtained, resulting communities are recursively merged using a merging process here proposed (see pseudocode below), to ensure that all sectors comply with a series of pre-established limits. Such limits can include, pipe length, number of connections, or a combination of several characteristics.

Pseudocode

1. *All pipes connecting communities are selected and put in a Set of Candidate Pipes* (*SCP*):

   given m if $IN_m \in C_i$ *and* $FN_m \in C_j \rightarrow m \in SCP$

2. *From SCP, extract subgroup of pipes* scp_i*, from which their corresponding communities do not exceed a pre-established limit for a given feature*:

   given $scp_i \subseteq SCP$*, where, for every m,* L_i *y* $L_j < L_{max}$

   for every m, if $L_i + L_j < L_{max} \rightarrow i + j = \{i, j\}$

3. *Steps 1-2 are repeated until no new pipes enter in* scp_i.

where *m* stands for pipe; IN_m for initial node in the pipe *m*; FN_m for final node in pipe *m*; *C* for community; and *L* for characteristic used as a criterion.

It is very important to set a lower limit for the feature used to define the size of each sector. If at the end of the merging process, there are some communities with a value lower than the minimum, they are established as mini-sectors (without closed valves or flowmeters). This only applies in case of mini-sectors that cannot be merged with other larger sectors. In the case of a given sector sharing pipes with another sector that has reached the maximum value for characteristic used as criterion, the upper criterion is slightly relaxed in order to allow their merging. For example, if the characteristic that is used as a reference is pipe length (e.g. 30 km as an upper limit), the greatest final length that a given sector could have is 30 km + the lowest length that a sector can have (e.g. 4 km). In other words, it results in a value ranging between 30 km and 34 km.

Finally, trunk is recoupled with distribution network and pipes connecting each sector with the first one are included among SCP. Each pipe within mentioned set can be defined either as a boundary valve or as a sector entrance. In the next section, optimization process through which such definition is carried out is described.

Optimization of entrances/boundary valves

Short Run Economic Leakage Level (SRELL)

Figure 1 is broadly used to describe how to tackle the problem of real losses in WSNs. In this figure, management of real losses is addresses through four components: (1) speed and quality of repairs; (2) pressure management; (3) active leakage control; (4) pipe surveys and pipes replacements.

Between unavoidable leakage volume and total leakage volume, there is an economic management level, which corresponds to the level where cost of a new repair exceeds benefits from savings.

A decade ago, Lambert & Fantozzi (2005) proposed a method to estimate the SRELL based on a combination of BABE concept (acronym for "Burst and Background Estimates"), and FAVAD theory (Acronym of "Fixed and Variable Area Discharge") (May, 1994). A very important result derived from this estimation is EURL (Lambert & Lalonde, 2005), which corresponds to the volume of unreported leaks that is feasible to let occur within one year.

According to FAVAD theory (equation 1), leakage flow from a pipe hole (or pipe crack or a joint) is equal to variation of pressure raised to the power of an exponent (N1), which depends on characteristic of the crack:

$$Q^1 / Q^0 = \left(\frac{P^1}{P^0}\right)^{N1}. \qquad (1)$$

where: variables Q indicate leakage flow before and after the change in pressure P.

The method for estimating SRELL starts by subdividing leakage flow according to the BABE concept, as shown in figure 2a. In the same figure it can be seen that, starting at time zero, background leakage remain constant over time; reported leaks appear and get repaired (vertical bars). Meanwhile, unreported leaks, gradually increase until they reach a point where their cost equals the entire network inspecting cost. Slope of this increase is known as "Rate of Rise" (RR). Average of these three components corresponds to SRELL and is represented by dotted (horizontal) line in same figure.

Of note is that reported leaks have two cost components, one associated to volume of water that is lost through them and another associated to repairing of pipes. The longer it takes a given pipe to get repaired, the higher is the first component, whereas, the second one remains invariable through time. Also, in networks with poor leakage control, component associated to lost volume is expected to be greater than in networks with a good leakage management program.

