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Case Study in a Small Municipality in a Developing Country

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Water losses management under data scarcity. A case study in a small municipality from a developing country

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Abstract

Urban areas are facing challenges for the provision of public services, with water scarcity arising as one of the main problems. A twin track approach of supply and demand management is essential and water loss management contributes to reducing water demand. However, small municipalities from developing countries have technical, information and financial limitations to locate and monitor water losses. This paper presents the estimation of real and apparent losses in a small municipality from a developing country in a data-scarce situation. For this, several tools were used allowing data integration that resulted in a water balance, from which water losses were estimated at 46%, and four alternatives for water losses reduction were developed. A cost-benefit analysis and financial indicators were estimated for the proposed alternatives, resulting in a saving of 19% of water, a payback period of 3 years and an internal rate of return of 39%. The proposed strategies have potential to improve water quantity and quality, the technical stability of the system, enhancing utility performance, and water security.

Keywords: apparent losses, distribution network, EPANET, geographic information systems, real losses, water loss management

Introduction

The increasing demand placed on water supply systems generates a wider pressure on water resources (Couto *et al.*, 2015), which is critical, taking into account population growth, reduced surface and groundwater availability (Muthukumaran *et al.*, 2011), and climate variability, that increase drought episodes that in turn affect water quality. Water scarcity has become a serious environmental problem (Pérez-Urdiales *et al.*, 2016). Currently, two thirds of the population live in regions which suffer water scarcity, at least once a year (WWAP, 2017). In this scenario, water use efficiency and conservation are prioritary alternatives to achieve Sustainable Development Goals (SDGs) for 2030, such as ensuring universal access to drinking water and reducing the number of people suffering from water scarcity (UN, 2015).

Several strategies are available for water use efficiency in the urban sector (Bello-Dambatta *et al.*, 2014), including water saving technologies at the household level, such as efficient washing machines, and dual-flush toilets; low-flow showers and faucets; and promotion of water conservation practices. However, the effectiveness of these technologies depends on the introduction of conservation habits and behaviour change among people (Pérez-Urdiales *et al.*, 2016). Other options include decentralized greywater reuse (GWR) and rainwater harvesting (RWH) (Matos *et al.*, 2014). However, implementation of these options requires policies and regulations in place, setting uses, technical norms and quality standards, together with economic incentives and capacity building for professionals in the building sector (Oviedo-Ocaña *et al.*, 2018).

Water loss management in the distribution network is another alternative to reduce demand in water supply systems (Samir *et al.*, 2017). The compensation of water losses represents increasing water supply at the source. Control and reduction of water losses is one of the biggest problems in the management of the water distribution network in the world, and constitutes a climate change adaptation strategy to face climatic variability phenomena (Cavaliere *et al.*, 2017).

Water losses in the distribution network can be divided in real and apparent; real losses are related to leaks in pipes, nodes and fittings, that can be associated to wrong connections, pipe corrosion, mechanical damage due to excessive loads, excavations, soil movement, high hydraulic pressure, pipe age and inadequate installation of pipes (Puust *et al.*, 2010). Apparent losses include unauthorised consumption, customer meter inaccuracies; and data handling and billing errors (Al-Washali *et al.*, 2016).

With regards to the estimation of real losses, according to Puust *et al.* (2010), most methodologies related to leak management, such as Minimum Night Flow (MNF), the leak reflection method (LRM) and SCADA systems can be classified as methods for evaluation, detection and control in order to: i) quantify the amount of water loss; ii) identify critical leakage points; and iii) effectively control the actual and future level of leaks.

Despite the importance of assessing losses in water distribution systems and the increasing interest in the optimal control of the distribution network to improve operational performance (Sankar *et al.*, 2015), systems in some contexts suffer from scarce infrastructure for monitoring and measuring flow and pressure in the network. The situation is even more critical in small municipalities from developing countries that have limited financial resources and lack of technical and decision support tools (Mazzolani *et al.*, 2017). This makes difficult to collect the information required to quantify and understand the magnitude of the water loss phenomenon, assess the costs and benefits of technical and managerial strategies and thus, prioritize investments (Xu *et al.*, 2014).

Methodologies and models for analysis, monitoring and detection of water losses in the supply network have been proposed for developed countries, contributing to optimization, and improved decision-making (Sharma and Vairavamoorthy, 2009). In developing countries, there are reports of water loss assessment or management initiatives in Southeast Asia (Araral and Wang, 2013; van den Berg, 2015) and Africa (Mutikanga *et al.*, 2009; Harawa *et al.*, 2016; Ndunguru and Hoko, 2016; Hoko and Chipwaila, 2017). In contrast, there is a limited number of studies focused on Latin American countries. Despite the existence of some experiences, implementation of water loss assessment and control in small municipalities from developing countries is scant and challenging since the methodologies demand the availability of infrastructure, technical capacity and data that most of the time are not available (Sharma and Vairavamoorthy, 2009; Mutikanga *et al.*, 2011). For these reasons, low-cost and easy to implement systems are required to estimate water losses, plan technical interventions (e.g. pressure control, renovation and rehabilitation), and allocate resources.

This research estimates real and apparent losses in a water system serving a small municipality from a developing country, in a context characterized by limited data and deficient water availability in the dry season. For this, a water balance was carried out in the distribution network, using a range of techniques for data collection, processing and analysis. The data were integrated using Geographical Information Systems (GIS) to determine the users' water demand. Alternatives for the management of real and apparent losses were technically proposed and financially assessed.

Methodology

The research was carried out in three phases: i) physical characterisation of the system and water demand estimation (Basic data); ii) quantification of real and apparent losses (water balance); and iii) formulation and testing of water loss management strategies. Figure 1 presents the methodological summary.

Description of the studied system

The studied system is located in the municipality of Malaga (Santander – Colombia), which has a population of 20,830, served by a water supply system with 5,251 urban customers registered by

March 2017, according to the records of the water service provider. These customers are linked to properties classified by the local authorithy according to strata, which are categories based on the socioeconomic conditions from stratum 1 to stratum 6, (i.e. 1 and 6 represent the lowest and highest socioeconomic level, respectively). In Colombia, stratification is a constitutional mandate carried out to charge differentially for public services (DANE, 2019).The system was divided into three independent service sectors (Figure 2).

This study focused on Sector 1, with 88.8% of the system customers (4,662), being the most representative of the population. Sector 1 is equipped with a bulk meter, customer meters and is completely fed by only one of the two Water Treatment Plants (WTPs). Sectors 2 and 3 are smaller, and have their own treatment systems (ECOCIALT S.A.S., 2014). These sectors are separate from sector 1.

The WTP for Sector 1 provides 43.07 L/s (ECOCIALT S.A.S., 2014) and has four storage tanks (2,014 m^3). There is a gravity-fed distribution network starting with 10 inch PVC transmission main. There is a 10 inch Woltman bulk flow meter and the system has eight water storage tanks without disinfection, that are used in times of drought.

For this study, due to the data-scarce situation, several assumptions were considered. These assumptions are listed below and further described in the appropriate sections in the methodology:

- Unbilled authorized consumption was set equal to zero since the utility established a policy indicating all consumptions must be billed, regardless the type of customer.

- Unauthorized consumption was considered zero in the water balance, since the utility lacked information on illegal users or theft.

• Real volume used to establish customer meter inaccuracies was calculated considering a percentage of error in meter readings of 3.1%, based on reports from the Water and Sewerage Master Plan (WSMP) (Fundación Bolivar, 2004).

• This study adopted the literature values for estimating the leakage night flow. It was assumed that 6% of the whole supplied population was active during the night, with a consumption of 10 L/person/hour (McKenzie, 1999). In addition, it was considered that due to the lower hydraulic pressure during the day, diurnal leakage was 75% of night leakage (Jiménez, 2003).

• The exponent N1 used to estimate the real losses reduction was based on literature recommendations: 1.5 for distribution networks from flexible materials such as PVC (Gomes, 2011) and 0.5 for rigid materials as asbestos-cement (Cassa *et al.*, 2010). This approach was adopted due to the lack of information such as burst frequency, required to implement more detailed Rl reduction models (Sewilam and Rudolph, 2011).

• Cost-benefit analysis of alternatives did not consider costs related to maintenance as there was not enough technical and field data such as burst frequency, pipeline leaks, overflow of the mains and general maintenance costs. The costs associated with the revenue loss caused by the reduction on the actual water demand which is pressure-dependent (Kanakoudis and Gonelas, 2016) were not included either.

