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Iterative Multi-Stage Method for a Large Water Network Sectorization into DMAs under Multiple Design Objectives

Denis. Gilbert Ph.D.¹, Edo Abraham Ph.D.^{2*}, Idel Montalvo Ph.D.³ and Olivier Piller Ph.D.⁴,

¹Research Engineer, Irstea, UR ETBX, Water Department, Bordeaux regional centre, Cestas F-33612, France, denis.gilbert@irstea.fr

²Assistant Professor, Faculty of Civil Engineering and Geosciences, TU Delft, Stevinweg 1, 2628 CN Delft, the Netherlands, e.abraham@tudelft.nl

³Founder and Chief Engineer, IngeniousWare GmbH, Jollystraße 11, 76137 Karlsruhe, Germany, imontalvo@ingeniousware.net

⁴Research scientist, Irstea, UR ETBX, Water Department, Bordeaux regional centre, Cestas F-33612, France, olivier.piller@irstea.fr

* Corresponding Author

Abstract:

This paper considers the sectorization of a large water distribution network into district metered areas (DMAs) and simultaneously optimizes rehabilitation of the network with new pipes, control valves, and storage tanks. Since the available water resources are much smaller in the dry season, both the design and operational settings are optimized to satisfy water demand, water quality and pressure constraints, and efficiency indices under stringent conditions. Because of the heterogeneity of the multiple decision variables and the complicated way they interact through the multiple objectives (some complimentary and some conflicting), it is not possible to fully automate the simultaneous sectorization, rehabilitation and operational optimization. Therefore, we employ a multi-stage approach where engineering judgment and network graph simplification and visualization tools are employed to find a good feasible solution that is used as a first guess for further optimization of sectors and operational settings, to achieve feasible solutions with better cost of implementation, demand similarity among DMAs and better pressure uniformity in operations. A multi-objective Agent Swarm Optimization framework is used to iteratively change the sectors at the boundaries. For

28 the final configuration, sequential linear programming is used to find optimal valve and pump
29 settings.

30 **Keywords:** Water Distribution Network, Graph Partitioning, DMA, Sectorization, Rehabilitation
31 Design, Agent Swarm Optimization, Pressure Management, Water Quality, Engineering Judgment
32