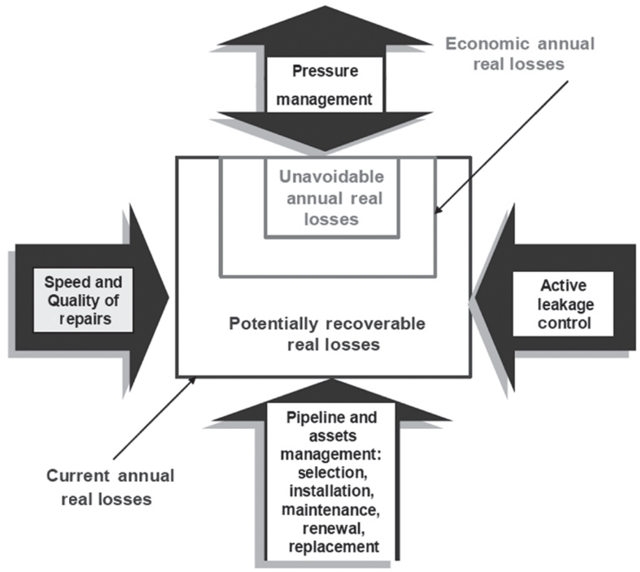

Figure 1. Fronts of action for economic management of real losses in WSN.
Source: Based upon Lambert (2002).

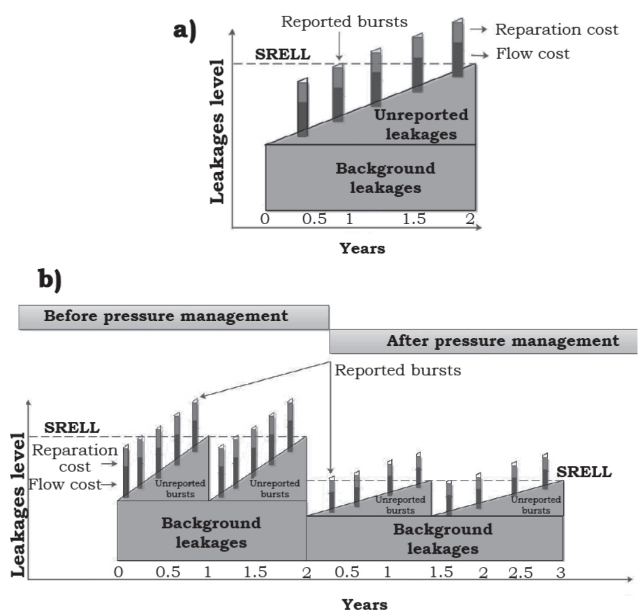

Figure 2. *a*) Division of leakage flow according to the BABE concept. *b*) Effect of reducing pressure over the SRELL.
Source: Based on Fantozzi & Lambert (2007).

The method to estimate SRELL includes an equation (2) to calculate Optimal Frequency of Inspection (OFI) of WSN, which is based on three components:

- *CI*: Cost of intervention (not including repairing costs) – ($)
- *CW*: Variable cost of water ($/m^3)
- *RR* (m^3/day/year)

RR is obtained by comparing the minimum night flow in a given moment, with respective value obtained at least one year after repairing all leaks. Variation of the minimum night flow expressed in m^3/day is then divided by amount of years of evaluation, obtaining a value expressed in m^3/day/year.

$$OFI\,(moths) = \sqrt{\frac{0.789 \times CI}{CW \times RR}}. \quad (2)$$

Result of previous equation can be used to calculate percentage of network to be annually inspected (*PI*):

$$PI(\%/year) = 100 \times 12/OFI. \quad (3)$$

And from there, it is possible to calculate budget that should be available every year for this purpose, or Annual Budget of Inspection (*ABI*).

$$ABI(\$/year) = PI \times CI. \quad (4)$$

EURL is then obtained by dividing *ABI* by *CW*.

$$EURL\,(m^3/year) = ABI/CW. \quad (5)$$

The previously presented calculation method can be used to predict benefits of pressure management in a WSN. According to FAVAD theory, pressure reduction entails a reduction in leakage flow (background, detectable and reported), as shown in figure 2b. The same figure shows that, by reducing pressure, both, *RR*, and time required to perform a complete inspection of WSN, are reduced, which translates into a reduction of *ABI*, *SRELL* and *EURL*.