Water supply system data

The record of the type and characteristics of the pipes and their hydraulic accessories was updated for this research, based on the review of the municipal WSMP proposed in 2004 (Fundación Bolivar, 2004), complemented with records from repositioning and installation of main pipes, service connections and fittings, developed in 2012 (T&MO Ltda., 2012). The information from

2004 and 2012 was checked, including the new network characteristics. These data were linked to addresses, and an estimation of lengths, pipe diameters, fittings, and the geometric layout of the distribution network was obtained. For updating the information from 2012 to 2017, a workshop was developed with the distribution network operator, who through social mapping techniques, completed information of the distribution networks, in relation to changes, and repairs.

The analysis of water demand in the system was carried out for the period between October 2016 and March 2017. For this, the customers' records and water consumption records were collected and analysed using the providers' database. The customers' water consumption was established from the assessment of the average amount charged to each subscriber, during the analysed period. Since the utility lacked a GIS, an address geocoder was developed, using ArcGIS, where the customers and their water consumptions were spatially located. Thus, the water demand at nodes was established, as a function of the customers' location to obtain a hydraulic scenario close to the conditions in the distribution network. This process included: i) determine the list of postal addresses, adapt the GIS with geocoding function and have maps of the roads; ii) location of addresses, which convert textual descriptions of locations into geographical entities; and iii) database comparison, in which the road infrastructure information and the standardized address records were related.

As result, the spatial location of each subscriber was obtained, and spatial relations were stablished in ArcGIS (spatial join), where the network nodes were linked to all the layer attributes (i.e. customers' data).

Estimation of water losses in the distribution system

The estimation of water losses was developed according to two approaches: Top-down and Bottom-up (Mazzolani *et al.*, 2017). The Top-down approach provides general information on the losses, without differentiation between real and apparent losses. For this, hystorical records from bulk meters and customers' meters are required. The Bottom-up approach allows estimation of losses associated with leaks, using the MNF (Mazzolani *et al.*, 2017). For our water losses estimation, the volume of real losses obtained from the Top down water balance was controlled through Bottom-up calculations based on the analysis of MNF. In this regard the Bottom up approach was used as a check. However, since MNF requires extensive data on the distribution network, which is difficult to obtain for the present case study, several assumptions were made based on recommendations from the literature and the conditions of the studied system. For the general desegregation of the losses, the methodology of the International Water Association (IWA) was used (Lambert, 2002; Lambert *et al.*, 2014). This methodology includes calculation or estimation of the following items:

1. System input volume

2. Authorized consumption

   - Billed authorized consumption
   - Unbilled authorized consumption

3. Apparent losses:

   - Theft of water and fraud
   - Meter inaccuracies
   - Data handling errors

4. Real losses

   - Leakage in transmission mains, distribution mains, reservoirs, overflows, and customer service connections

Detailed explanation of these items can be found in Lambert *et al.* (2014), or Al-Washali *et al.* (2016). The procedure to obtain the items required in the water balance methodology for the present study are explained as follows:

System input volume (SIV) was established using historic records from volumes supplied into the WTP. Due to the lack of daily continuous records during the analysed period, monthly data were obtained from the summation of 448 daily records of volume delivered to the system, registered by the utility, distributed according to the different months.

Authorised consumption (Ac) was calculated by summing ***Billed authorised consumption*** (Bac) and ***Unbilled authorised consumption*** (Uac). Bac included *Billed metered consumption* (Bmc) and *Billed unmetered consumption* (Buc). The former (Bmc) was obtained from working customers' meters, while the latter (Buc) was obtained from customers' meters working improperly (i.e. making it impossible to take actual consumption readings). For Buc, bill came from the average of the six months previous records, obtained and processed from the utility database.

The ***Uac*** is comprised of *Unbilled metered consumption* and *Unbillled unmetered consumption*. It includes consumption regarding firefighting, flushing of mains and sewers, cleaning of suppliers, storage tanks, filtering of water tankers, water taken from hydrants, street cleaning, watering of municipal gardens, among others, and it is typically a small component of the water balance (Lambert, 2002). In this case, the utility established a policy indicating all consumptions must be billed, regardless the type of customer. Therefore, Unbilled authorized consumption was set equal to zero.

Water losses (L): was calculated as the difference between SIV and Ac (Equation 1). Such losses are classified as ***Apparent losses*** (*Al)* and ***Real losses*** (*Rl*) (Equation 2).

$$L(m^3/month) = SIV - Ac \qquad (1)$$

$$L\ (m^3/month) = Al + Rl \qquad (2)$$

Regarding Al, these are divided in *Unauthorized consumption (Uc)*, *Data handling and billing errors* (*Dhbe*) and *Customer meter inaccuracies* (*Cmi*):

$$Al(m^3/month) = Uc + Dhbe + Cmi \qquad (3)$$

With regards to the *Uc*, the utility lacked information on illegal users or theft, for this reason, this item was included as zero in the water balance. In relation to Cmi, customers' meters tend to under-register consumption over time (Al-Washali *et al.*, 2016). This item was obtained from the real volume of consumption, calculated using the monthly readings of the customers' meters working properly, and the the typical measurement error of the used meters, i.e. as follows:

$$Rv\ (m^3/month) = Bmc\ * \left(1 + \frac{\%\ error}{100}\right) \qquad (4)$$

Where, Rv is the real volume from customers with readings and Bmc is the billed volume for customers with meter readings. The percentage of error was assumed as 3.1% based on reports from WSMP (Fundación Bolivar, 2004). Thus, *Cmi* were estimated by subtracting the monthly billed volume of customers with readings from the real monthly volume for these customers, i.e. as follows:

$$Cmi\ (m^3/month) = Rv - Bmc \qquad (5)$$

Regarding Dhbe, customers with consumptions billed as the average of historical consumption were identified in the utility database. This situation was associated to poorly functioning customers' meters, which make impossible their monthly readings to be made. Likewise, the causes that motivate this situation and the status of the customers' meters were recorded. Additionally, the average consumption of a customer in each stratum was determined, analyzing the utility's database. For this system, each customer in socioeconomic stratum 1 had an average consumption of 7.2 m^3/month. This value was assigned to all the customers who had billed consumptions obtained as the average of historical consumption, resulting in an estimate of the total volume that should be billed to these customers according to consumption per stratum (TVb) (Equation 6).

$$TVb\ (m^3/month) = Nac * a_v c\ . \qquad (6)$$

Where N$a_v c$ is the number of customers with average consumption, and $a_v c$ is the average consumption from the customers with readings. Then, the volume billed to customers with average historical consumption Vbc$a_v c$ was subtracted from TVb (Equation 7), obtaining the Dhbe volume.

$$Dhbe\ (m^3/month) = TVb - \ Vbca_v c \ \ (7)$$

Finally, ***Rl*** were estimated. These losses included: a) *Leakage on transmission or distribution mains*; b) *Leakage on service connections*; and c) *Leakage and overflows on utility´s storage tanks*. ***Rl*** were calculated by subtracting ***Al*** from the volume of ***L*** (Equation 8):

$$Rl\ (m^3/month) = L - Al \qquad (8)$$

To check ***Rl*** obtained from Equation 8, the MNF, which has been widely used as the most accurate method to assess ***Real losses,*** was adopted (Babić *et al.*, 2014). This method is typically used in a District Metered Area (DMA), a hydraulically isolated part of the network, with a permanent boundary, usually defined by the closure of valves, in which the quantities of water entering and leaving the area are metered, and that include between 500 and 3000 customer service connections (Karadirek *et al.*, 2012). This methodology was applied to the study of Sector 1, despite having 4662 connections, which is above the recommended range, since this was the sector that provided the other recommended characteristics (hydraulic isolation, permanent boundary, and metering). MNF considers that leakage in the supply sectors can be estimated when the flow is at its low level (i.e. 1:00AM - 4:00AM), when customer demand registers the minimum value, and thus, leakages are the main component of the flow (Cheung *et al.*, 2010). The leakage flow was estimated using Equation 9 (Tabesh *et al.*, 2009):

$$Qnf(m^3/hour) = Qmnf - Qlnf \qquad (9)$$

Where Qnf is the net night flow (leakage), $Qmnf$ and $Qlnf$, are the minimum night flow and the legitimate night flow, respectively. To obtain $Qmnf$, flow measurement campaigns were undertaken at the outlet of the treatment plant between 1:00AM and 3:00AM. To obtain an accurate $Qlnf$ rigorous field investigations need to be undertaken to ascertain the number of possible night users (Al-Washali *et al.*, 2016). When these studies are not possible, literature values can be used. This study adopted the literature values where 6% of the whole supplied population is active during the night, with a consumption of 10 L/person/hour (McKenzie, 1999)).. In addition, it was considered that due to the lower hydraulic pressure during the day, diurnal leakage (Qdl) will be 75% of night leakage (Jiménez, 2003) (Equation 10).

$$Qdl\ (m^3/hour) = 0.75 * Qnf \qquad (10)$$

The consumption pattern for the system was considered based on the modulation curve (Blanco and Celis, 2017) . For the low consumption hours, the total leakage was estimated using the measurement of the night flow and for the diurnal hours, it was estimated considering the percentage in relation to the night leakage.