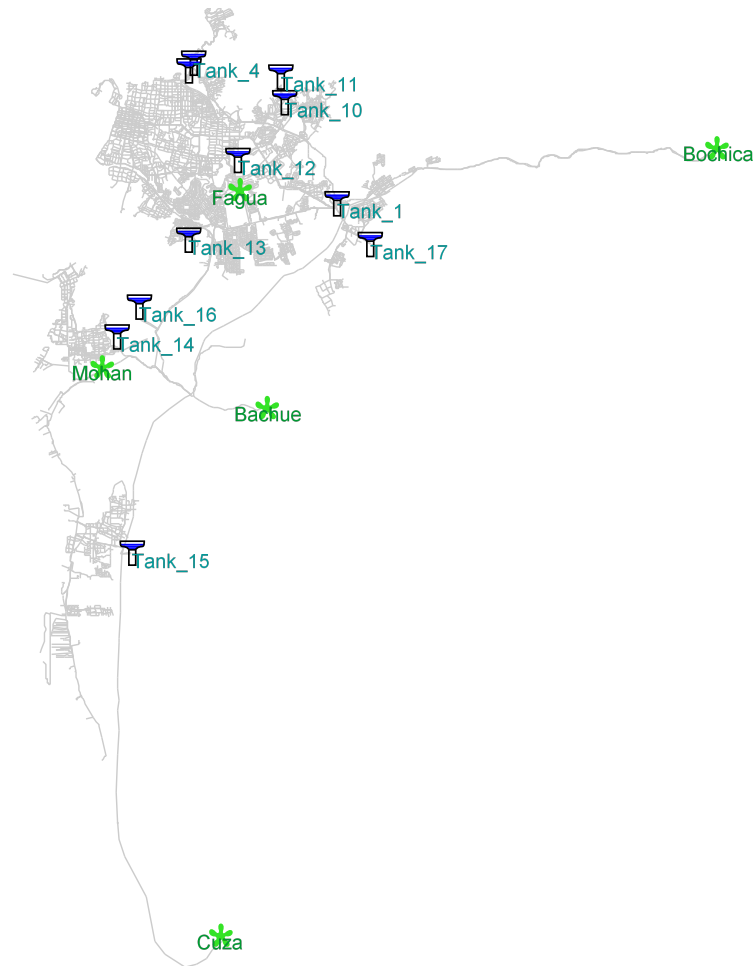
33 **INTRODUCTION**

34 This manuscript presents our work on the optimal sectorization of the E-town network, which was
35 part of the Battle of Water Networks District Metered Areas (BWNDMA 2016), a special contest with
36 14 participants that was presented at WDSA 2016 in Cartagena, Colombia, the sixth one in a series of
37 contests since 1985 (Giustolisi et al., 2015). Firstly, we describe the network and the problem
38 objectives and constraints. Then, the methodology employed is explained, which consists of some
39 engineering judgment and network analysis tools to simplify the problem, and the use of mathematical
40 optimization and agent swarm optimization for design and operational decisions. We subsequently
41 present our results and discuss lessons of general validity that have been learned from this exercise.
42 Finally, we conclude with a summary.

43
44 The schematic shown in Figure 1 represents a large water network of the E-Town city in Colombia.
45 As a result of a swelling tourist industry and overall economic growth, the city is no longer able to
46 meet its increasing water demand. Having modelled the network and made an inventory of the
47 forecasted demands, demand patterns, existing pump and tank characteristics, and the actual controls
48 of valves, the municipality has determined that the current DMA configuration and operational and
49 tactical management of the network do not allow it to meet demands in dry and rainy seasons
50 (BWNDMA 2016). For example, as depicted in Figure 2, some of the tanks are empty and out of use
51 because there are considerable differences in the pressure conditions of the city, and because the water
52 use is not efficient. Therefore, the objective of this work was to sectorize the network into a new
53 DMA configuration that allows the water utility to satisfy its customer needs while keeping a minimal
54 number of DMAs (each with a similar number of users or demand), guarantying pressure uniformity

55 across the municipality, meeting regulatory water quality specifications, and ensuring an efficient
56 system operation during both the dry and wet seasons of the year.

57



58

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Figure 1: E-Town network Map with resources and used tanks.

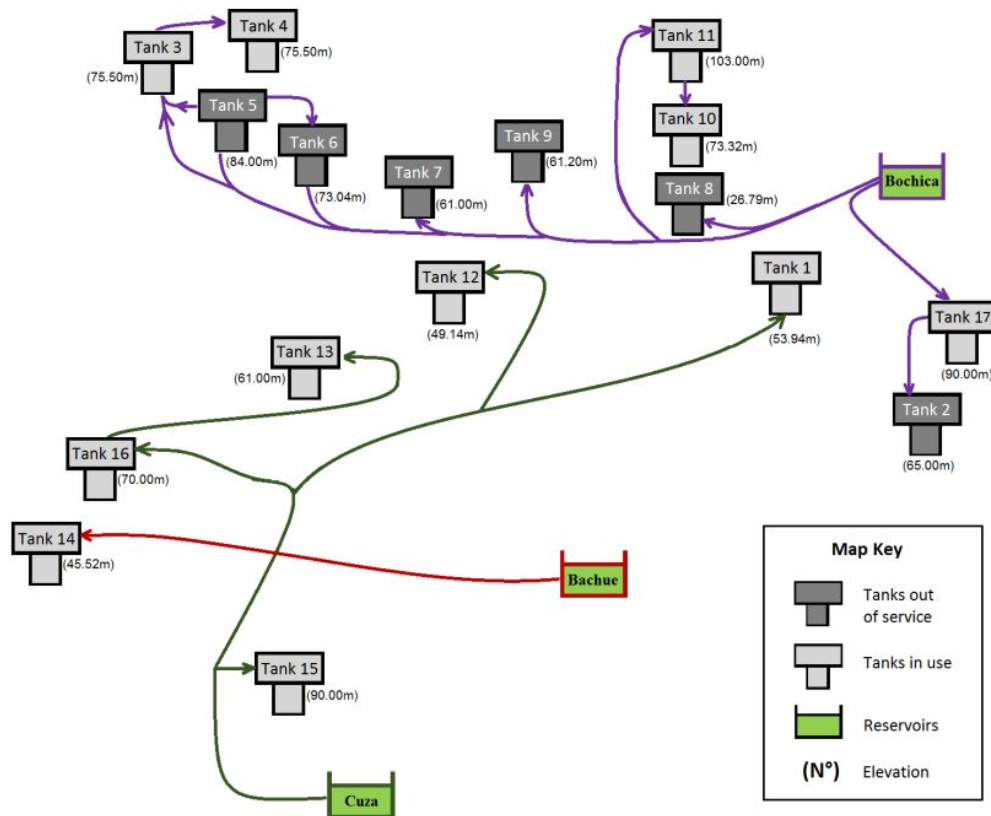
60

61 The competition committee had specified a few decision variables and multiple cost functions for the
62 design. The objectives that were evaluated to compute overall grades for the competitors were as
63 follows (BWNDMA 2016):

- 64 i) To minimize the number of DMAs, subject to a minimum of 15 DMAs. The cost function
65 given was $DMA_{index} = \#DMAs - 15$.