Benefits of Pressure Management over the Reduction of Burst Frequency

In 2006, current approach to assess effect of pressure reduction over reduction of bursts frequency was put in place. Such approach is based on data (relationship between pressure variation and reduction of bursts) collected from 112 WSNs from 10 countries (Thornton & Lambert, 2006a, 2006b). Specifically, three constants (2.8, 1.4 and 0.7) were proposed. Such constants are multiplied by the maximum pressure variation and, as result, a maximum, average and minimum burst reduction factors are obtained. With this reduction factors, effect of pressure reduction over frequency of bursts can be estimated:

$$r' = r * FR. \quad (6)$$

where *r'* is amount of bursts once pressure is reduced; *r* is initial amount of burst and *FR* is average, maximum or minimum reduction factor.

According to "Conceptual Model", proposed by Thornton & Lambert (2007), significant reductions in frequency of bursts can only be expected if current burst frequency is significantly greater than value of initial burst frequency used in equation to calculate "Unavoidable Annual Real Losses" (UARL) (Lambert, Brown, Takizawa & Weimer, 1999).

Benefits of Pressure Management over the Reduction of Domestic Consumption

Both types of domestic consumption: internal (hydration and hygiene activities) and external (e.g. gardens watering) consumption, are also affected by pressure variation. This variation is represented by a modification of FAVAD equation (7), in which flow terms now refer to (internal and external) domestic consumption and exponent is represented by $N3$. For external consumption, a value of $N3$ around 0.5 is usually suitable, while for internal residential use, a value around 0.1 is recommended, unless, majority of connections rely on private tanks, in which case recommended value would be 0:

$$Q^0/Q^1 = \left(\frac{P^0}{P^1}\right)^{N3}. \quad (7)$$

Here variables *Q* represent domestic consumption (internal and external) before and after change in pressure *P*.

Leakage management by means of sectorization

From the above discussion, it can be concluded that benefits of pressure reduction are associated to:

- Reduction of background leakage
- Reduction of reported leaks
- Reduction of unreported leaks

- Reduction of domestic consumption.

Depending on final sectorization layout, energy consumption could increase or decrease. If increase of head loss due to sectorization implementation is not excessive, energy consumption is expected to be reduced due to leakage flow reduction.

Pressure reduction can be generated by setting pressure reducing valves, implementing sectors, or using pressure reducing valves in sectors. Pressure reducing valves used in combination with sectors is, obviously, the more expensive alternative.

In general terms, sectorization is not intended to reduce pressures but to enhance leakage control. However, when a sectorization layout is deployed, some pressure reduction is unavoidable (at least in distribution network). It is important to note that if all sectors are delimited with flowmeters, pressure should not vary. The idea proposed in this work is to account net profit generated by sectorization as a result of reducing pressure and due to capacity of permanently controlling flow entering each sector. To this end, (1) reduction in: background leakage, reported leaks, domestic consumptions and EURL is calculated for every pressure variation; (2) then, updated flow value associated to reported leaks and EURL is distributed among sectors, based on technical criteria from WSN technical staff; (3) depending on pipe length and number of entrances of each sector, percentage of leakage events that can be detected (an immediately repaired) is defined; (4) leakage flow values are updated once again; and (5) all benefits are added to obtain annual profit.

From the annual profit, a penalty cost, associated to nodes unable to meet a minimum pressure constrain, is subtracted. Also, an annual maintenance cost for valves and flowmeters is defined and subtracted. Since profit is calculated on an annual basis, cost of investment is multiplied by an Amortization Factor (AF) (equation 8), to obtain percentage of investment that should be covered every year:

$$AF = \frac{(1 + r)^{T} \times r}{(1 + r)^{T} - r} \quad (8)$$

where AF is amortization factor; r stands for discount rate in %, and T is lifetime of assets (in this case, flowmeters and boundary valves).