Alternatives for water loss reduction

The information from the water balance allowed proposing strategies to improve the performance of the water supply system, including activities for the control and reduction of apparent and real losses.

<u>Alternatives to reduce Apparent losses</u>

Customer meter renovation and detection of illegal users were proposed. Customer meter renovation could contribute to reducing the inaccuracies associated to the aging of these devices, together with the low sensitivity at the start, which are characteristic of some meters. In this study, customers with incorrectly working meters were identified, using georeferenced data obtained in the first stage of the study, and a map was prepared with the location of these customers. Regarding strategies for detection of illegal users, this study identified users with consumption below 25% of the average consumption within the analysis of the historic records of legal users, in each socioeconomic strata. These users were spatially located, providing the utility with tools to corroborate the composition and occupancy, consumption records, meter and service connection status (Jiménez, 2003).

Alternatives to reduce Real losses

To tackle Rl in this system, Pressure Management (PM) was proposed. PM keeps the pressure within a desirable range throughout the supply period (Haider *et al*., 2019), and it is recognized as one of the most efficient and cost-effective measures available to water utilities (Nicolini and Zovatto, 2009) to reduce leakage and bursts on mains, limiting water losses (Darvini and Soldini, 2015). For this, the physical configuration of the network was obtained from the developed GIS, and integrated through a model built using the freely available hydraulic network simulation software EPANET (Rossman, 2000).

For model building, data from ArcView and EPANET were linked using the GISRed extension, intended for water distribution network modelling and calibration (Alzamora *et al.*, 2004). This linkage automatically provided a characteristic network topology in EPANET (e.g. pipe diameters, coordinates of nodes, pipes, pipe lengths), which was complemented with the fittings (e.g. control valves, tanks, reservoirs) (Motiee *et al.*, 2007). In addition, a consumption modulation curve was prepared (Blanco and Celis, 2017) to obtain the behavior of the hourly population water demand.

A preliminary calibration process for the hydraulic model was carried out, in which pressure values measured in the network were compared to the pressures provided by the model in different locations. This was done for a typical day and for a low demand day. This process showed variability between the two datasets, but this variability was constant in different network locations. Blanco and Celis (2017) show the comparison between these values. Although the calibration process was not developed exhaustively, the hydraulic model allowed identifying high and low pressure zones in the system. These zones were consistent with pressures measured in the network.

With regards to the prioritized renovation of pipes, five criteria regarding pipe characteristics were considered: age, break history, diameter, material and average pressure (Tlili and Nafi, 2012). These data were spatially located and analysed using GIS to identify the pipes that under the selected criteria had greater tendency to suffer breaks or structural damage.

A search using ArcMap was conducted according to the criteria defined and clusters of similar characteristics that showed critical conditions were identified and, priority replacements were defined to improve the system performance.

Sectorization of the system was proposed according to hydraulic criteria: i) range of pressure between 15 and 60 m (MVCT, 2017), looking for smaller sectors having different pressure regimes (Nicolini and Zovatto, 2009); ii) areas between 5 and 15% of the total service area (i.e. to control infrastructure and leaks); iii) similar topographic conditions, regular shapes, boundaries defined considering geographical features (e.g. canals, rivers, waterways); and iv) similar socioeconomic conditions and customer category (Jiménez, 2003). Having analysed the pertinent criteria, the principal pipe to supply the different areas and the districts were defined, checking the boundaries and the effectiveness of the pressure reduction achieved, using the EPANET hydraulic simulation model to check the hydraulic performance of the proposed changes.

Financial assessment of alternatives

A cash flow analysis was carried out for three different alternatives to asses their financial feasibility: Alt1 customer meter renovation, (reduction of Al), Alt2 pipeline renovation and sectorization (reduction of Rl), and Alt3 simultaneous implementation of Alt1 and Alt2.

For Alt2 and Alt3, the reduction of Rl associated to PM interventions was established using a simple pressure relationship (Equation 11) proposed by Thornton (2003) and widely used in the literature (Vicente *et al.*, 2016).

$$\left(\frac{L_o}{L_1}\right) = \left(\frac{P_0}{P_1}\right)^{N1} \quad (11)$$

The losses relation $\left(\frac{L_o}{L_1}\right)$ corresponds to the leak reduction rate, $\left(\frac{P_0}{P_1}\right)$ is the pressure reduction and N1 is the leakage exponent that shows interdependency of leakage on pressure. Field and laboratory studies have found that the exponent N1 lies within the range of 0.5 – 1.5 (Thornton and Lambert, 2005) . For the current study, N1 was set at 1.17 as a result of a weighted average corresponding to the proportion of asbestos-cement (AC) and PVC pipes in the network, taking N1 as 1.5 for PVC (Gomes, 2011) and 0.5 for AC (Cassa *et al.*, 2010). This approach was adopted due to the lack of information such as burst frequency, required to implement more detailed Rl reduction models (Sewilam and Rudolph, 2011).

Finally, a cost-benefit analysis was prepared for a 15-year period, recommended lifetime for meters and pipelines (Sewilam and Rudolph, 2011) and used in other studies (e.g. Kanakoudis and Gonelas, 2016). The annual income of water utilities, considering the reduction of SIV, was obtained multiplying the saved water volume by the unsubsidized fee charged to the users, which represents the avoided cost of energy and water treatment. This value includes an annual inflation of 4.16%, according to the average change over the last 10 years on the consumer price index (CPI) in Colombia (DANE, 2018). The costs involved in the financial assessment were initial investments at year zero related to: for Alt1, replacement of poorly functioning meters (purchase, transport and installation of new meters); for Alt 2, replacement (purchase, transport, and installation of pipes, fittings, pressure valves, and bulk meters) of pipes operating under the most critical conditions that could generate leaks. The cost of replacing the pavement of roads was also considered for Alt 1 and Alt 2. Costs related to maintenance were not included as there was not enough technical and field data such as burst frequency, pipeline leaks, overflow of the mains and general maintenance costs. The costs associated with the revenue loss caused by the reduction on the actual water demand which is pressure-dependent (Kanakoudis and Gonelas, 2016) were not included either. The benefits considered on the financial assessment were limited to the water savings potentially achieved with the implementation of the different alternatives, which results in reduced SIV. The indicators: net present value (NPV), using a discount rate of 3.51% as recommended for environmental projects in Colombia (Correa, 2009); payback period (PP), to measure how long it will take to recover the initial investment; and internal rate of return (IRR) (the discount rate that produces a level of the NPV equal to zero) were estimated.

Results

Characterisation of the distribution network

It was found that distribution network was made of AC -10,497 m (33%)- and PVC pipes -21,737 m (67%). Pipe diameters were between 2” and 10”, and customer service connections had diameters between 1” and 1.5”. The network was complemented with elbows (222), reductions (48), tees (446), crosses (82), hydrants (35), and isolation valves (157). There were not records of air valves, pressure reducing valves, or purge valves (see Figure 3).

Table 1 presents the distribution of customers according to category and their monthly average consumption. Residential customers were 88.8% of the total customers and had the highest monthly Bac (83.2%).

The majority of customers consumed between 10 and 20 m^3/month (see Table 2), which is consistent with the Colombian technical regulation for municipalities with this population size (i.e. 15 m^3/customer/month) (MVCT, 2017).

Figure 4 shows the spatial location of all customers. The database included customer name, monthly consumption, customer category, stratum, and customer meter status. A spatial relation was established between georeferenced customers and network nodes. This relation allowed stablishing the water demand at each node, which was approximately 186 m^3/month (i.e. 0.072 L/s). This demand was obtained as the monthly average for the analysis period.

Water balance for the distribution system

SIV was 118,982 m^3/month (± 6,162 m^3/month), as shown in Table 3.

Ac on average was 63,624 m^3/month. With regards to Bmc, from all the billed consumption, a proportion was from customer meters working properly. Table 4 includes the distribution of customers with records and their consumption, where the average measured volume was obtained for the analysis period, and it was approximately 44,443 m^3/month.

The Buc was 19,182 m^3/month, which indicates that, from Ac, around 30% was billed with average consumption values. As explained in the methodology section, since all the customers in this system were billed, regardless of their category, Uac was zero (0).

The average monthly volume of losses in the system was estimated at 55,358 m^3/month, equivalent to 46% of the SIV.