- 66 ii) To maximize demand similarity among DMAs. The cost function set was $DS =$
67 $\sqrt{\frac{1}{\#DMAs} \sum_{i=1}^{\#DMAs} (V_{in,i} - V_{out,i} - V_{av})}$, where $V_{in,i}$, $V_{out,i}$ are the volume of water entering and
68 leaving the i th DMA and V_{av} volume consumed per DMA, averaged over all DMAs.
- 69 iii) To minimize solution implementation cost CC_{net} . This consists of the cost of pipe
70 replacements or installations (as a function of length and discrete set of available diameters),
71 the cost of control valve installations (as a function of diameters), and the cost of new tanks
72 installed (as a function of volume).
- 73 iv) To minimize the pressure Uniformity index (PU_{net}) during the rainy and dry seasons as two
74 separate objectives. These objectives specify that all demand nodes in the network should
75 have similar pressure and as close as possible to the minimum set pressure constraint. Please
76 see Equation (3) of this manuscript for details.
- 77 v) Minimize demand weighted water age (WA_{net}) throughout the network. This minimizes the
78 deviation of the water age from the local regulatory maximum age of 60 hours. Please see
79 (BWNDMA 2016) for detailed expressions.
- 80 vi) Minimize the total number of operational changes ($OpCH_{net}$) in the valve settings (for
81 pressure reducing valves (PRVs) and flow control valves (FCVs)) and opening and closing of
82 isolation valves for boundary pipes from dry season to rainy season.

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Figure 2: The original supply routes for the E-Town network (BWNDMA 2016)

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This design problem is a very difficult since there are multiple decision variables that are not easy to incorporate in one optimization problem and because the multiple objectives interact in complicated ways. For example, one of the design stage decision variables is the isolation valves to be closed (i.e. sectorization is done by closing some of the pipes on the boundary of DMAs). Since each DMA is specified to have only a maximum of two pressure controlled inlets, this will implicitly determine the number of PRVs and so the objective CC_{net} , in addition to DMA_{index} and DS . The new tanks to be installed and their volume is not easy to incorporate in this same sectorization problem as it is not clear a priori, where additional storage is needed or what the volumes should be. Similarly, we have the discrete decisions of introducing additional new pipes. These design decisions also affect the optimal level of water PU_{net} , WA_{net} , $OpCH_{net}$ and to a lesser extent $OpCH_{net}$, that can be achieved through operational optimization of PRVs, FCVs and pump settings for the two seasons. Therefore, because of the magnitude of the search space and the large number of decision variables, the multiple interactions between the objective functions (some complimentary and some conflicting) and

99 heterogeneity of the decision variables, it is not possible to derive a design process that is fully
100 automatic.

101

102 In the literature, several methodologies have been proposed to tackle the problem of water network
103 sectorization, often with respect to one decision variable and fewer objectives. For example,
104 motivated to maximize security against contamination events, (Di Nardo et al. 2013) employ graph
105 theory principles and a heuristic optimization to form isolated district meter areas, each of which is
106 supplied by its own source (or sources). Although they use graph theory tools for sectorization, in
107 Scarpa et al. (2016) the two objectives are enhancing the quality of delivered water and reducing the
108 risk of contaminant spread. Most other work also uses graph theory and energy criteria (Di Nardo &
109 Di Natale 2011; Giustolisi et al., 2015) and some have applied multi-agent systems for finding the
110 best combination of sectors (Herrera et al. 2011,2, Montalvo et al. 2014) for other multi-objective
111 problems. There are also approaches that try to tackle the problem directly with heuristic optimization
112 algorithms (Di Nardo et al. 2014) and recently with concepts derived from social network theory
113 (Diao et al. 2013). A reference to a plethora of other related work on sectorization approaches and
114 specific objectives for sectorization can be found in these references and literature cited therein.

115

116 The approach followed in our work is not exclusively based on any one method presented in the
117 literature but a combination of several approaches together with engineering judgement to solve the
118 overall problem in multiple stages. As previously demonstrated in Khedr & Tolson (2015) for a
119 water distribution system rehabilitation problem, the use of engineering judgement to simplify a rather
120 complex design and operational optimization problem can be very effective. We use graph theory
121 tools to better understand the network topology, visualize the elevation map and identify redundant
122 and isolated network elements, which were corrected before automating some processes. We then
123 optimize iteratively the DMAs using agent swarm optimization. The operational settings of valves and
124 pumps are determined using convex optimization tools. In the following section, we describe the
125 methodologies in detail.