To calculate the total cost of energy, energy consumption of each hour (kWh) in which pumps are used is multiplied by cost of energy ($ / kWh) (according to an energy price pattern). Resulting hourly costs are added to obtain daily energy consumption. Next, this value is converted to an annual value and added to profit although, as explained below, it can also be added to costs, depending on final sectorization layout.

Figure 3 depicts the relationship between benefits and expenditures. The top line corresponds to the net the profit (Annual profit-Annual expenditure), which should never cross the established limit of supply quality. It is also important to note how the savings curve crosses SRELL, which is associated with additional benefits that come along with reducing pressure by means of sectorization.

Objective function

In a WSN of hundred kilometers of pipe length, the number of pipes that can be set as boundary pipes or as sector entrances can be significantly high, and number of possible combinations entrances/boundary valves can become very large. The more entrances a given sector has, the lower is negative impact of sectorization over nodal pressure, but the more difficult is to detect leakage events. In contrast, the greater is number of entrances, the costlier sectorization becomes. In this paper, a GA is implemented to maximize net benefit of sectorization. Status (closed/open) of pipes, delimiting sectors (candidate pipes), is established as decision variable (every candidate pipe's status is set as decision variable).

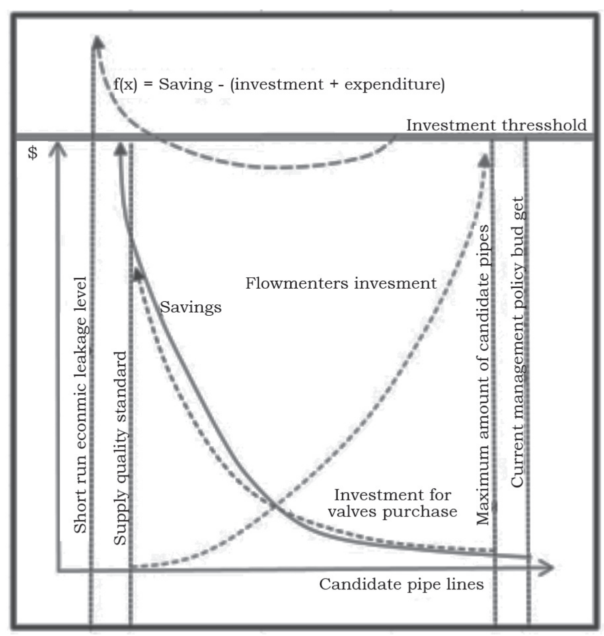

Figure 3. Relations between costs and benefits of sectorization.
Source: Author's own elaboration.

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Equation 9 shows the objective function to maximize.

$$Max\ f(x) = A + B + C + D + E + F \pm G - A' - B' - C'. \quad (9)$$

Subject to: $\Delta I_r < \Delta I_r^{rmax}$; $P_{min} < P_{min}^{req}$; $0 < A + B < (A + B)^{max}$

A: Saving by reducing background leakage (volume) ($/year)

B: Saving by reducing reported bursts (volume) ($/year)

C: Saving by reducing number of pipes to repair (reported bursts) ($/year)

D: Saving by reducing number of pipes to repair (unreported bursts) ($/year)

E: Saving by reducing internal domestic consumption (volume) ($/year)

F: Saving by reducing external domestic consumption (volume) ($/year)

G: Saving/Expenditure by reducing/increasing energy consumption ($/year)

A': Amortized cost of valves and flowmeters ($/year)

B': Compensation cost for pressure deficit ($/year)

C': Maintenance cost of flowmeters and valves ($/year)

ΔI_r and ΔI_r^{req}: Variation of resilience index (current and maximum allowed)

P_{min} and P_{min}^{req}: Maximum pressure and minimum required pressure

$A + B$ and $(A + B)^{max}$: Budget for purchase of flowmeters and boundary valves and threshold budget.