In relation to Al, those associated with customer meter inaccuracies were established with a volume of 1,378 m^3/month. Al due to Dhbe, were associated to 1,331 customer meters poorly functioning, from which 1012 were stopped, 108 needed readings to be checked, 122 lacked the meter, 9 meters were covered, 4 had broken tachometer, 71 were in poor conditions, 2 were inverted and 3 were cut. Synthesizing, 76% of customer meters were working incorrectly. The volume loss due to customer meter inaccuracies is detailed in Table 5. Besides, customers with uninhabited households, which theoretically should not have consumption values but did, were considered. Likewise, lost volumes linked to customers with working meters registering zero consumption during all the analysed period were included.

The negative value on the covered meter category means that a quantity above the estimated consumption of these customers were charged. Thus, taking to account, losses due to Dhbe (2,096 m^3/month) and records of the billed volume for users with inhabited premises (i.e. 927 m^3/month), the value of Al due to Dhbe was 3,024 m^3/month. Consequently, the total Al were 4,402 m^3/month.

Finally, real losses were estimated at 50,956 m^3/month. Table 6 presents a synthesis of the water balance for the analysis period.

Real losses in the distribution system

Based on the criteria and steps detailed in the Methodology, the MNF analysis provided a value for $Qmnf$ of 95 m^3/hour. Taking into account the number of customers (4,662) and the population (16,783 inhabitants) in the analysed sector (Sector 1, 88.8% of the total population) (ECOCIALT S.A.S., 2014), legitimate night users were estimated at 1,007 people (6% of the population). The consumption in the system during the hours of minimum demand, using the reference value of 10 L/percapita/hour was 10.07 m^3/hour, and provided a Qnf of approximately 84.9 m^3/hour.

According to the modulation curve of consumption, the minimum consumption occurred during the period between 21:00 and 5:00 hours, being the night leakage flow volume 679 m^3. For the remaining time (between 5:00 and 20:00), the leakage flow was assumed at 75% of the night leakage, 64 m^3/hour. Thus, the leakage volume estimated for the diurnal hours was 1,019 m^3. This way, total leakage in a typical day was estimated for a daily leakage flow of 1,699 m^3/month. This information was extrapolated for a monthly period, to estimate the volume of technical losses or real losses in the system, that was found as 50,959 m^3/month. This value was similar to that obtained from the water balance (50,956 m^3/month).

Finally, the ratio of SIV and L was established for the analysis period at 46%, which is a value significantly above the standard set by the National Authority of Water and Sanitation from Colombia (25%) (MVCT, 2017).

Alternatives for water loss reduction

Based on the previous results, alternatives were proposed to reduce Al and Rl as described below:

<u>Renovation of customer meters</u>

The renovation of customer meters was identified as a potential alternative to improve system performance and data accuracy to assist with further modelling. Figure 5 shows the location of the 1,331 devices with problems, prioritized for a renovation program.

<u>Detection of water theft</u>

Figure 6 includes the spatial location of the customers with consumption less than 25% of the average per category, excluding from this group, customers with low consumption due to poorly functioning meters. According to these criteria, 274 customers could be potentially participating in water theft. From this, 125 were stratum 2 and 83 were commercial customers.

Pressure management

The hydraulic model in EPANET allowed identifying pipes in the distribution network with issues of pressure or velocity (Figure 7).

Pipes were selected and clustered in relation to the most critical conditions that could generate breaks and leakage and thus, could be prioritized for renovation: a) pipe age: above 40 years; b) break history: yes; c) pipe diameter: 2 to 6 inches; d) material: AC; and e) average pressure: less than 15 m and higher than 60 m. Pipes with these characteristics had a total length of 1,526 m (Figure 8).

Further to this, sectorization of the distribution network was carried out considering the criteria of reducing pressures, and defining areas with similar hydraulic characteristics (e.g. pressure, velocity, topography). The proposal of pressure areas includes the installation of isolation valves, bulk meters, and pressure reducing valves. Figure 9 shows the improvement proposal selected. Table 7 describes the proposed PM interventions.

With the proposed sectorization, the current maximum pressure in the low demand hours will reduce from 101 m to 71 m, and the average pressure will reduce from 64 m to 44 m. Figure 10 and Figure 11 provide pressure maps, depicting the pressure distribution at the time of the study and the pressure with the sectorization.

Financial assessment of the alternatives

Table 8 summarizes the cash flow projection for a 15-year period after the implementation of the different alternatives proposed (Alt 1, Alt 2 and Alt 3). Each different alternative results in a reduction of SIV, when compared to the initial state. For the financial analysis of Alt1, the replacement of the 1331 customer water meters was considered, presuming a total reduction in Al of 4,402 m^3/month.

This assumption was made because there was not a reliable database that included information such as the age of the water meters, and their performance in terms of water consumption under-registration. These data are usually collected with constant monitoring of the water meters conditions, through failure patterns and testing. Ideally this information would allow an accurate calculation of the water losses reduction. Lack of information has been a common factor in other studies from developing countries (Couvelis and van Zyl, 2015). However, the initial total Al reduction assumption could be valid since this volume (3.7%) represents only a 8% of the total water losses of the system (46%).

In Alt2, the replacement of 1,526 m of existing AC pipelines for new PVC pipelines (typically used in water systems from developing countries), and the installation of valves and flow meters to carry out the sectorization were considered. As a result, the average system pressure drops from 64 m to 44 m, and given the initial real losses L_0 = 50,956 (42.86%) m^3/month, applying Equation 11, a L_1 value of 32,817 (27.58%) m^3/month was obtained, giving a 15.24% of loss reduction. This is a conservative value of Rl that would still be above the standards according to Colombian and International regulations. As explained before, Alt3 integrates Alt1 and Alt2.

According to the financial analysis, by year 5, each of the alternatives have generated a positive net cash flow.

Discussion

Losses in the water distribution system were estimated at 46%, higher than the standard set by the Colombian regulation (25%) (MVCT, 2017), but consistent with typical values from Colombia, which are around 43% (DNP, 2017), Latin America and The Caribbean (40 – 55%) (Berg, 2008) and for developing countries (40 – 50%) (Kingdom *et al.*, 2006). Real losses were 92% of the total losses, a value considerably above than that reported for developed countries such as France (25 - 50%) (Garcia and Thomas, 2003), Germany (5%) and Bulgaria (50%) (Egenhofer *et al.*, 2012).

Concerning apparent losses, it was proposed that the renovation of customer meters and identifying areas with greater problems for service monitoring and the detection of potential illegal users could be further analysed to discern the causes of their low consumption. Despite the values found, the estimation of apparent losses in the water balance method has limitations, since it depends on several assumptions that are not always applicable to systems in developing countries, as well as the lack of a more objective methodology (Al-Washali *et al.*, 2016). This is an aspect that must be refined and further studied. For example, in this case, illegal users were not considered in the water balance due to lack of data, and this could be an important component of losses in developing countries (González-Gómez *et al.*, 2011), where levels of 10% billed water have been recommended to be used for the estimation of this component (Mutikanga *et al.*, 2009).

In relation to activities to control and reduce real losses, rehabilitation of pipes is one of the most important factors influencing the water industry worldwide (Cavaliere *et al.*, 2017). In this research, a prioritized rehabilitation of the pipes with the most unfavourable operational conditions (pressure, diameter, damage records, material and age) was proposed. For instance, although PVC pipes were dominant (67%), there was an important proportion of AC pipes (33%), which represent a public health risk (Andersen *et al.*, 1993), and are more likely to break (Wang and Cullimore, 2010) (e.g. 37% of water losses were due to leaks in AC pipes in the Napoca municipality (Romania) (Aşchilean *et al.*, 2017). Despite the high investment costs associated to pipe rehabilitation, in the long term, this can represent a reduction in the variable costs associated to the decrease in the energy consumption and repair of social damages. This water loss strategy was financially assessed as part of this study together with other Pressure Management interventions (Alt2), providing an IRR of 50% and PP of 3 years. This is a critical strategy to contribute to sustainable urban development, and can prevent intermittent water supply, degradation of water quality and higher operational costs for service providers (Tlili and Nafi, 2012).

Considering that the majority of losses in this system were associated to leakage and due to the direct relation between flow and pressure, the implementation of a hydraulic sectorization was proposed as an alternative with high potential to reduce real losses, due to the ability to control and manage pressure by implementing districts in the distribution network (Aldana, 2017). This alternative can be complemented by installing fittings such as pressure reducing valves, isolating valves and bulk meters (Samir *et al.*, 2017). This is recognized as a popular and effective strategy, and has been implemented in urban cities in Colombia, such as Bogotá, achieving reductions in losses from 48% to 22%, associated to the decrease on pressure and leakage (Saldarriaga and Salas, 2003).

The financial analysis performed, despite being based on several assumptions and not considering costs such as maintenance and revenue loss caused by the reduction on the pressure-dependent component of water demand (e.g. (Kanakoudis and Gonelas, 2016)), it is a starting point for improved decision making. The results obtained are appealing for the utility managers, since the proposed alternatives generate a positive net cash flow from year 3 to 5.