126

127 **METHODOLOGY**

128

129 **Engineering principles and Porteau**

130

131

132 The Porteau software solution (2017) is a hydraulic toolkit for Water Distribution Analysis that is

133 developed by IRSTEA research institute in France. It was designed with the help of a Computer-

134 Aided Software Engineering tool and object oriented programming. This software is an alternative to

135 the well-known EPANET solution (Rossman, 2000) and it provides different additional tools for

136 analyzing complex WDNs such as simplification of the network, detection of isolated parts and

137 duplicated pipes, and it owns a stochastic module for assessing the hydraulic state at peak period

138 (Piller and Bremond, 2002). The technologic choice and the software possibilities are described in

139 Piller et al. (2011).

140

141 Porteau was first used in the model validation step to identify parts that are isolated from water

142 resources and to check errors in the data file itself. In the original network file provided for the

143 competition, a set of pipes was discovered to be disconnected from the rest of the network. This may

144 cause problems for a hydraulic solver with the presence of customer nodes with no reference of head.

145 One pipe, originally closed (i.e.: Pipe '8872' in the INP file provided), was opened to avoid problems

146 in hydraulic analysis and force the hydraulic solver to compute a correct rather than arbitrary

147 piezometric head. Another issue we identified was regarding the two tanks 'Tank_3' and 'Tank_4'

148 connected by a short pipe. This caused mass oscillation between the two tanks at each iteration and

149 extended period simulation (EPS) hydraulic equations like in Porteau and EPANET were not able to

150 find a correct physical solution since they ignore pipe inertia; such problems would not be an issue if

151 a rigid water-column model was used (Piller & Propato, 2006; Nault and Karney, 2016). We also

152 found that this modeling flaw increased considerably the executable time of the EPS. Since the supply

153 flow direction is from 'Tank_3' to 'Tank_4', both in rainy and dry seasons, we placed check valves

154 on the outgoing pipes from both tanks. This prevention of two-way flow in the numerical model

155 prevented the mass oscillation, both decreasing the computational time and giving correct and

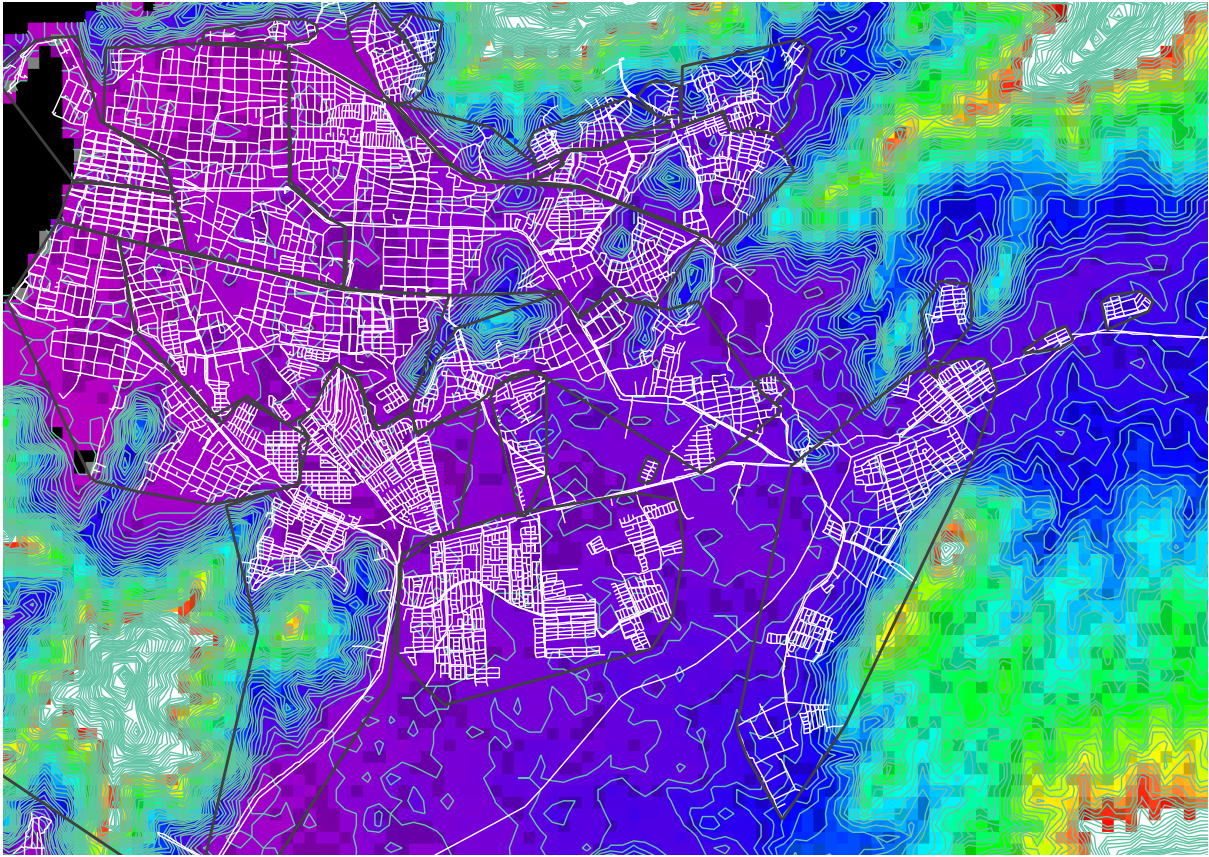
156 physically meaningful results. In valve and pump setting optimization problems (see last subsection),
157 the same set of issues were resolved by putting a unidirectional constraint on the flow of the links
158 originating from ‘Tank_3’ and ‘Tank_4’.

