Water-Loss Management under Data Scarcity

Case Study in a Small Municipality in a Developing Country

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Important note
To cite this publication, please use the final published version (if applicable).
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9   **Water losses management under data scarcity. A case study in a small municipality from a**

10   **developing country**

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76   **Abstract**

77   Urban areas are facing challenges for the provision of public services, with water scarcity arising as

78   one of the main problems. A twin track approach of supply and demand management is essential

79   and water loss management contributes to reducing water demand. However, small municipalities

80   from developing countries have technical, information and financial limitations to locate and

81   monitor water losses. This paper presents the estimation of real and apparent losses in a small

82   municipality from a developing country in a data-scarce situation. For this, several tools were used

83   allowing data integration that resulted in a water balance, from which water losses were estimated at

84   46%, and four alternatives for water losses reduction were developed. A cost-benefit analysis and

85   financial indicators were estimated for the proposed alternatives, resulting in a saving of 19% of

86   water, a payback period of 3 years and an internal rate of return of 39%. The proposed strategies

87   have potential to improve water quantity and quality, the technical stability of the system,

88   enhancing utility performance, and water security.

89   **Keywords**: apparent losses, distribution network, EPANET, geographic information systems, real

90   losses, water loss management

91
92

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

116   management of the water distribution network in the world, and constitutes a climate change

117   adaptation strategy to face climatic variability phenomena (Cavaliere *et al.*, 2017).

118   Water losses in the distribution network can be divided in real and apparent; real losses are related

119   to leaks in pipes, nodes and fittings, that can be associated to wrong connections, pipe corrosion,

120   mechanical damage due to excessive loads, excavations, soil movement, high hydraulic pressure,

121   pipe age and inadequate installation of pipes (Puust *et al.*, 2010). Apparent losses include

122   unauthorised consumption, customer meter inaccuracies; and data handling and billing errors (Al-

123   Washali *et al.*, 2016).

124   With regards to the estimation of real losses, according to Puust *et al.* (2010), most methodologies

125   related to leak management, such as Minimum Night Flow (MNF), the leak reflection method

126   (LRM) and SCADA systems can be classified as methods for evaluation, detection and control in

127   order to: i) quantify the amount of water loss; ii) identify critical leakage points; and iii) effectively

128   control the actual and future level of leaks.

129   Despite the importance of assessing losses in water distribution systems and the increasing interest

130   in the optimal control of the distribution network to improve operational performance (Sankar *et al.*,

131   2015), systems in some contexts suffer from scarce infrastructure for monitoring and measuring

132   flow and pressure in the network. The situation is even more critical in small municipalities from

133   developing countries that have limited financial resources and lack of technical and decision

134   support tools (Mazzolani *et al.*, 2017). This makes difficult to collect the information required to

135   quantify and understand the magnitude of the water loss phenomenon, assess the costs and benefits

136   of technical and managerial strategies and thus, prioritize investments (Xu *et al.*, 2014).

137   Methodologies and models for analysis, monitoring and detection of water losses in the supply

138   network have been proposed for developed countries, contributing to optimization, and improved

139   decision-making (Sharma and Vairavamoorthy, 2009). In developing countries, there are reports of

140   water loss assessment or management initiatives in Southeast Asia (Araral and Wang, 2013; van

141   den Berg, 2015) and Africa (Mutikanga *et al.*, 2009; Harawa *et al.*, 2016; Ndunguru and Hoko,

142   2016; Hoko and Chipwaila, 2017). In contrast, there is a limited number of studies focused on Latin

143   American countries. Despite the existence of some experiences, implementation of water loss

144   assessment and control in small municipalities from developing countries is scant and challenging

145   since the methodologies demand the availability of infrastructure, technical capacity and data that

146   most of the time are not available (Sharma and Vairavamoorthy, 2009; Mutikanga *et al.*, 2011). For

147   these reasons, low-cost and easy to implement systems are required to estimate water losses, plan

148   technical interventions (e.g. pressure control, renovation and rehabilitation), and allocate resources.

149   This research estimates real and apparent losses in a water system serving a small municipality from

150   a developing country, in a context characterized by limited data and deficient water availability in

151   the dry season. For this, a water balance was carried out in the distribution network, using a range

152   of techniques for data collection, processing and analysis. The data were integrated using

153   Geographical Information Systems (GIS) to determine the users' water demand. Alternatives for the

154   management of real and apparent losses were technically proposed and financially assessed.

155   **Methodology**

156   The research was carried out in three phases: i) physical characterisation of the system and water

157   demand estimation (Basic data); ii) quantification of real and apparent losses (water balance); and

158   iii) formulation and testing of water loss management strategies. Figure 1 presents the

159   methodological summary.

160   ***Description of the studied system***

161   The studied system is located in the municipality of Malaga (Santander – Colombia), which has a

162   population of 20,830, served by a water supply system with 5,251 urban customers registered by

163   March 2017, according to the records of the water service provider. These customers are linked to

164   properties classified by the local authorithy according to strata, which are categories based on the

165   socioeconomic conditions from stratum 1 to stratum 6, (i.e. 1 and 6 represent the lowest and highest

166   socioeconomic level, respectively). In Colombia, stratification is a constitutional mandate carried

167   out to charge differentially for public services (DANE, 2019).The system was divided into three

168   independent service sectors (Figure 2).

169

170   This study focused on Sector 1, with 88.8% of the system customers (4,662), being the most

171   representative of the population. Sector 1 is equipped with a bulk meter, customer meters and is

172   completely fed by only one of the two Water Treatment Plants (WTPs). Sectors 2 and 3 are smaller,

173   and have their own treatment systems (ECOCIALT S.A.S., 2014). These sectors are separate from

174   sector 1.

175   The WTP for Sector 1 provides 43.07 L/s (ECOCIALT S.A.S., 2014) and has four storage tanks

176   (2,014 m^3). There is a gravity-fed distribution network starting with 10 inch PVC transmission

177   main. There is a 10 inch Woltman bulk flow meter and the system has eight water storage tanks

178   without disinfection, that are used in times of drought.

179   For this study, due to the data-scarce situation, several assumptions were considered. These

180   assumptions are listed below and further described in the appropriate sections in the methodology:

181   •   Unbilled authorized consumption was set equal to zero since the utility established a policy

182   indicating all consumptions must be billed, regardless the type of customer.

183   •   Unauthorized consumption was considered zero in the water balance, since the utility

184   lacked information on illegal users or theft.

185 •   Real volume used to establish customer meter inaccuracies was calculated considering a

186 percentage of error in meter readings of 3.1%, based on reports from the Water and Sewerage

187 Master Plan (WSMP) (Fundación Bolivar, 2004).

188 •   This study adopted the literature values for estimating the leakage night flow. It was

189 assumed that 6% of the whole supplied population was active during the night, with a consumption

190 of 10 L/person/hour (McKenzie, 1999). In addition, it was considered that due to the lower

191 hydraulic pressure during the day, diurnal leakage was 75% of night leakage (Jiménez, 2003).

192 •   The exponent N1 used to estimate the real losses reduction was based on literature

193 recommendations: 1.5 for distribution networks from flexible materials such as PVC (Gomes, 2011)

194 and 0.5 for rigid materials as asbestos-cement (Cassa *et al.*, 2010). This approach was adopted due

195 to the lack of information such as burst frequency, required to implement more detailed Rl

196 reduction models (Sewilam and Rudolph, 2011).

197 •   Cost-benefit analysis of alternatives did not consider costs related to maintenance as there

198 was not enough technical and field data such as burst frequency, pipeline leaks, overflow of the

199 mains and general maintenance costs. The costs associated with the revenue loss caused by the

200 reduction on the actual water demand which is pressure-dependent (Kanakoudis and Gonelas, 2016)

201 were not included either.

202

203 ***Water supply system data***

204 The record of the type and characteristics of the pipes and their hydraulic accessories was updated

205 for this research, based on the review of the municipal WSMP proposed in 2004 (Fundación

206 Bolivar, 2004), complemented with records from repositioning and installation of main pipes,

207 service connections and fittings, developed in 2012 (T&MO Ltda., 2012). The information from

208   2004 and 2012 was checked, including the new network characteristics. These data were linked to

209   addresses, and an estimation of lengths, pipe diameters, fittings, and the geometric layout of the

210   distribution network was obtained. For updating the information from 2012 to 2017, a workshop

211   was developed with the distribution network operator, who through social mapping techniques,

212   completed information of the distribution networks, in relation to changes, and repairs.