Table 9 compares financial indicators, from different water losses reduction projects carried out in developing countries. The results show auspicious financial feasibility in terms of PP, with values ranging from 2 to 10 years.

By comparing the results of this study with those reported from systems in other developing countries, the scarce representation of small utilities is evident (most studies are from systems serving populations above 50,000 people). However, in all cases Payback Periods are less than 10 years. The difference among cases in the % of SIV reduction, which varies from around 7 to 33%, could be associated to the infrastructure, methodologies and assumptions in each study. Even when the accuracy of the results from this study can be improved with future research, this attemp helped to identify needs on information, infrastructure, monitoring, maintenance and administration to improve the understanding and quantification of the water losses magnitude and its components. In addition, progressing on environmental valuation associated to water losses due to leakage, should start to be included in these analysis (Xu *et al.*, 2014).

Conclusions

Research presented in this paper addressed water scarcity in a water system from the perspective of demand, which is opposite to the supply perspective, typically adopted in small-municipalities from developing countries, due to the lack of data, technical capacity and political will. For this, a Water Balance was carried using the IWA methodology, complemented with MNF analysis to obtain values of water losses from two approaches (Top-down and Bottom-up). The use of these recognized, standaridised and widely adopted methodologies allowed benchmarking, which is a valuable improvement tool.

The study case had most of the characteristics of systems from small utilities in developing countries, which make managers believe the water loss problem is impossible to address, leading to inaction: poorly structured and maintained network; insufficient information on pipe characteristics, age, valve locations, connections, and flows; lack of modern tools and techniques for leakage detection and control; outdated and uncomplete map; deficient metering; and lack of flow and pressure monitoring. Despite these challenges, water loss assessment methodologies were used, providing results on the water balance components that increase system knowledge and help to devise strategies to improve the information on the system and the level of water loss.

Water Balance and MNF analysis are commonly used in systems from developed countries or large cities from developing countries, which have in place updated information on the distribution network, commercial databases regarding customers, GIS, and online schemes to capture information such as flows and pressures at different locations. To overcome the lack of most of this information in the system under study, a variety of methdologies and tools were used. In particular, GIS, with its GisRed extension, allowed optimizing activities in the distribution network modelling, using the maps from the distribution network, to establish the nodes. In addition, GIS was used to estimate the nodal demand through the preparation of an address geocodifier, which allowed spatial location of each customer and from allocation of customers' demand to different areas related to the nodes defined in the distribution system. Therefore, this research provides a reference for small utilities to approach water balance studies when the basic information has to be collected.

Results highlighted estimated water losses, which were around 46%, a higher value compared to what is recommended by the Colombian standards, and the goal for developing countries. However, it was consistent with values found in distribution networks of capital cities from developing countries. The results highlight the importance of addressing leakage, which in this case, was 92% of the real losses, for which pressure management can be an effective solution, since high pressures are strongly linked to breaks and thus, water losses. The process developed shows that it is possible to develop this type of research even in small and scarce-data systems, since information gaps can be progressively filled, and such approaches are the basis of informed decision-making under uncertainty that can lead to improvements in service provision and reducing water scarcity. Furthermore, the alternatives considered for water loss control are promising in financial terms, leading to the rapid recovery of investments.

Data Availability

Data, models and code generated and used during the study may be available from the corresponding author by request on a case by case basis.

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Table 1. Distribution and consumption of customers according to their category

Category	Number	Proportion from the total number (%)	Billed Authorized Consumption (Bac) [m^3/month]	Proportion of consumption from total (%)
Residential	4,140	88.8	52,937	83.2
Industrial	6	0.13	121	0.19
Commercial	480	10.3	7,128	11.2
Institutional	36	0.77	3,438	5.4
Total	4,662	100	63,624	100

Note: Stratum 1: 979 customers (consumption 12,576 m^3/month); Stratum 2: 2,581 customers (consumption 33,251 m^3/month); Stratum 3: 573 customers (consumption 7,024 m^3/month); Stratum 4: 7 customers (consumption 86 m^3/month). In Malága there are no customers in stratum 5 and 6.

Total refers to the total water consumption in m^3/month of the population according to the average consumption in each customer category.

Table 2. Distribution of the monthly water consumption in the study area

Range average consumption [m^3/month]	**N° customers**	**%**	**% Acum. customers**	**Total water consumption [m^3/months]**	**%**	**% Cummulated. [m^3/months]**
0-10	1,768	37.9	37.9	9,143	14.4	14.4
10-20	2,255	48.4	86.3	30,978	48.7	63.1
20-30	429	9.20	95.5	10,153	15.9	79.0
30-40	98	2.10	97.6	3,331	5.24	84.2
40-50	51	1.09	98.7	2,262	3.60	87.8
50-100	41	0.88	99.6	2,764	4.34	92.2
≥100	20	0.43	100	4,993	7.85	100

TOTAL	4,662	100	63,624	100

Table 3. System input volume per month

Month	**System Input Volume (SIV) [m^3/month]**	**Authorised consumption (Ac) [m^3/month]**
October 2016	115,800	64,030
November 2016	118,200	51,410
December 2016	118,600	59,005
January 2017	131,100	60,547
February 2017	114,100	78,996
March 2017	116,100	67,759

Table 4. Authorised consumption according to customer category and stratum

Category	**Bmc [m^3/month]**	**Customer**
Stratum 1	8,119	642
Stratum 2	24,061	1,776
Stratum 3	5,050	369
Stratum 4	86	7
Industrial	95	4
Commercial	5,473	301
Instittutional	1,559	19
Total	44,443	3,118

Table 5. Volume of losses due to meter functioning issues

Customer meter status	Estimated real volumes [m^3/month]	Billed volume [m^3/month]	Losses [m^3/month]
Zero reading	748	0	748
Stopped meter	14,993	14,306	686
Readings to be checked	1,482	1,081	401
Lack of meter	1,900	1,706	194
Covered meter	130	161	31
Broken tachometer	55	40	14
Poor condition meter	990	914	77
Inverted meter	27	21	7
Total	20,325	18,229	2,096

Table 6. Water balance for the average month in period October 2016 – March 2017

<table>
<tr><td rowspan="4">Authorised consumption (Ac)
(63,624 m^3/month)</td><td rowspan="2">Billed authorised consumption
(Bac)
(63,624 m^3/month)</td><td>Billed metered consumption (Bmc) (including water exported)
(44,442 m^3/month)</td><td rowspan="2">Billed</td><td rowspan="2">Revenue water</td></tr>
<tr><td>Billed unmetered consumption (Buc)
(19,182 m^3/month)</td></tr>
<tr><td rowspan="2">Unbilled authorised consumption
(Uac)</td><td>Unbilled metered consumption (Umc)
(0 m^3/month)</td><td rowspan="2">Commercial losses</td><td rowspan="2"></td></tr>
<tr><td>Unbilled unmetered consumption (Uuc)</td></tr>
</table>

System Input Volume (SIV) (118,982 m^3/month)		(0 m^3/month)	(0 m^3/month)		Non-revenue water
	Water losses (L) (55,358 m^3/month)	Apparent losses (Al) (4,402 m^3/month)	Unauthorised consumption (Uc) (n.e., assumed 0 m^3/month)		
			Customer metering inaccuracies (1,378 m^3/month)		
			Data handling and billing errors (Dhbe) (3,024 m^3/month)		
		Real losses (Rl) (50,956 m^3/month)	Leakage on transmission and/or distribution mains	Technical losses	
			Leakage and overflow at utility´s storage tanks		
			Leakage on service connections up to point of customer metering		

Note: n.e: not estimated

Table 7. Requirements for the subsectors proposed for pressure management in the distribution network

Subsector	Description
S01	Permanent isolating valves, bulk meter to control consumption and cut valves to regulate flow.
S02	Permanent isolating valves. Pressure control is not required since this was in the admissible range.
S03	Pressure reducing valve of 1½" (outlet pressure 40 m) and permanent isolating valves.
S04	Permanent isolating valves, pressure reducing valve of 2" (outlet pressure 20 m) and bulk meter to control water consumption.
S05	Pressure reducing valve of 2½" (outlet pressure 30 m) and permanent isolating valves.
S06	Pressure reducing valve of 2" (outlet pressure 30 m) and permanent isolating valves.

S07	Permanent isolating valves. Pressure control valves are not required.