Monte Carlo simulation for dealing with uncertainties in Optimization

As explained above, implementing pressure management based on sectorization has as an advantage capacity to detect new leakage events in the moment they occur. Ability to detect and locate new leakage events will depend on two characteristics of each sector, namely, pipe length and number of connections, and in technical capacity of water operator. The larger is a given sector and the more entrances it has, the more difficult becomes detection and location of a new leakage event. Table 1 shows some example detection rates based on the size of sectors and number of entrances.

Table 1.
Example of expected percentages of leakage detection according to length and number of entrances in each sector (estimated values).

Sector size (length of pipe-km)	Number of entrances		Percentage of detection
0-10	0	1	50%
	2	3	40%
	4	5	20%
	6	7	5%
	8	9	5%

Source: Authors' own elaboration.

Values in table 1 may be established as single values (fixed values) and then be used in a classic optimization model. That is to say, at each iteration, volume of leakage that is saved due to sectorization implementation is calculated. However, prediction of percentage of leaks that can be detected has a high degree of uncertainty; therefore, prediction of such percentage can be better represented as a range of probabilistic values. This range can be defined either by probability curves or by an equation describing probability density.

Among range of existing probability distribution curves, the main advantage of "triangular" distribution is that only needs a minimum, a maximum and a mode value. This means that curve can be useful for situations where there is a lack of data (due to the high cost of collection), but it is possible to guess relationship between them.

Leakage rates are expected to be different for each sector sectors located in older areas or areas with lower maintenance, are expected to have greater leakage rates than sectors located in newer areas with more continuous maintenance. Distribution of expected leakage rates among sectors must be performed by technical staff of water utility.

Once detection probability curve for each sector is established, optimization process is initialized. However, differently from classical optimization, for every iteration, a Monte Carlo simulation is carried out. In this simulation, values are probabilistically sampled from aforementioned probability curves. For every iteration, net profit is re-computed. At the end, average of all iterations is calculated. Solutions in which simulation result meet all the restrictions marked as valid, and are used as a feedback to generate new solutions. The rest of solutions are discarded. The number of iterations of Monte Carlo simulation can be very large; the bigger the number, the greater degree of accuracy in results is obtained. Nevertheless, it also means more processing time. Therefore, it must be defined according required accuracy and computing capacity.

Figure 4 depicts the whole methodology. First column (left) shows sector definition algorithm; while section to the right shows process to optimize arrangement entrances/boundary valves.

Example of implementation

To exemplify methodology, it is implemented over a fraction (246 km of pipe length, 4351 nodes, 4391 pipes and three pumps) of WSN of Managua city, Capital of Nicaragua. First, supply trunk was identified; then, a set of 21 sectors, with pipe length between 3 km and 34 km and with their respective candidate pipes (47 in total) were established. From 21 sectors, six had one single entrance and the rest had a set of 2 – 4 candidate pipes. The maximum difference of elevation allowed between nodes of each sector was set at 20 m.

Table 2 shows list of prices of flowmeters and valves that were used to calculate investment.

To calculate *AF*, for both, valves and flowmeters, annual interest rate was set at 12%, and time of investment was established at 10 years. Cost of maintenance was set to a value equal to 50% of percentage of investment to be covered every year.

Figure 5. Shows output of implementing methodology in example network.