213   The analysis of water demand in the system was carried out for the period between October 2016

214   and March 2017. For this, the customers' records and water consumption records were collected

215   and analysed using the providers' database. The customers' water consumption was established

216   from the assessment of the average amount charged to each subscriber, during the analysed period.

217   Since the utility lacked a GIS, an address geocoder was developed, using ArcGIS, where the

218   customers and their water consumptions were spatially located. Thus, the water demand at nodes

219   was established, as a function of the customers' location to obtain a hydraulic scenario close to the

220   conditions in the distribution network. This process included: i) determine the list of postal

221   addresses, adapt the GIS with geocoding function and have maps of the roads; ii) location of

222   addresses, which convert textual descriptions of locations into geographical entities; and iii)

223   database comparison, in which the road infrastructure information and the standardized address

224   records were related.

225   As result, the spatial location of each subscriber was obtained, and spatial relations were stablished

226   in ArcGIS (spatial join), where the network nodes were linked to all the layer attributes (i.e.

227   customers' data).

228   ***Estimation of water losses in the distribution system***

229   The estimation of water losses was developed according to two approaches: Top-down and Bottom-

230   up (Mazzolani *et al.*, 2017). The Top-down approach provides general information on the losses,

231   without differentiation between real and apparent losses. For this, hystorical records from bulk

232 meters and customers' meters are required. The Bottom-up approach allows estimation of losses

233 associated with leaks, using the MNF (Mazzolani *et al.*, 2017). For our water losses estimation, the

234 volume of real losses obtained from the Top down water balance was controlled through Bottom-up

235 calculations based on the analysis of MNF. In this regard the Bottom up approach was used as a

236 check. However, since MNF requires extensive data on the distribution network, which is difficult

237 to obtain for the present case study, several assumptions were made based on recommendations

238 from the literature and the conditions of the studied system. For the general desegregation of the

239 losses, the methodology of the International Water Association (IWA) was used (Lambert, 2002;

240 Lambert *et al.*, 2014). This methodology includes calculation or estimation of the following items:

241 1. System input volume

242 2. Authorized consumption

243 • Billed authorized consumption

244 • Unbilled authorized consumption

245 3. Apparent losses:

246 • Theft of water and fraud

247 • Meter inaccuracies

248 • Data handling errors

249 4. Real losses

250 • Leakage in transmission mains, distribution mains, reservoirs, overflows, and customer service
251 connections

252   Detailed explanation of these items can be found in Lambert *et al.* (2014), or Al-Washali *et al.*

253   (2016). The procedure to obtain the items required in the water balance methodology for the present

254   study are explained as follows:

255   ***System input volume*** (SIV) was established using historic records from volumes supplied into the

256   WTP. Due to the lack of daily continuous records during the analysed period, monthly data were

257   obtained from the summation of 448 daily records of volume delivered to the system, registered by

258   the utility, distributed according to the different months.

259   ***Authorised consumption*** (Ac) was calculated by summing ***Billed authorised consumption*** (Bac)

260   and ***Unbilled authorised consumption*** (Uac). Bac included *Billed metered consumption* (Bmc) and

261   *Billed unmetered consumption* (Buc). The former (Bmc) was obtained from working customers'

262   meters, while the latter (Buc) was obtained from customers' meters working improperly (i.e.

263   making it impossible to take actual consumption readings). For Buc, bill came from the average of

264   the six months previous records, obtained and processed from the utility database.

265   The ***Uac*** is comprised of *Unbilled metered consumption* and *Unbillled unmetered consumption*. It

266   includes consumption regarding firefighting, flushing of mains and sewers, cleaning of suppliers,

267   storage tanks, filtering of water tankers, water taken from hydrants, street cleaning, watering of

268   municipal gardens, among others, and it is typically a small component of the water balance

269   (Lambert, 2002). In this case, the utility established a policy indicating all consumptions must be

270   billed, regardless the type of customer. Therefore, Unbilled authorized consumption was set equal

271   to zero.

272   ***Water losses (L):*** was calculated as the difference between SIV and Ac (Equation 1). Such losses

273   are classified as ***Apparent losses*** (*Al)* and ***Real losses*** (*Rl*) (Equation 2).

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

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

276   Regarding Al, these are divided in *Unauthorized consumption (Uc)*, *Data handling and billing*

277   *errors* (*Dhbe*) and *Customer meter inaccuracies* (*Cmi*):

278
$$Al(m^3/month) = Uc + Dhbe + Cmi \qquad (3)$$

279   With regards to the *Uc*, the utility lacked information on illegal users or theft, for this reason, this

280   item was included as zero in the water balance. In relation to Cmi, customers' meters tend to under-

281   register consumption over time (Al-Washali *et al.*, 2016). This item was obtained from the real

282   volume of consumption, calculated using the monthly readings of the customers' meters working

283   properly, and the the typical measurement error of the used meters, i.e. as follows:

284
$$Rv\ (m^3/month) = Bmc\ *\left(1 + \frac{\%\ error}{100}\right) \qquad (4)$$

285   Where, *Rv* is the real volume from customers with readings and *Bmc* is the billed volume for

286   customers with meter readings. The percentage of error was assumed as 3.1% based on reports from

287   WSMP (Fundación Bolivar, 2004). Thus, *Cmi* were estimated by subtracting the monthly billed

288   volume of customers with readings from the real monthly volume for these customers, i.e. as

289   follows:

290
$$Cmi\ (m^3/month) = Rv - Bmc \qquad (5)$$

291   Regarding Dhbe, customers with consumptions billed as the average of historical consumption were

292   identified in the utility database. This situation was associated to poorly functioning customers'

293   meters, which make impossible their monthly readings to be made. Likewise, the causes that

294   motivate this situation and the status of the customers' meters were recorded. Additionally, the

295   average consumption of a customer in each stratum was determined, analyzing the utility's

296   database. For this system, each customer in socioeconomic stratum 1 had an average consumption

297   of 7.2 m³/month. This value was assigned to all the customers who had billed consumptions

298   obtained as the average of historical consumption, resulting in an estimate of the total volume that

299   should be billed to these customers according to consumption per stratum (TVb) (Equation 6).

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

301 Where Na_vc is the number of customers with average consumption, and a_vc is the average

302 consumption from the customers with readings. Then, the volume billed to customers with average

303 historical consumption $Vbca_vc$ was subtracted from TVb (Equation 7), obtaining the Dhbe volume.

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

305 Finally, **Rl** were estimated. These losses included: a) *Leakage on transmission or distribution*

306 *mains*; b) *Leakage on service connections*; and c) *Leakage and overflows on utility's storage tanks*.

307 **Rl** were calculated by subtracting **Al** from the volume of **L** (Equation 8):

308

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

310 To check **Rl** obtained from Equation 8, the MNF, which has been widely used as the most accurate

311 method to assess **Real losses,** was adopted (Babić *et al.*, 2014). This method is typically used in a

312 District Metered Area (DMA), a hydraulically isolated part of the network, with a permanent

313 boundary, usually defined by the closure of valves, in which the quantities of water entering and

314 leaving the area are metered, and that include between 500 and 3000 customer service connections

315 (Karadirek *et al.*, 2012). This methodology was applied to the study of Sector 1, despite having

316 4662 connections, which is above the recommended range, since this was the sector that provided

317 the other recommended characteristics (hydraulic isolation, permanent boundary, and metering).

318 MNF considers that leakage in the supply sectors can be estimated when the flow is at its low level

319 (i.e. 1:00AM - 4:00AM), when customer demand registers the minimum value, and thus, leakages

320 are the main component of the flow (Cheung *et al.*, 2010). The leakage flow was estimated using

321 Equation 9 (Tabesh *et al.*, 2009):

322

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

324   Where Qnf is the net night flow (leakage), $Qmnf$ and $Qlnf$, are the minimum night flow and the

325   legitimate night flow, respectively. To obtain $Qmnf$, flow measurement campaigns were

326   undertaken at the outlet of the treatment plant between 1:00AM and 3:00AM. To obtain an accurate

327    $Qlnf$ rigorous field investigations need to be undertaken to ascertain the number of possible night

328   users (Al-Washali $et~al.$, 2016). When these studies are not possible, literature values can be used.