159

160 Several parallel pipes (with the same positions) were found in the original network data. An attentive
161 check was made to ensure it was not an error coming from the GIS. In Porteau, a connectivity analysis
162 highlights parallel pipes and visualizes them. Then they are manually checked to see if they are
163 different pipes. Since we found no duplicated pipes, the parallel pipes were kept in the model. Five
164 out of service tanks were transformed into junction nodes. Practically, this allows water to cross the
165 valve chamber and bypass the tank. Another abandoned tank (‘Tank_7’) was isolated because its
166 elevation was too high to be supplied with sufficient pressure coming from another tank or through
167 nodes around it.

168

169 The second step was to analyze the supply routes (Figure 2) and elevation map (Figure 3) to
170 understand the supply network (see Figure 1). In the rainy season, the water has three origins. The
171 source in the south, Cuza WTP, constitutes more than half of the supply and provides water to a large
172 part of the city. The source at the central east of the network, Bachue WTP, is at a low elevation and
173 can only supply the low elevation parts close to it, including Tank_14. Bochica WTP, although it has
174 half the capacity of the south supply, it has the highest elevation and so supplies areas with a large
175 variation in elevation across the north of the network.



176

177 Figure 3: Altimetry for Downtown E-Town network (network pipes in white; sectors delimited by
178 black lines; elevation contour lines in blue; and the DEM in the background.)

179

180 To reduce energy losses in distribution, one of the objectives to be minimized in the new sectorization
181 is pressure uniformity (i.e. the PU_{net} function in the BWNDMA Problem Description and Rules
182 (BWNDMA, 2016)). This was taken into account in forming a first feasible DMA configuration using
183 engineering know how and Porteau Software for graph sectorization and hydraulic and water quality
184 simulation tool. Initially, the elevation information of the network data was used to visualize a digital
185 elevation model (DEM). The contours of homogeneous elevations were then used to form the sector
186 frontiers, where each sector would have a small variance in the elevation. In this way 15 DMAs were
187 chosen as first guess based on elevation similarity, since the other objective specified in the battle was
188 also minimizing the number of DMAs with a minimum number of 15 DMAs. The contours were then
189 moved sufficiently to make sure the DMAs have similar volumes of demand. Closed valves were
190 placed for isolation from the rest of the network, and one main entry point was chosen for each DMA

191 and tagged “meters/compteurs”. A graph theoretic tool was used to check that each DMA was
192 connected only through the tagged inlets: using the network incidence matrix of the connected
193 components and the PRIM algorithm (a greedy depth-first-search algorithm) the inlets to each DMA
194 were confirmed (Bartnik & Minoux, 1986). For double-checking the results, a modified version of the
195 Lee algorithm (Lee, 1961) was used for identifying existing sectors in the network model. The
196 algorithm uses graph decomposition and the information of the network elements for traversing in
197 depth search until the border of a potential sector is reached.