Table 8. Financial projection for water loss reduction alternatives

Year	Income (USD)[1]			Initial Investment (USD)			Net cash flow accumulated (USD)[2]		
	Alt 1	Alt 2	Alt 3	Alt 1	Alt 2	Alt 3	Alt 1	Alt 2	Alt 3
0	-	-	-	48,488	81,838	130,326	-48,488	-81,838	-130,326
1	9,076	37,397	46,472	-	-	-	-39,412	-44,442	-83,854
2	9,453	38,952	48,406				-29,959	-5,489	-35,448
3	9,846	40,573	50,419				-20,113	35,084	14,971
4	10,256	42,261	52,517	-	-	-	-9,856	77,345	67,488
5	10,683	44,019	54,702	-	-	-	825	121,363	122,190
15	16,058	66,168	82,226	-	-	-	135,415	675,945	811,360

[1] Income comes from reduced SIV: Alt 1(4,402 m^3/month), Alt 2(18,138 m^3/month), Alt 3(22,540 m^3/month).

[2]Financial indicators NPV, PP, IRR: Alt 1: 85,953 USD, 5 years, 21%. Alt 2: 468,142 USD, 3 years, 50%. Alt 3: 554,097 USD, 3 years, 39%.

Table 9. Financial indicators of water loss management strategies from different study cases in developing countries

Location	Population served	Alternatives description	Water Savings % SIV	Results*	Reference
Kozani, Greece	50,000	Sectorization (DMAs) by installing pressure reducing valves.	33	PP 2 years	Kanakoudis and Gonelas (2016)
Chipata, Zambia	84,633	Water audit, leak detection surveys, repair of the backlog leaks, sectorization, and pipe replacement.	11	PP 2.6 years	Wyatt (2010)

New Providence, Bahamas	271,600	Pump control, bulk meter replacement, sectorization, leak detection and repair.	25	PP 9.6 years, IRR (10) 46%	Wyatt (2018)
Silay City, Philippines	21,899	Water audit, leak detection surveys, repair of the backlog leaks, sectorization and pipe replacement	28	PP 5.1 years	Wyatt (2010)
Kampala, Uganda	1,215,273	Customer meter replacement and leak detection survey	8	PP 1.0 year	Wyatt (2010)
Colombia	20,830	Customer meter replacement, sectorization and pipe replacement.	19	PP 3 years, IRR average (15) 39 %	This research

* PP payback period, IRR internal rate of return at specified year. All systems had 24 hours of supply.