329   This study adopted the literature values where 6% of the whole supplied population is active during

330   the night, with a consumption of 10 L/person/hour (McKenzie, 1999)).. In addition, it was

331   considered that due to the lower hydraulic pressure during the day, diurnal leakage (Qdl) will be

332   75% of night leakage (Jiménez, 2003) (Equation 10).

333

334    $$Qdl~(m^3/hour) = 0.75 * Qnf \quad (10)$$

335   The consumption pattern for the system was considered based on the modulation curve (Blanco and

336   Celis, 2017) . For the low consumption hours, the total leakage was estimated using the

337   measurement of the night flow and for the diurnal hours, it was estimated considering the

338   percentage in relation to the night leakage.

339   *Alternatives for water loss reduction*

340   The information from the water balance allowed proposing strategies to improve the performance of

341   the water supply system, including activities for the control and reduction of apparent and real

342   losses.

343   ***Alternatives to reduce Apparent losses***

344   Customer meter renovation and detection of illegal users were proposed. Customer meter

345   renovation could contribute to reducing the inaccuracies associated to the aging of these devices,

346   together with the low sensitivity at the start, which are characteristic of some meters. In this study,

347   customers with incorrectly working meters were identified, using georeferenced data obtained in the

348   first stage of the study, and a map was prepared with the location of these customers. Regarding

349   strategies for detection of illegal users, this study identified users with consumption below 25% of

350   the average consumption within the analysis of the historic records of legal users, in each

351   socioeconomic strata. These users were spatially located, providing the utility with tools to

352   corroborate the composition and occupancy, consumption records, meter and service connection

353   status (Jiménez, 2003).

354   ***Alternatives to reduce Real losses***

355   To tackle Rl in this system, Pressure Management (PM) was proposed. PM keeps the pressure

356   within a desirable range throughout the supply period (Haider *et al.*, 2019), and it is recognized as

357   one of the most efficient and cost-effective measures available to water utilities (Nicolini and

358   Zovatto, 2009) to reduce leakage and bursts on mains, limiting water losses (Darvini and Soldini,

359   2015). For this, the physical configuration of the network was obtained from the developed GIS,

360   and integrated through a model built using the freely available hydraulic network simulation

361   software EPANET (Rossman, 2000).

362   For model building, data from ArcView and EPANET were linked using the GISRed extension,

363   intended for water distribution network modelling and calibration (Alzamora *et al.*, 2004). This

364   linkage automatically provided a characteristic network topology in EPANET (e.g. pipe diameters,

365   coordinates of nodes, pipes, pipe lengths), which was complemented with the fittings (e.g. control

366   valves, tanks, reservoirs) (Motiee *et al.*, 2007). In addition, a consumption modulation curve was

367   prepared (Blanco and Celis, 2017) to obtain the behavior of the hourly population water demand.

368   A preliminary calibration process for the hydraulic model was carried out, in which pressure values

369   measured in the network were compared to the pressures provided by the model in different

370   locations. This was done for a typical day and for a low demand day. This process showed

371 variability between the two datasets, but this variability was constant in different network locations.

372 Blanco and Celis (2017) show the comparison between these values. Although the calibration

373 process was not developed exhaustively, the hydraulic model allowed identifying high and low

374 pressure zones in the system. These zones were consistent with pressures measured in the network.

375 With regards to the prioritized renovation of pipes, five criteria regarding pipe characteristics were

376 considered: age, break history, diameter, material and average pressure (Tlili and Nafi, 2012). These

377 data were spatially located and analysed using GIS to identify the pipes that under the selected

378 criteria had greater tendency to suffer breaks or structural damage.

379 A search using ArcMap was conducted according to the criteria defined and clusters of similar

380 characteristics that showed critical conditions were identified and, priority replacements were

381 defined to improve the system performance.

382 Sectorization of the system was proposed according to hydraulic criteria: i) range of pressure

383 between 15 and 60 m (MVCT, 2017), looking for smaller sectors having different pressure regimes

384 (Nicolini and Zovatto, 2009); ii) areas between 5 and 15% of the total service area (i.e. to control

385 infrastructure and leaks); iii) similar topographic conditions, regular shapes, boundaries defined

386 considering geographical features (e.g. canals, rivers, waterways); and iv) similar socioeconomic

387 conditions and customer category (Jiménez, 2003). Having analysed the pertinent criteria, the

388 principal pipe to supply the different areas and the districts were defined, checking the boundaries

389 and the effectiveness of the pressure reduction achieved, using the EPANET hydraulic simulation

390 model to check the hydraulic performance of the proposed changes.

391 ***Financial assessment of alternatives***

392   A cash flow analysis was carried out for three different alternatives to asses their financial

393   feasibility: Alt1 customer meter renovation, (reduction of Al), Alt2 pipeline renovation and

394   sectorization (reduction of Rl), and Alt3 simultaneous implementation of Alt1 and Alt2.

395   For Alt2 and Alt3, the reduction of Rl associated to PM interventions was established using a

396   simple pressure relationship (Equation 11) proposed by Thornton (2003) and widely used in the

397   literature (Vicente *et al.*, 2016).

398
$$\left(\frac{L_o}{L_1}\right) = \left(\frac{P_0}{P_1}\right)^{N1} \quad (11)$$

399   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

400   N1 is the leakage exponent that shows interdependency of leakage on pressure. Field and

401   laboratory studies have found that the exponent N1 lies within the range of $0.5 – 1.5$ (Thornton and

402   Lambert, 2005) . For the current study, N1 was set at 1.17 as a result of a weighted average

403   corresponding to the proportion of asbestos-cement (AC) and PVC pipes in the network, taking N1

404   as 1.5 for PVC (Gomes, 2011) and 0.5 for AC (Cassa *et al.*, 2010). This approach was adopted due

405   to the lack of information such as burst frequency, required to implement more detailed Rl

406   reduction models (Sewilam and Rudolph, 2011).

407   Finally, a cost-benefit analysis was prepared for a 15-year period, recommended lifetime for meters

408   and pipelines (Sewilam and Rudolph, 2011) and used in other studies (e.g. Kanakoudis and

409   Gonelas, 2016). The annual income of water utilities, considering the reduction of SIV, was

410   obtained multiplying the saved water volume by the unsubsidized fee charged to the users, which

411   represents the avoided cost of energy and water treatment. This value includes an annual inflation of

412   4.16%, according to the average change over the last 10 years on the consumer price index (CPI) in

413   Colombia (DANE, 2018). The costs involved in the financial assessment were initial investments at

414   year zero related to: for Alt1, replacement of poorly functioning meters (purchase, transport and

415   installation of new meters); for Alt 2, replacement (purchase, transport, and installation of pipes,

416   fittings, pressure valves, and bulk meters) of pipes operating under the most critical conditions that

417   could generate leaks. The cost of replacing the pavement of roads was also considered for Alt 1 and

418   Alt 2. Costs related to maintenance were not included as there was not enough technical and field

419   data such as burst frequency, pipeline leaks, overflow of the mains and general maintenance costs.

420   The costs associated with the revenue loss caused by the reduction on the actual water demand

421   which is pressure-dependent (Kanakoudis and Gonelas, 2016) were not included either. The

422   benefits considered on the financial assessment were limited to the water savings potentially

423   achieved with the implementation of the different alternatives, which results in reduced SIV. The

424   indicators: net present value (NPV), using a discount rate of 3.51% as recommended for

425   environmental projects in Colombia (Correa, 2009); payback period (PP), to measure how long it

426   will take to recover the initial investment; and internal rate of return (IRR) (the discount rate that

427   produces a level of the NPV equal to zero) were estimated.

428   **Results**

429   ***Characterisation of the distribution network***

430   It was found that distribution network was made of AC -10,497 m (33%)- and PVC pipes -21,737 m

431   (67%). Pipe diameters were between 2" and 10", and customer service connections had diameters

432   between 1" and 1.5". The network was complemented with elbows (222), reductions (48), tees

433   (446), crosses (82), hydrants (35), and isolation valves (157). There were not records of air valves,

434   pressure reducing valves, or purge valves (see Figure 3).