198

199 The third step is iterative and includes the use of two different steady state hydraulic models to check
200 the pressure at demand nodes during the peak period. The conventional deterministic models predict
201 too large flow rates in main pipes, which are improbable to occur simultaneously. On the contrary,
202 flow rates in branched pipes supplying few consumers are underestimated by the latter. More
203 representative values can be derived by considering stochastic demands and upper limits of
204 different confidence intervals; we use the stochastic model Opointe in Porteau that exploits
205 peak demand diversity/simultaneity curves (Piller and Brémond, 2002) to more accurately
206 approximate the flow rate at pipes as a function $(an + b\sqrt{n})$ of the number of domestic
207 consumers, n , served. This way a less pessimistic pressure is calculated in the core network
208 that corresponds to a satisfaction risk.

209

210 Additionally, EPANET was used for simulation from within a c-code with conventional analysis of
211 low and peak periods. If the lower constraint limit of 15m for pressure was not satisfied it was
212 necessary to adjust the DMA boundary and specify a new DMA with a more homogenous pressure.
213 Following this, another steady state for low demand consumption was run to check for the pressure
214 upper limit of 60m. Among the main results, it was necessary to reinforce the network with two new
215 pipes of length approximately 800m and 1.2km (connecting node ‘5675’ to nodes ‘4466’ and ‘5374’,
216 respectively) in order to limit the head loss in supplying the DMA below ‘Tank_15’. This high
217 elevation area (e.g., node ‘4252’ has an elevation of 47m) couldn’t be supplied with a pressure above

218 15m without violating the 60m pressure constraints upstream of it – feasible solutions are obtained
219 only with this reinforcement with new parallel pipes.

220

221 The fourth step was to tune the setting of the flow control valves (FCVs) and of the pressure
222 regulating devices (PRVs) that are added at entry points of DMAs. The main role of the FCV is to
223 control the distribution of water and it was possible to set each FCV to the supply of one or several
224 DMAs. This has simplified the problem of finding feasible initial settings for the FCVs. An automatic
225 procedure that requires solving a convex optimization problem was also devised for that task and
226 linked to the pressure uniformity criterion (see the next subsection). This has led to a feasible solution
227 for the rainy season. The average demand of each DMA and the mass balance of each tank were used
228 to determine the initial setting of the FCV.

229

230 The solution of the rainy season with pumps working and reduced flows from the water treatment
231 plants was adapted for the dry season. It was necessary to make two kinds of change: closing and
232 opening valves to introduce new water routes (shortcuts) and to supply some tanks with insufficient
233 water inflow with alternative sources. We added a pressure-sustaining valve to raise the pressure in
234 order to limit the water coming from the south source ‘Cuza WTP’ and force it to go to ‘Tank_16’ and
235 decreased the flow going to ‘Tank_1’. We also reinforced with set pipes of diameter 762 mm and total
236 length 721 m, starting from ‘Fagua_Pump_Station’ to transport the supply to ‘Tank_12’.

237

238 **Sequential Convex Programming for Operational Optimization**

239 In the problem description and rules for the competition (BWNDMA, 2016), the objectives
240 DMA_{index} , DS , CC_{net} , $OpCH_{net}$, (and implicitly PU_{net}) were taken into account only while choosing
241 the DMA configurations in the design iterations as they are not a function of operational setting
242 changes. The operational decisions affect the two objective functions relating to pressure uniformity
243 (PU_{net}) and water age (WA_{net}). By posing the water quality objective function WA_{net} as a constraint,
244 i.e. all designs would need to satisfy the stipulated water age limit, this objective function could be
245 removed from the multi-objective design problem. For the dry season, in the operational optimization,

246 we consider the simultaneous tuning of the settings for the FCVs, the PRVs and the flows from the
 247 fixed-speed pumps with the two objective functions PU_{net} and WA_{net} such that the following (linear
 248 constraints) are satisfied:

- 249 • pressure constraints of 15m-60m for the specified nodes at all time steps,
- 250 • flow constraints on all water sources between 0 and the maximum specified, and additional
 251 constraint for the two Mohan sources to sum to 206 L/s,
- 252 • tank levels between 10-90 % full, at all time steps, and
- 253 • mass balance at all nodes.

254 In the rainy season, all the above except for the flow from the pumps are considered.

255

256 This optimization problem is a difficult nonlinear programming problem (NLP), with non-convex
 257 constraints. An optimization method based on the strictly feasible sequential convex programming
 258 (SCP) described in (Wright *et al.*, 2015) was used. This SCP method solves the non-convex NLP
 259 problem by sequentially solving convex approximations (linearized sub-problems). The convexity of
 260 the approximations means each sub-problem can be solved accurately and efficiently. In the
 261 optimization problem considered here, we start from feasible PRV and FCV and pump flow settings
 262 that were determined in the DMA design stage. Let $x := [q^T \ h^T \ \eta^T]^T$ be the vector of the flows in
 263 all links (q), the heads at all unknown head nodes (h) and the headloss across the PRVs (η),
 264 respectively. The NLP for calculating η and flows through FCVs at each time instant is as follows:

$$\begin{aligned}
 & \min_{\eta, q, h} f(h; \eta, q) \\
 & \text{subject to: } g(x) = 0 \\
 & \underline{q}_i < q_i \leq \bar{q}_i, \forall i \in N_{FCV} \\
 & \underline{h}_j < h_j \leq \bar{h}_j, \forall j \in N_N \\
 & \eta_i \geq 0, \forall i \in N_{PRV}
 \end{aligned} \tag{1}$$