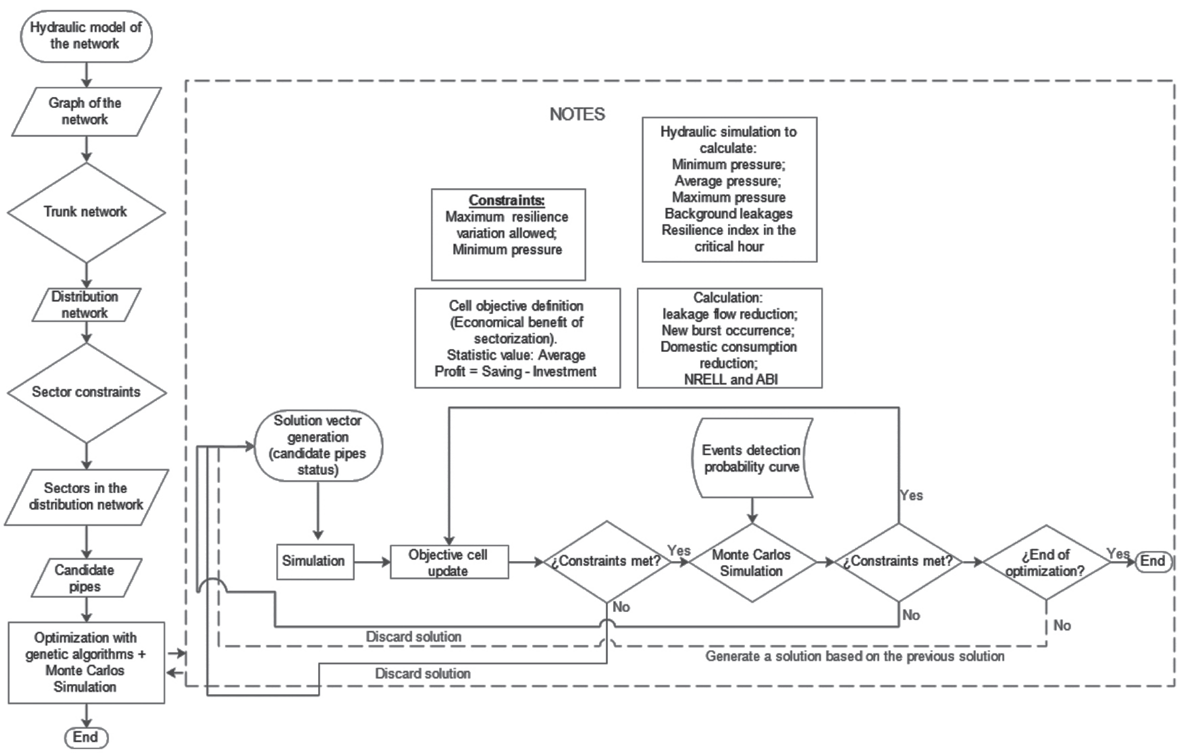

Figure 4. Proposed Methodology.
Source: Authors' own elaboration.

Table 2.
Example of expected percentages of leakage detection according to length and number of entrances in each sector (estimated values).

Diameter (mm)	75	100	150	200	250	300	400	500
Flowmeters (monetary units)	5625	7500	11 250	15 000	18 750	22 500	30 000	35 625
Valves (monetary units)	2250	3000	4500	6000	7500	9000	12 000	14 250

Source: Authors' own elaboration.

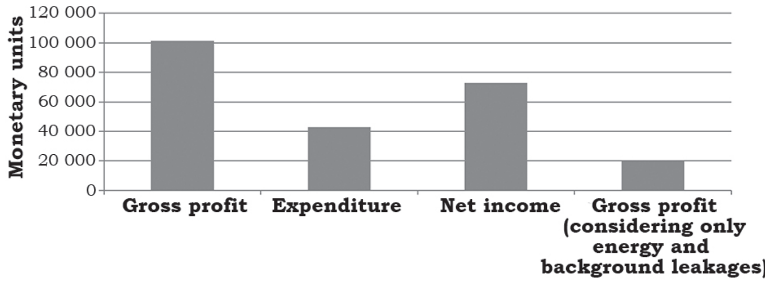

Figure 5. Comparison between annual benefits and annual expenditures.
Source: Authors' own elaboration.