435

436   Table 1 presents the distribution of customers according to category and their monthly average

437   consumption. Residential customers were 88.8% of the total customers and had the highest monthly

438   *Bac* (83.2%).

439 The majority of customers consumed between 10 and 20 m^3/month (see Table 2), which is

440 consistent with the Colombian technical regulation for municipalities with this population size (i.e.

441 15 m^3/customer/month) (MVCT, 2017).

442

443 Figure 4 shows the spatial location of all customers. The database included customer name, monthly

444 consumption, customer category, stratum, and customer meter status. A spatial relation was

445 established between georeferenced customers and network nodes. This relation allowed stablishing

446 the water demand at each node, which was approximately 186 m^3/month (i.e. 0.072 L/s). This

447 demand was obtained as the monthly average for the analysis period.

448 ***Water balance for the distribution system***

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

450

451 *Ac* on average was 63,624 m^3/month. With regards to *Bmc*, from all the billed consumption, a

452 proportion was from customer meters working properly. Table 4 includes the distribution of

453 customers with records and their consumption, where the average measured volume was obtained

454 for the analysis period, and it was approximately 44,443 m^3/month.

455 The *Buc* was 19,182 m^3/month, which indicates that, from *Ac*, around 30% was billed with average

456 consumption values. As explained in the methodology section, since all the customers in this system

457 were billed, regardless of their category, *Uac* was zero (0).

458 The average monthly volume of losses in the system was estimated at 55,358 m^3/month, equivalent

459 to 46% of the *SIV*.

460   In relation to Al, those associated with customer meter inaccuracies were established with a volume

461   of 1,378 m³/month. Al due to Dhbe, were associated to 1,331 customer meters poorly functioning,

462   from which 1012 were stopped, 108 needed readings to be checked, 122 lacked the meter, 9 meters

463   were covered, 4 had broken tachometer, 71 were in poor conditions, 2 were inverted and 3 were cut.

464   Synthesizing, 76% of customer meters were working incorrectly. The volume loss due to customer

465   meter inaccuracies is detailed in Table 5. Besides, customers with uninhabited households, which

466   theoretically should not have consumption values but did, were considered. Likewise, lost volumes

467   linked to customers with working meters registering zero consumption during all the analysed

468   period were included.

469   The negative value on the covered meter category means that a quantity above the estimated

470   consumption of these customers were charged. Thus, taking to account, losses due to Dhbe (2,096

471   m³/month) and records of the billed volume for users with inhabited premises (i.e. 927 m³/month),

472   the value of Al due to Dhbe was 3,024 m³/month. Consequently, the total Al were 4,402 m³/month.

473   Finally, real losses were estimated at 50,956 m³/month. Table 6 presents a synthesis of the water

474   balance for the analysis period.

475   ***Real losses in the distribution system***

476   Based on the criteria and steps detailed in the Methodology, the MNF analysis provided a value for

477    $Qmnf$ of 95 m³/hour. Taking into account the number of customers (4,662) and the population

478   (16,783 inhabitants) in the analysed sector (Sector 1, 88.8% of the total population) (ECOCIALT

479   S.A.S., 2014), legitimate night users were estimated at 1,007 people (6% of the population). The

480   consumption in the system during the hours of minimum demand, using the reference value of 10

481   L/percapita/hour was 10.07 m³/hour, and provided a Qnf of approximately 84.9 m³/hour.

482 According to the modulation curve of consumption, the minimum consumption occurred during the

483 period between 21:00 and 5:00 hours, being the night leakage flow volume 679 m^3. For the

484 remaining time (between 5:00 and 20:00), the leakage flow was assumed at 75% of the night

485 leakage, 64 m^3/hour. Thus, the leakage volume estimated for the diurnal hours was 1,019 m^3. This

486 way, total leakage in a typical day was estimated for a daily leakage flow of 1,699 m^3/month. This

487 information was extrapolated for a monthly period, to estimate the volume of technical losses or

488 real losses in the system, that was found as 50,959 m^3/month. This value was similar to that

489 obtained from the water balance (50,956 m^3/month).

490 Finally, the ratio of *SIV* and *L* was established for the analysis period at 46%, which is a value

491 significantly above the standard set by the National Authority of Water and Sanitation from

492 Colombia (25%) (MVCT, 2017).

493 ***Alternatives for water loss reduction***

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

495 ***<u>Renovation of customer meters</u>***

496 The renovation of customer meters was identified as a potential alternative to improve system

497 performance and data accuracy to assist with further modelling. Figure 5 shows the location of the

498 1,331 devices with problems, prioritized for a renovation program.

499 ***<u>Detection of water theft</u>***

500 Figure 6 includes the spatial location of the customers with consumption less than 25% of the

501 average per category, excluding from this group, customers with low consumption due to poorly

502 functioning meters. According to these criteria, 274 customers could be potentially participating in

503 water theft. From this, 125 were stratum 2 and 83 were commercial customers.

504   ***Pressure management***

505   The hydraulic model in EPANET allowed identifying pipes in the distribution network with issues

506   of pressure or velocity (Figure 7).

507   Pipes were selected and clustered in relation to the most critical conditions that could generate

508   breaks and leakage and thus, could be prioritized for renovation: a) pipe age: above 40 years; b)

509   break history: yes; c) pipe diameter: 2 to 6 inches; d) material: AC; and e) average pressure: less

510   than 15 m and higher than 60 m. Pipes with these characteristics had a total length of 1,526 m

511   (Figure 8).

512   Further to this, sectorization of the distribution network was carried out considering the criteria of

513   reducing pressures, and defining areas with similar hydraulic characteristics (e.g. pressure, velocity,

514   topography). The proposal of pressure areas includes the installation of isolation valves, bulk

515   meters, and pressure reducing valves. Figure 9 shows the improvement proposal selected. Table 7

516   describes the proposed PM interventions.

517

518   With the proposed sectorization, the current maximum pressure in the low demand hours will

519   reduce from 101 m to 71 m, and the average pressure will reduce from 64 m to 44 m. Figure 10 and

520   Figure 11 provide pressure maps, depicting the pressure distribution at the time of the study and the

521   pressure with the sectorization.

522   ***Financial assessment of the alternatives***

523   Table 8 summarizes the cash flow projection for a 15-year period after the implementation of the

524   different alternatives proposed (Alt 1, Alt 2 and Alt 3). Each different alternative results in a reduction

525   of SIV, when compared to the initial state. For the financial analysis of Alt1, the replacement of the

526   1331 customer water meters was considered, presuming a total reduction in Al of 4,402 m^3/month.

527 This assumption was made because there was not a reliable database that included information such

528 as the age of the water meters, and their performance in terms of water consumption under-

529 registration. These data are usually collected with constant monitoring of the water meters conditions,

530 through failure patterns and testing. Ideally this information would allow an accurate calculation of

531 the water losses reduction. Lack of information has been a common factor in other studies from

532 developing countries (Couvelis and van Zyl, 2015). However, the initial total Al reduction assumption

533 could be valid since this volume (3.7%) represents only a 8% of the total water losses of the system

534 (46%).

535 In Alt2, the replacement of 1,526 m of existing AC pipelines for new PVC pipelines (typically used

536 in water systems from developing countries), and the installation of valves and flow meters to carry

537 out the sectorization were considered. As a result, the average system pressure drops from 64 m to

538 44 m, and given the initial real losses $L_0 = 50,956$ (42.86%) m^3/month, applying Equation 11, a L_1

539 value of 32,817 (27.58%) m^3/month was obtained, giving a 15.24% of loss reduction. This is a

540 conservative value of Rl that would still be above the standards according to Colombian and

541 International regulations. As explained before, Alt3 integrates Alt1 and Alt2.

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

543 cash flow.

544

Discussion

546 Losses in the water distribution system were estimated at 46%, higher than the standard set by the

547 Colombian regulation (25%) (MVCT, 2017), but consistent with typical values from Colombia,

548 which are around 43% (DNP, 2017), Latin America and The Caribbean (40 – 55%) (Berg, 2008)

549 and for developing countries (40 – 50%) (Kingdom et $al.$, 2006). Real losses were 92% of the total

550   losses, a value considerably above than that reported for developed countries such as France (25 -

551   50%) (Garcia and Thomas, 2003), Germany (5%) and Bulgaria (50%) (Egenhofer *et al.*, 2012).