265

266 where the vector equation $g(x)$ contains the head loss across each link and mass balance equations at
 267 all nodes, respectively. Where the link indexed in $g(x)$ is a pump, the head gain across the pump is
 268 represented by the pump curve equations (Rossman 2000). The upper and lower bounds on the flows
 269 q_i represent constraints on flows through FCV from different sources, and the minimum and

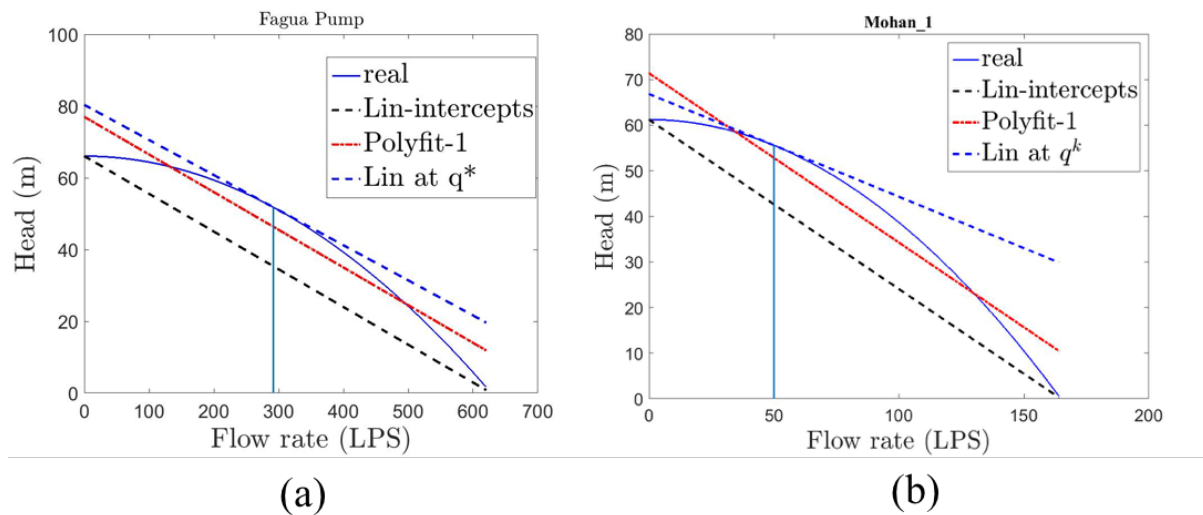
270 maximum pressure levels at demand and non-demand nodes and tank level constraints are imposed
 271 using the constraints on the heads h_j . The respective η_i values are constrained as non-negative for
 272 PRVs and positive for pressure sustaining valves (PSVs), where the direction of flow is already
 273 determined. For entrance to DMAs with only flow meters, the flow direction constraints can be
 274 omitted. At each iteration of the SCP, the nonlinear objective function $f(\cdot)$ and the nonlinear
 275 constraints $g(x)$ are approximated by their linearization and the following problem is solved:

$$\begin{aligned}
 & \min_x \nabla f(x^k)^T x \\
 & \text{subject to:} \\
 & \nabla g(x^k)^T (x - x^k) + g(x^k) = 0, \\
 & \underline{q}_i < q_i \leq \bar{q}_i, \forall i \in N_{FCV} \\
 & \underline{h}_j < h_j \leq \bar{h}_j, \forall j \in N_N \\
 & \eta_i \geq 0, \forall i \in N_{PRV}
 \end{aligned} \tag{2}$$

276 where x^k is the variable at the k-th iteration of the SCP, $\nabla f(x^k)$ and $\nabla g(x^k)$ are the gradients (i.e.
 277 partial derivatives) of the objective function and constraints, respectively, computed at current iterate
 278 x^k and x is the solution we seek, at which we shall compute the linearized gradients at the next iterate
 279 $k + 1$. In addition to these, we impose flow direction constraints for the supply pipes (i.e., the FCVs
 280 from the sources), and inlet PRVs by setting the corresponding lower bound \underline{q}_i to zero.