Figure 1. Methodological summary

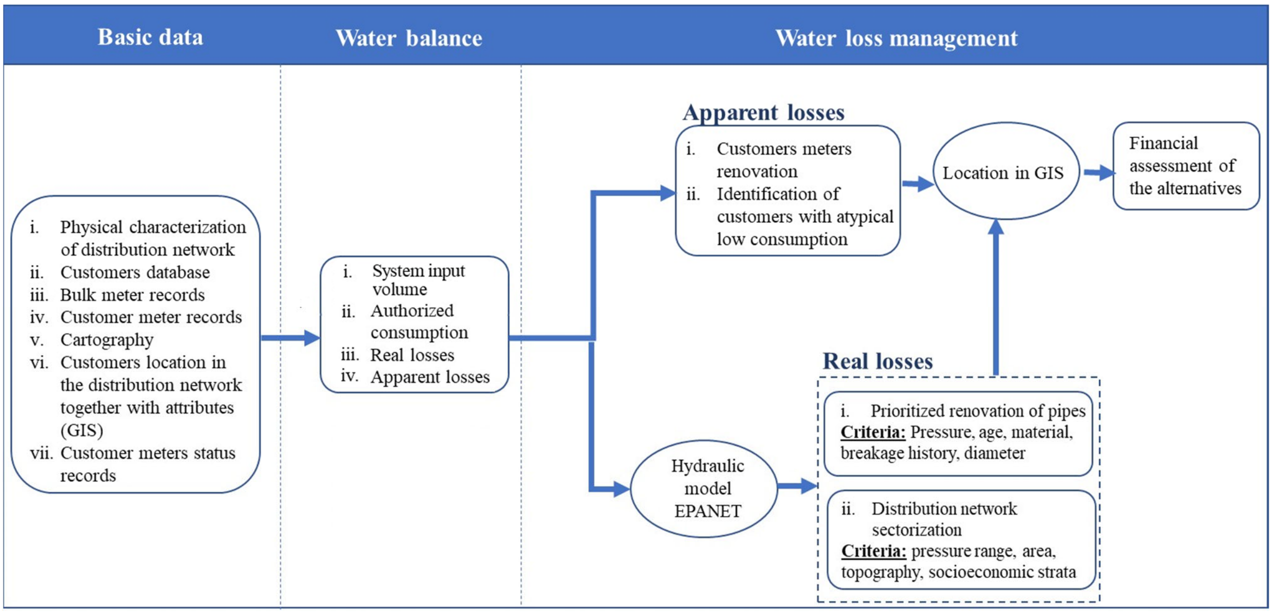

Figure 2. Sectors of the water distribution network for Malaga municipality

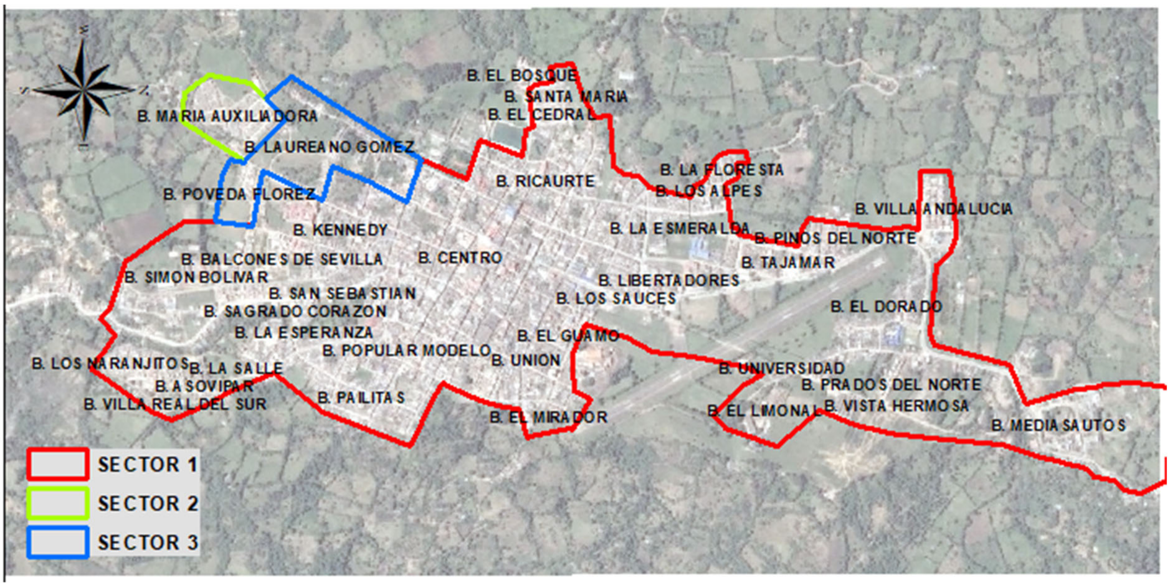

Figure 3. Pipes and valves in the distribution network

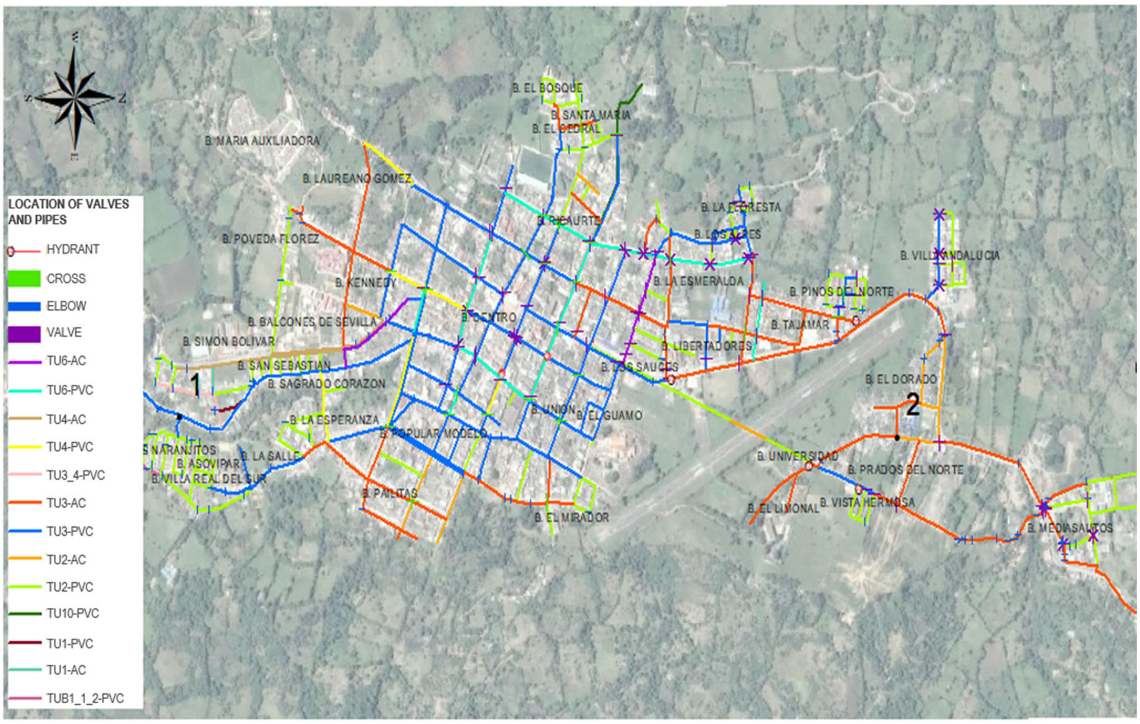

Figure 4. Georeferenced customers in the water supply system

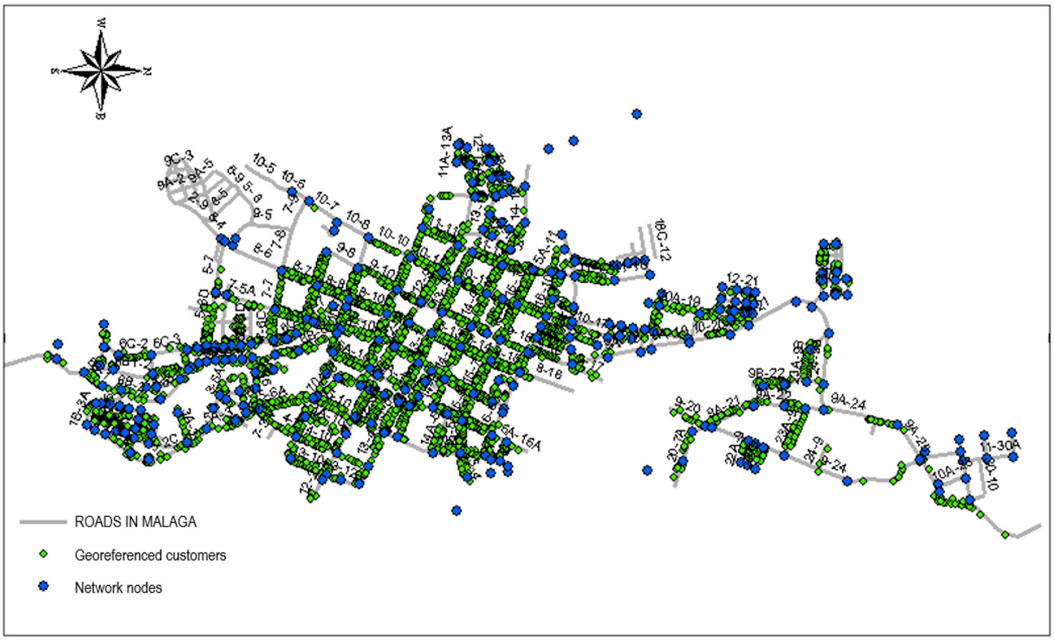

Figure 5. Spatial location of customer meters working incorrectly

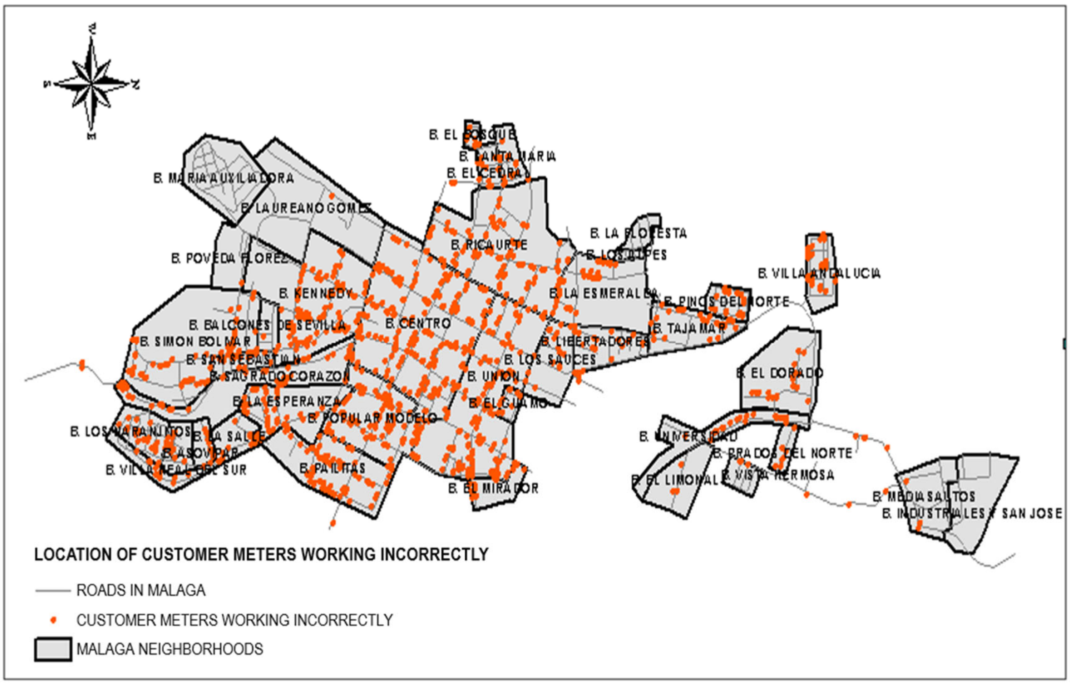

Figure 6. Spatial location of customers who could be potentially participating in water theft