552   Concerning apparent losses, it was proposed that the renovation of customer meters and identifying

553   areas with greater problems for service monitoring and the detection of potential illegal users could

554   be further analysed to discern the causes of their low consumption. Despite the values found, the

555   estimation of apparent losses in the water balance method has limitations, since it depends on

556   several assumptions that are not always applicable to systems in developing countries, as well as the

557   lack of a more objective methodology (Al-Washali *et al.*, 2016). This is an aspect that must be

558   refined and further studied. For example, in this case, illegal users were not considered in the water

559   balance due to lack of data, and this could be an important component of losses in developing

560   countries (González-Gómez *et al.*, 2011), where levels of 10% billed water have been

561   recommended to be used for the estimation of this component (Mutikanga *et al.*, 2009).

562   In relation to activities to control and reduce real losses, rehabilitation of pipes is one of the most

563   important factors influencing the water industry worldwide (Cavaliere *et al.*, 2017). In this research,

564   a prioritized rehabilitation of the pipes with the most unfavourable operational conditions (pressure,

565   diameter, damage records, material and age) was proposed. For instance, although PVC pipes were

566   dominant (67%), there was an important proportion of AC pipes (33%), which represent a public

567   health risk (Andersen *et al.*, 1993), and are more likely to break (Wang and Cullimore, 2010) (e.g.

568   37% of water losses were due to leaks in AC pipes in the Napoca municipality (Romania)

569   (Așchilean *et al.*, 2017). Despite the high investment costs associated to pipe rehabilitation, in the

570   long term, this can represent a reduction in the variable costs associated to the decrease in the

571   energy consumption and repair of social damages. This water loss strategy was financially assessed

572   as part of this study together with other Pressure Management interventions (Alt2), providing an

573   IRR of 50% and PP of 3 years. This is a critical strategy to contribute to sustainable urban

574   development, and can prevent intermittent water supply, degradation of water quality and higher

575   operational costs for service providers (Tlili and Nafi, 2012).

576   Considering that the majority of losses in this system were associated to leakage and due to the

577   direct relation between flow and pressure, the implementation of a hydraulic sectorization was

578   proposed as an alternative with high potential to reduce real losses, due to the ability to control and

579   manage pressure by implementing districts in the distribution network (Aldana, 2017). This

580   alternative can be complemented by installing fittings such as pressure reducing valves, isolating

581   valves and bulk meters (Samir *et al.*, 2017). This is recognized as a popular and effective strategy,

582   and has been implemented in urban cities in Colombia, such as Bogotá, achieving reductions in

583   losses from 48% to 22%, associated to the decrease on pressure and leakage (Saldarriaga and Salas,

584   2003).

585   The financial analysis performed, despite being based on several assumptions and not considering

586   costs such as maintenance and revenue loss caused by the reduction on the pressure-dependent

587   component of water demand (e.g. (Kanakoudis and Gonelas, 2016)), it is a starting point for

588   improved decision making. The results obtained are appealing for the utility managers, since the

589   proposed alternatives generate a positive net cash flow from year 3 to 5.

590   Table 9 compares financial indicators, from different water losses reduction projects carried out in

591   developing countries. The results show auspicious financial feasibility in terms of PP, with values

592   ranging from 2 to 10 years.

593   By comparing the results of this study with those reported from systems in other developing

594   countries, the scarce representation of small utilities is evident (most studies are from systems

595   serving populations above 50,000 people). However, in all cases Payback Periods are less than 10

596   years. The difference among cases in the % of *SIV* reduction, which varies from around 7 to 33%,

597   could be associated to the infrastructure, methodologies and assumptions in each study. Even when

598   the accuracy of the results from this study can be improved with future research, this attemp helped

599   to identify needs on information, infrastructure, monitoring, maintenance and administration to

600   improve the understanding and quantification of the water losses magnitude and its components. In

601   addition, progressing on environmental valuation associated to water losses due to leakage, should

602   start to be included in these analysis (Xu *et al.*, 2014).

Conclusions

604   Research presented in this paper addressed water scarcity in a water system from the perspective of

605   demand, which is opposite to the supply perspective, typically adopted in small-municipalities from

606   developing countries, due to the lack of data, technical capacity and political will. For this, a Water

607   Balance was carried using the IWA methodology, complemented with MNF analysis to obtain

608   values of water losses from two approaches (Top-down and Bottom-up). The use of these

609   recognized, standaridised and widely adopted methodologies allowed benchmarking, which is a

610   valuable improvement tool.

611   The study case had most of the characteristics of systems from small utilities in developing

612   countries, which make managers believe the water loss problem is impossible to address, leading to

613   inaction: poorly structured and maintained network; insufficient information on pipe characteristics,

614   age, valve locations, connections, and flows; lack of modern tools and techniques for leakage

615   detection and control; outdated and uncomplete map; deficient metering; and lack of flow and

616   pressure monitoring. Despite these challenges, water loss assessment methodologies were used,

617   providing results on the water balance components that increase system knowledge and help to

618   devise strategies to improve the information on the system and the level of water loss.

619   Water Balance and MNF analysis are commonly used in systems from developed countries or large

620   cities from developing countries, which have in place updated information on the distribution

621   network, commercial databases regarding customers, GIS, and online schemes to capture

622 information such as flows and pressures at different locations. To overcome the lack of most of this

623 information in the system under study, a variety of methdologies and tools were used. In particular,

624 GIS, with its GisRed extension, allowed optimizing activities in the distribution network modelling,

625 using the maps from the distribution network, to establish the nodes. In addition, GIS was used to

626 estimate the nodal demand through the preparation of an address geocodifier, which allowed spatial

627 location of each customer and from allocation of customers' demand to different areas related to the

628 nodes defined in the distribution system. Therefore, this research provides a reference for small

629 utilities to approach water balance studies when the basic information has to be collected.

630 Results highlighted estimated water losses, which were around 46%, a higher value compared to

631 what is recommended by the Colombian standards, and the goal for developing countries. However,

632 it was consistent with values found in distribution networks of capital cities from developing

633 countries. The results highlight the importance of addressing leakage, which in this case, was 92%

634 of the real losses, for which pressure management can be an effective solution, since high pressures

635 are strongly linked to breaks and thus, water losses. The process developed shows that it is possible

636 to develop this type of research even in small and scarce-data systems, since information gaps can

637 be progressively filled, and such approaches are the basis of informed decision-making under

638 uncertainty that can lead to improvements in service provision and reducing water scarcity.

639 Furthermore, the alternatives considered for water loss control are promising in financial terms,

640 leading to the rapid recovery of investments.

641 **Data Availability**

642 Data, models and code generated and used during the study may be available from the

643 corresponding author by request on a case by case basis.

644 **Acknowledgements**

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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) [m³/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

829 Note: Stratum 1: 979 customers (consumption 12,576 m³/month); Stratum 2: 2,581 customers (consumption 33,251
830 m³/month); Stratum 3: 573 customers (consumption 7,024 m³/month); Stratum 4: 7 customers (consumption 86 m³/month).
831 In Malága there are no customers in stratum 5 and 6.
832 Total refers to the total water consumption in m³/month of the population according to the average consumption in each
833 customer category.