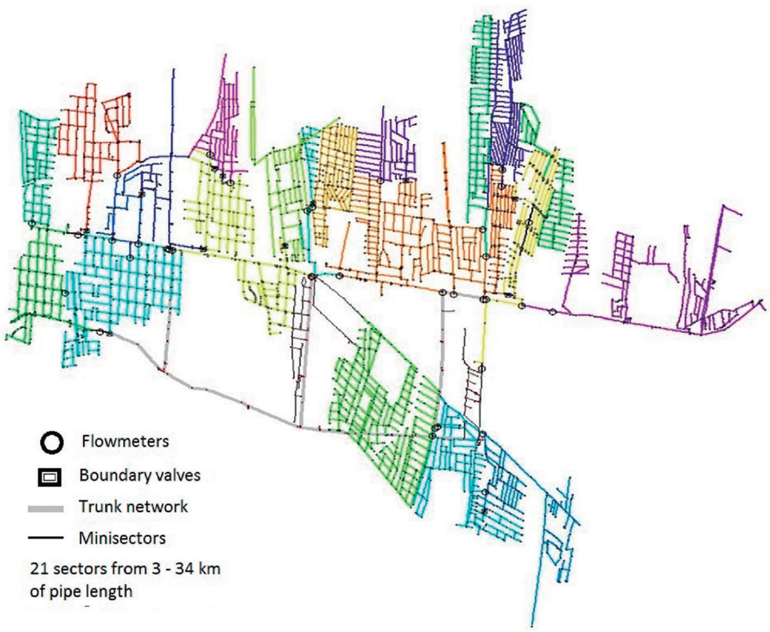

Figure 6. Sectorization layout in example network.
Source: Authors' own elaboration.

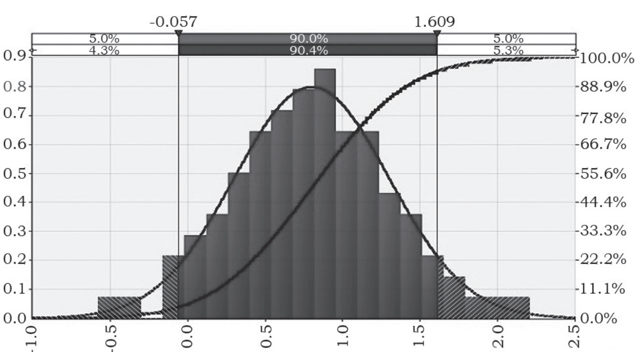

Figure 7. Depicts simulation of probabilistic values of percentage of detection of leakage events in one sector.
Source: Authors' own elaboration.

As a result of optimization of entrances/boundary valves, 35 flowmeters and 12 valves were allocated. As it can be seen in figure 5, annual net profit (savings – expenditures) is 72 397$/year (figure 6). According to latest Monte Carlo simulation performed (taking into account only difference between profit – expenditure), net profit is 58 302 $/year.

Figure 7 depicts simulation of probabilistic values of percentage of detection of leakage events in one sector.

Community detection process was carried out using Igraph package (Csárdi & Nepusz, 2006) in software R and optimization process was carried out using software RiskOptimizer® from Palisade corporation

(Palisade Corporation, 2010). The community detection process runs in approximately 5 min and optimization process converges in 8 min using a computer with processor Intel(R) Core™ i7@2.5GHz.

CONCLUSIONS

In this paper we put in place a framework to account for benefits of sectorization, beyond only considering benefits in terms of background leakage reduction. As shown in implementation example, by considering such benefits as: savings by reducing reported leaks; savings by reducing unreported detectable leaks; savings by reducing number of pipes to repair (reported and unreported leaks) and savings due to reduction of domestic consumption (internal and external). Savings/Investment balance can be extremely different than when only background leakage is taken into consideration. In the presented example, net profit obtained by implementing proposed methodology is 72.397 $/year, significantly above result obtained by only considering reduction of background leakage and energy, in which case, project is unfeasible.

This work introduces novel concepts to sectorization research field, namely, Social Network Community Detection algorithms and Monte Carlo Simulation. With the first one, along with a merging process proposed in this work, it is possible to define sectors in WSNs depending on a trunk network. With Monte Carlo Simulation, it is possible to take into consideration inherent uncertainty in prediction of new leakage events detection within process of optimization of entrances/boundaries valves. This is the first sectorization research work that entails an analysis of sectorization layouts effect over detection of leakage events and, therefore, we hope that this approach could provide new guidelines for researchers and professionals involved in WSN sectorization research field.

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