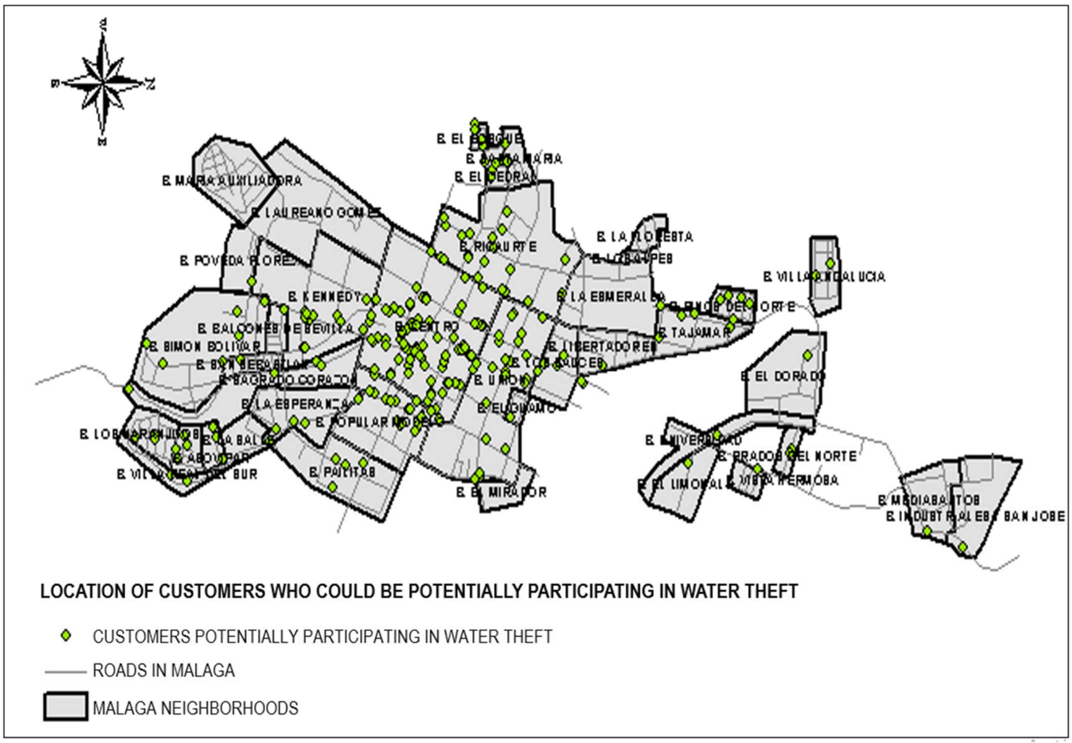

Figure 7. Hydraulic modelling of the distribution network

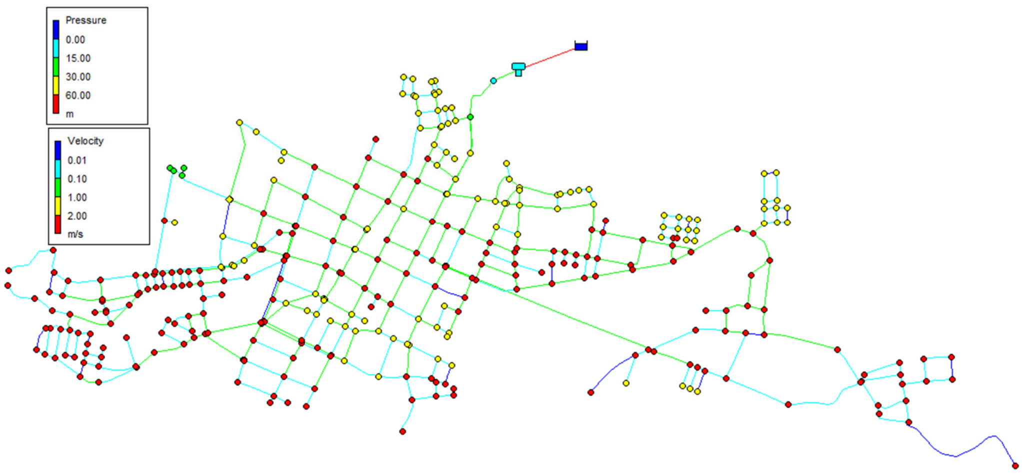

Figure 8. Pipes that fulfil critical conditions for renovation

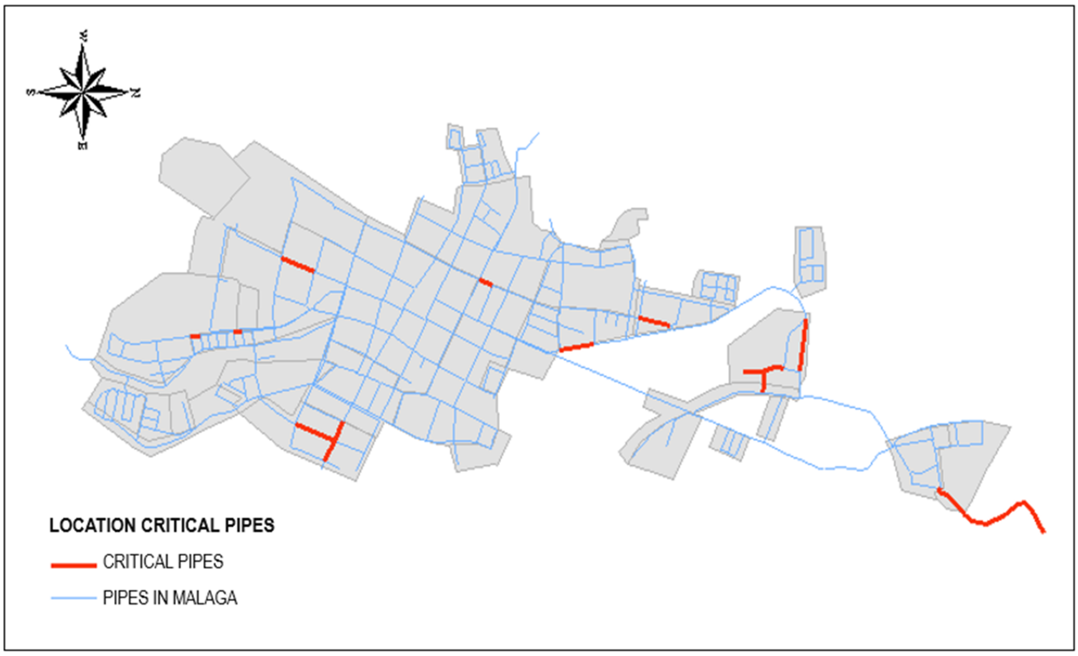

Figure 9. Network sectorization for proposed pressure management strategy

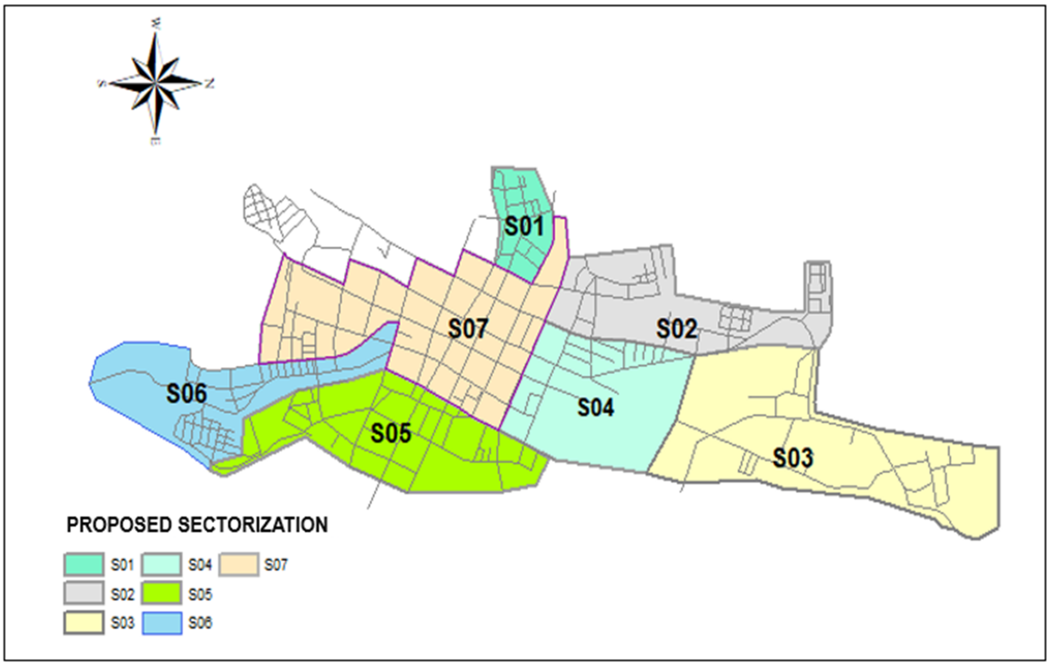

Figure 10. Current pressure of the distribution network

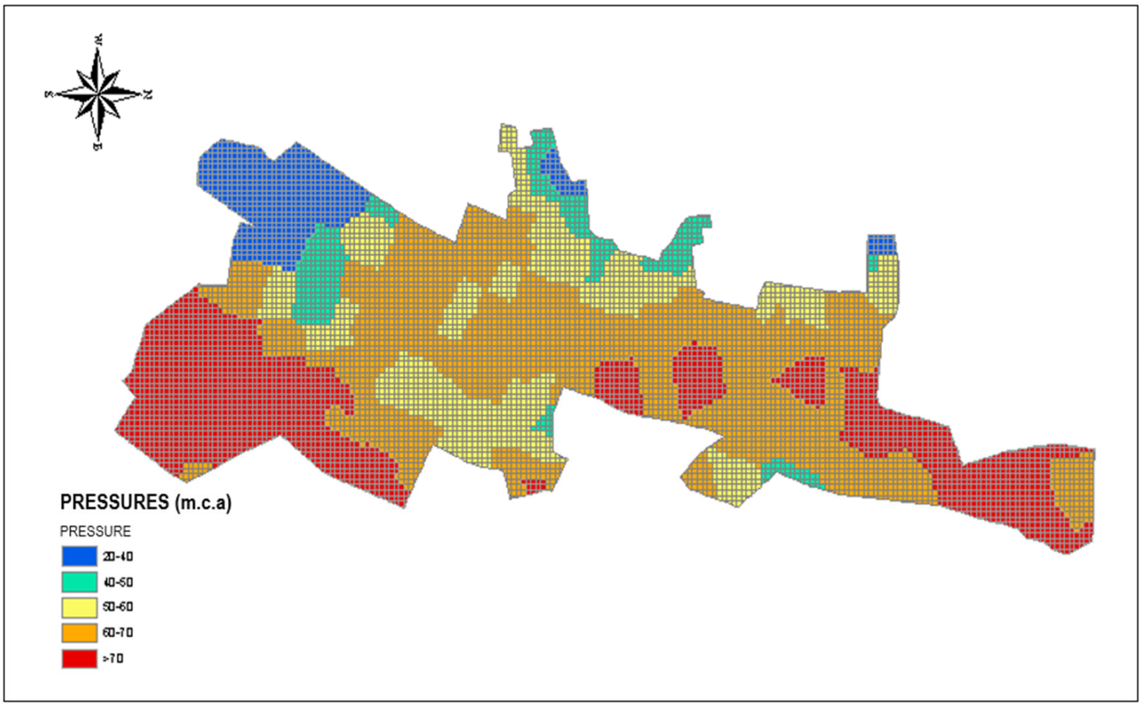

Figure 11. Pressure distribution with the proposed sectorization strategy.