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

Range average consumption [m³/month]	N° customers	%	% Acum. customers	Total water consumption [m³/months]	%	% Cummulated. [m³/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

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Table 3. System input volume per month

Month	System Input Volume (SIV) [m³/month]	Authorised consumption (Ac) [m³/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

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837   **Table 4.** Authorised consumption according to customer category and stratum

Category	Bmc [m³/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

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Table 5. Volume of losses due to meter functioning issues

Customer meter status	Estimated real volumes [m³/month]	Billed volume [m³/month]	Losses [m³/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

Authorised consumption (Ac) (63,624 m³/month)	Billed authorised consumption (Bac) (63,624 m³/month)	Billed metered consumption (Bmc) (including water exported) (44,442 m³/month)	Billed	Revenue water
		Billed unmetered consumption (Buc) (19,182 m³/month)		
	Unbilled authorised consumption (Uac)	Unbilled metered consumption (Umc) (0 m³/month)	Commercial losses	
		Unbilled unmetered consumption (Uuc)		

System Input Volume (SIV) (118,982 m³/month)		(0 m³/month)	(0 m³/month)	Non-revenue water
		Unauthorised consumption (Uc)	(n.e., assumed 0 m³/month)	
	Water losses (L) (55,358 m³/month)	Apparent losses (Al) (4,402 m³/month)	Customer metering inaccuracies (1,378 m³/month)	
			Data handling and billing errors (Dhbe) (3,024 m³/month)	
		Real losses (Rl) (50,956 m³/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	

844   Note: n.e: not estimated

845   **Table 7.** Requirements for the subsectors proposed for pressure management in the distribution
846   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

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

854   **Figure 1**. Methodological summary

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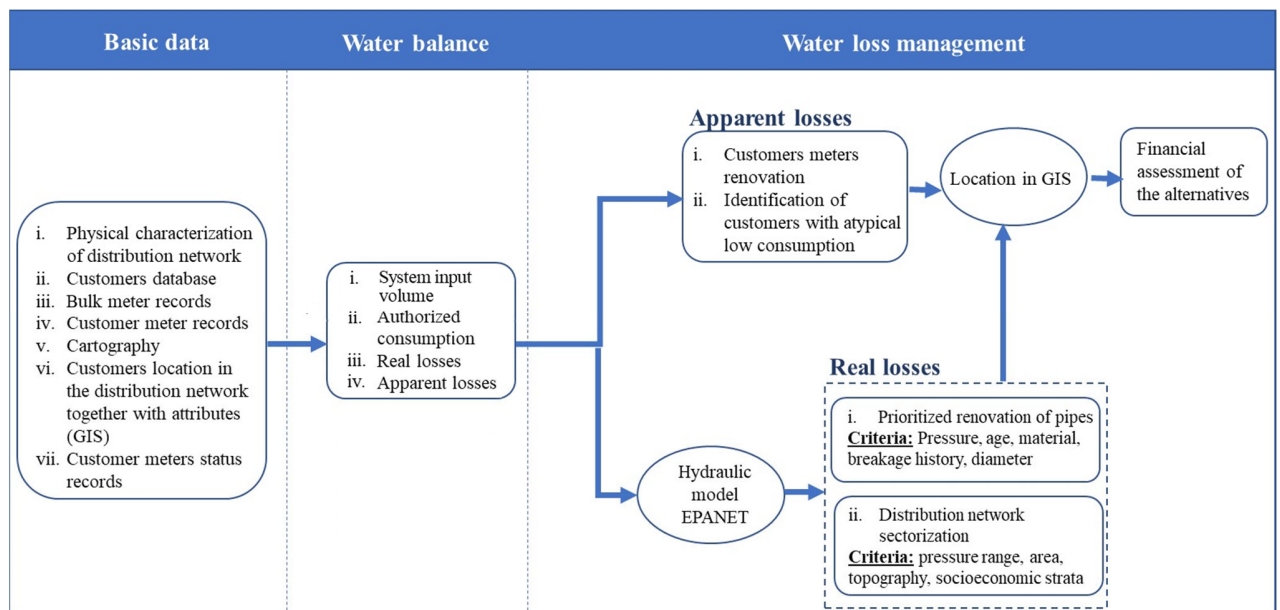
859   **Figure 2**. Sectors of the water distribution network for Malaga municipality

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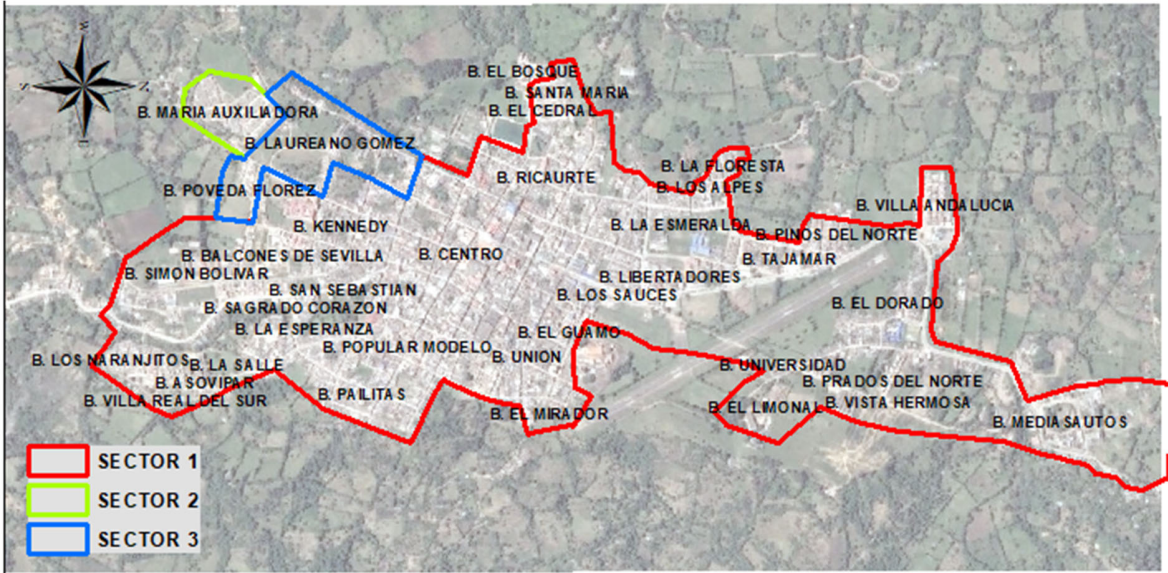
861   **Figure 3.** Pipes and valves in the distribution network

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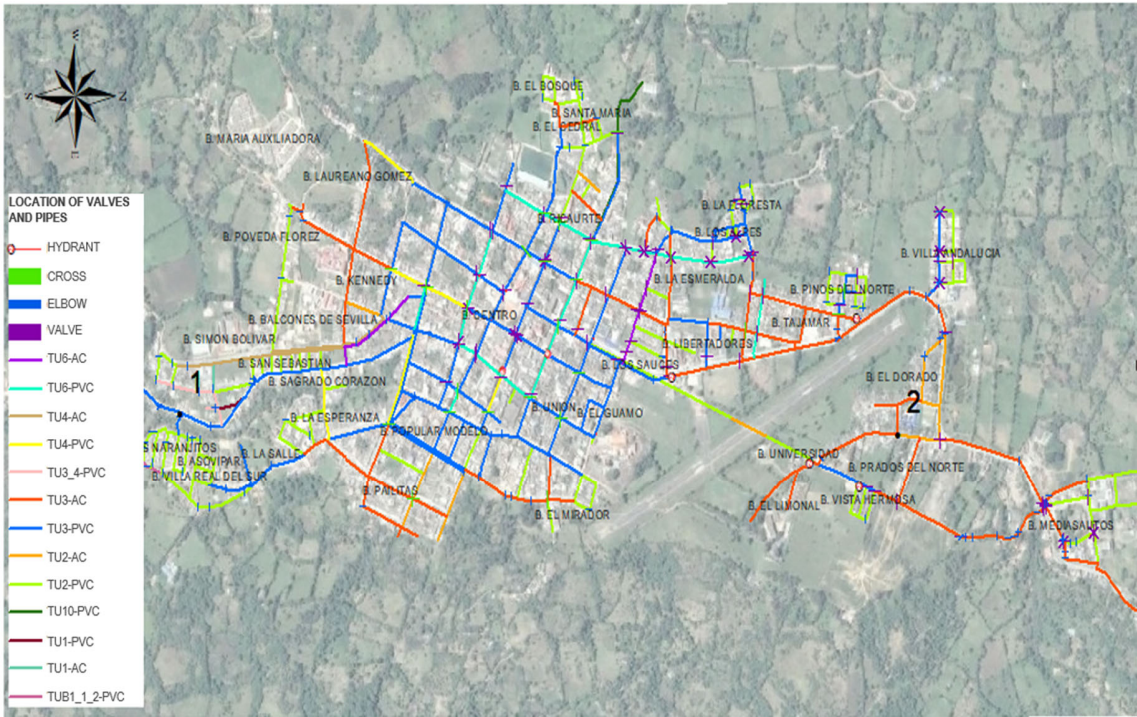
864   **Figure 4**. Georeferenced customers in the water supply system
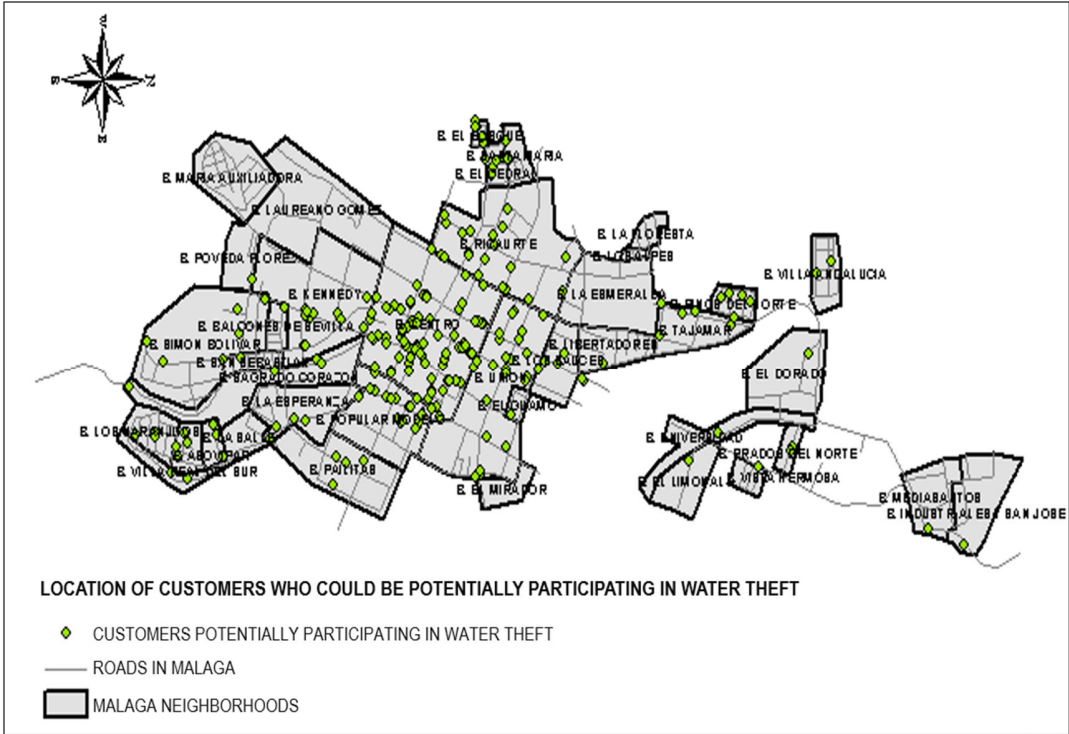

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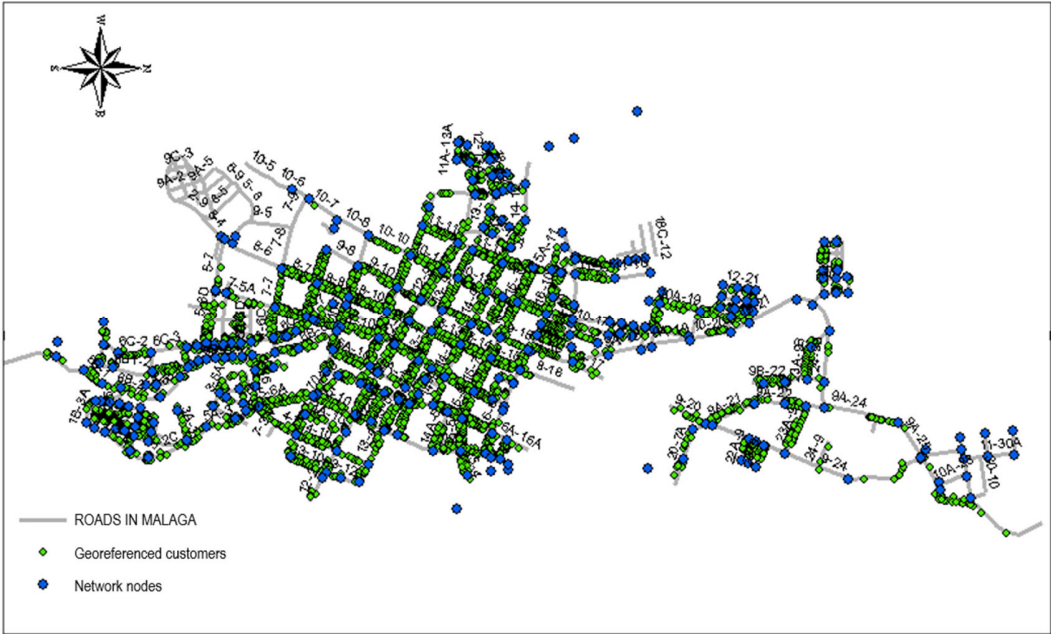
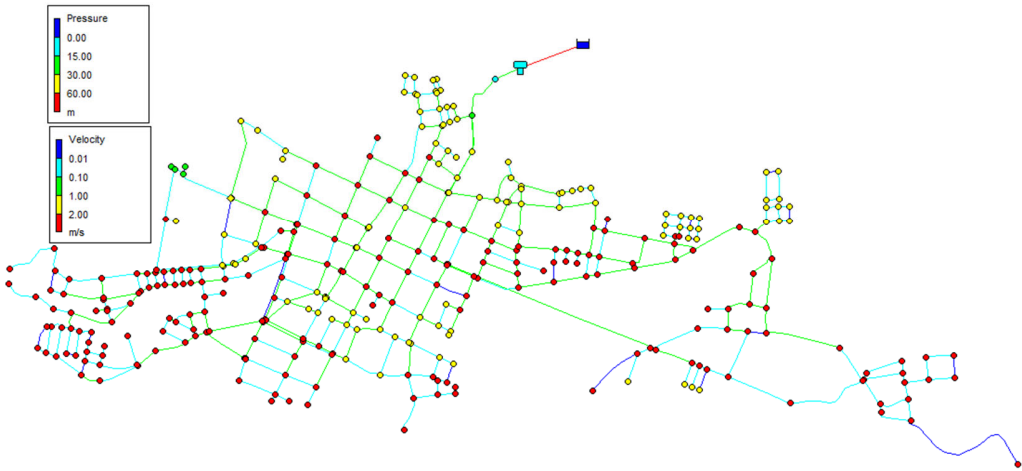866   **Figure 5.** Spatial location of customer meters working incorrectly

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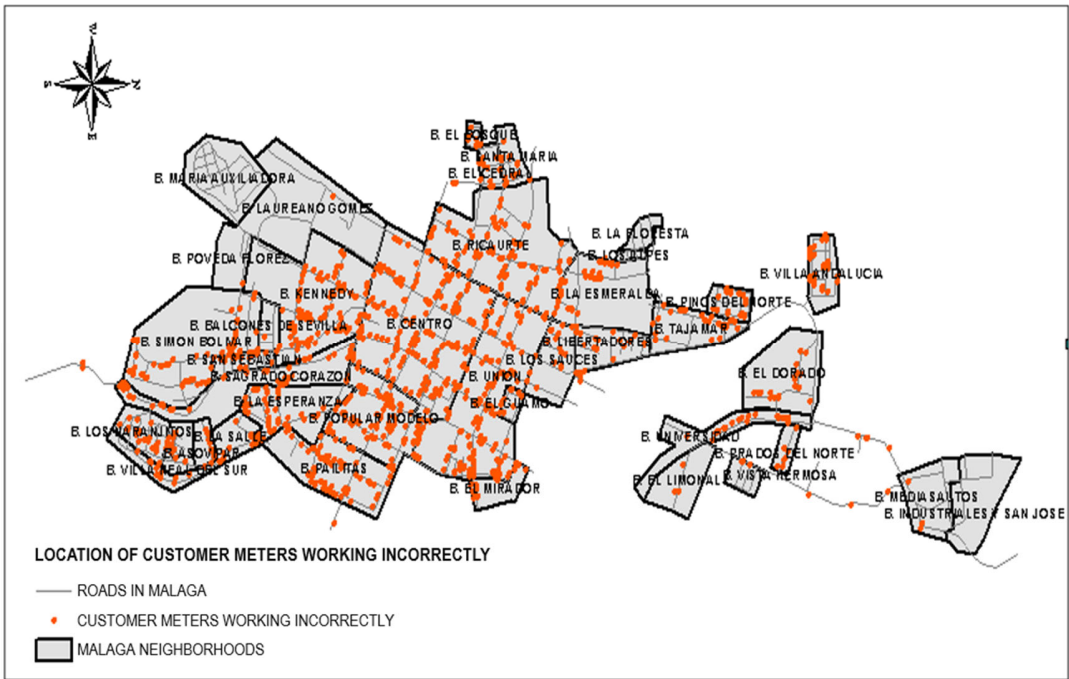
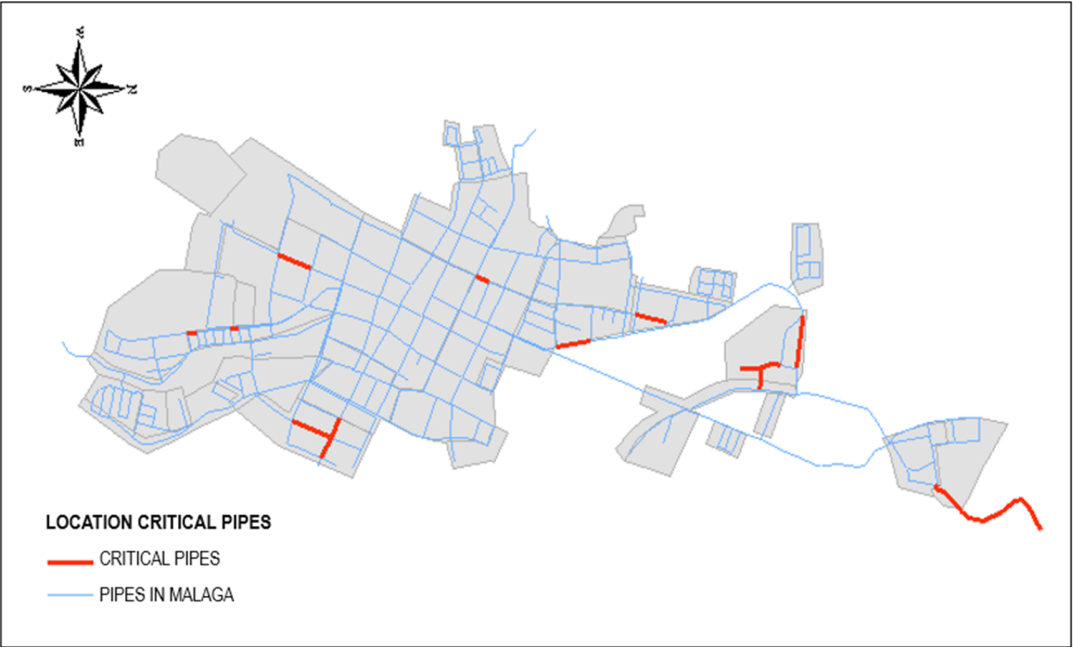869   **Figure 6.** Spatial location of customers who could be potentially participating in water theft

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871   **Figure 7**. Hydraulic modelling of the distribution network
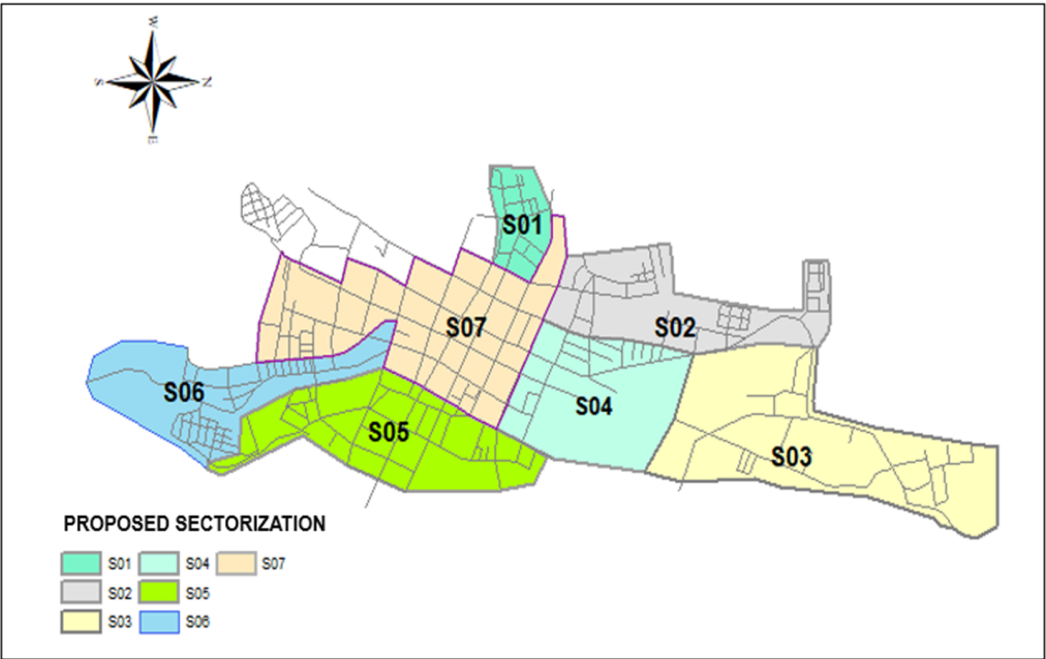

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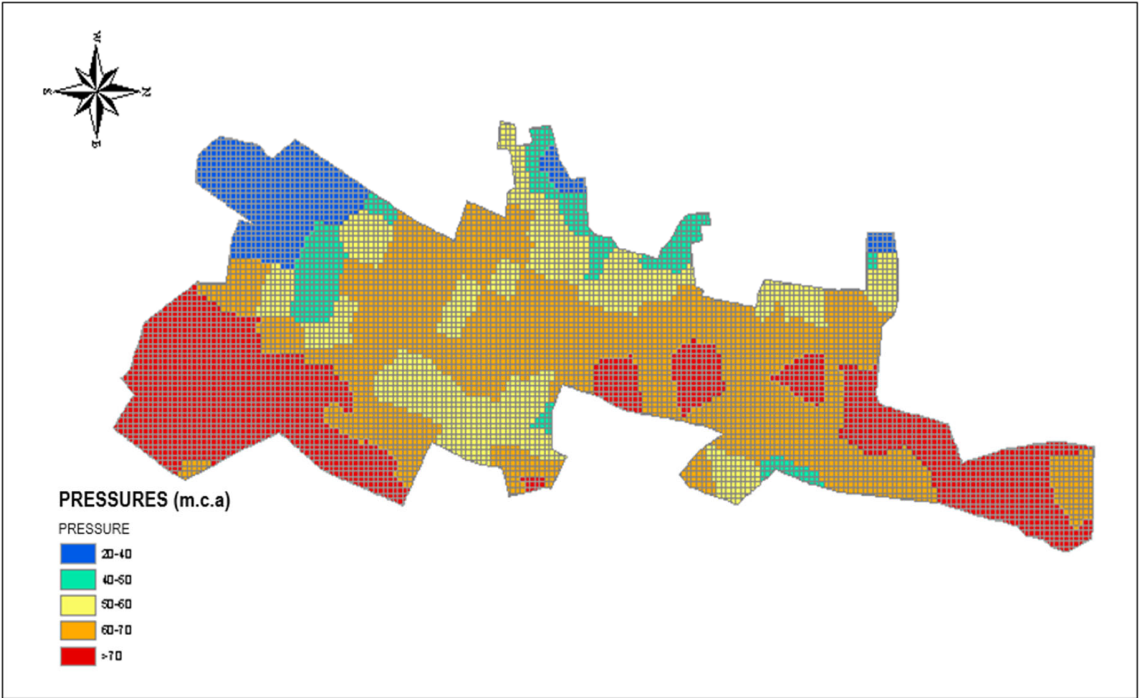874   **Figure 8**. Pipes that fulfil critical conditions for renovation

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877   **Figure 9.** Network sectorization for proposed pressure management strategy

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879 **Figure 10.** Current pressure of the distribution network

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881 **Figure 11.** Pressure distribution with the proposed sectorization strategy.

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