281
 282
 283 In the optimization problem (1), the flows from the pumps at Fagua and Mohan water treatment plants
 284 and the head difference across the pumps are decision variables, constrained by the corresponding
 285 pump curves. In the SCP subproblems, the heads are approximated using the linearization of the
 286 pump curve at a given flow. In Figure 4, we show different approaches that can be used to
 287 approximate the pump curves. A simple approximation of the pump-curve (left side of Figure 4a and
 288 Figure 4b) can be derived by drawing a line between the head and flow axis intercepts; this
 289 underestimates the head of the pump for a given flow and sometimes can result in violation of the
 290 maximum head constraints. Alternatively, (right side of Figure 4a and Figure 4b), a least-squares fit of
 291 the pump curve can overestimate or underestimate the head depending on the flow rate. A first-order
 292 Taylor linearization of the pump-curve around flow q^k (at the k-th iteration of the SCP) gives an

293 overestimator for the head that is tight near q^k . From simulations, we found that the last linearization
 294 had the least hydraulic infeasibility, a faster convergence for the SCP and therefore it was adopted; the
 295 details of this pump approximation approach and how the tank levels are discretized using a first-
 296 order finite-difference model is described in (Menke *et al.*, 2016).



297
 298 Figure 4: (a) Different linear approximations for the Pump Curve of Fagua compared to the given
 299 quadratic pump curve labelled 'real'. (b) Different linear approximations for the Pump Curves of
 300 Mohan compared to the given quadratic pump curve labelled 'real'. The vertical line shows the flow
 301 q^* at the current iterate.

302 Three more aspects of the SCP application in our implementation that are important to mention are:

- 303 • The objective function WA_{net} was ignored for the SCP because it was mostly zero when
 304 perturbing the feasible initial solution from the design subproblem. Moreover, ignoring this
 305 objective function means that the water quality simulations are not needed at each iteration of
 306 the SCP but only an extended period hydraulic simulation to check feasibility in taking a step
 307 in decision variables. This results in faster CPU time of the SCP. WA_{net} was checked once
 308 the SCP had converged.
- 309 • The PRV technology used by the utility are specified to have fixed-head settings that change
 310 only once from dry to rainy season and vice versa. Therefore, in the operational optimization
 311 we enforce a constraint on the pressure at the downstream nodes of the regulating PRVs to be
 312

313 fixed in time. Most times, this caused infeasibility in the linearized subproblems of the SCP,
 314 even when starting from a feasible point. The linearized feasibility spaces at different times
 315 (and therefore at different states for flows and pressures) seem to no longer have an
 316 intersection with a fixed head constraint for the PRVs. This was relaxed by putting a penalty
 317 term for temporal changes in the downstream heads of PRVs instead. However, it is not clear
 318 how to find appropriate penalty weights to guarantee that we don't introduce too much
 319 suboptimality in the objective PU_{net} . Thus, the SCP's results do not always give significant
 320 improvement. It is also not clear how optimal our initial feasible guess was since we are
 321 using a local optimization solver. Therefore, this is left as an interesting study for future
 322 work.

- 323 • The nonlinear objective PU_{net} was studied by decomposing it into the two parts:
 324

$$325 \sum_{j=1}^M \left[\frac{1}{N} \sum_{i=1}^N \frac{(P_{i,j} - P_{min})}{P_{min}} + \frac{\sqrt{\frac{\sum_{i=1}^N (P_{i,j} - P_{Avj})^2}{N}}}{P_{Avj}} \right] \quad (3)$$

326 Where P_{min} was fixed to be 15 mH₂O, $P_{i,j}$ is the pressure at node i and time j ; and P_{Avj}
 327 is the average pressure at time j for all the demand nodes.

328 Using the semidefiniteness of the numerator in the second term of equation (3) and the
 329 positivity of its denominator, perhaps it is possible to show convexity of PU_{net} , which
 330 simulations seem to imply. Nonetheless, we use a linearization of PU_{net} in the SCP.

331 Network design optimization by an ASO method

332 Creating sectors in a water network is a challenging problem from the engineering point of view.
 333 Even more so when it is approached using optimization methods trying to find optimal DMA
 334 configurations:

- 335 • Classic optimization based on derivatives would be very limited for solving this
 336 problem as they need rigorous formulation and the decision variable should be
 337 continuous.

- 338 • Checking all alternatives by enumerating solutions is infeasible in terms of
339 calculation time as the problem scales combinatorically (Pecci *et al.*, 2016)
- 340 • The use of “pure” evolutionary algorithms would have difficulties to find good
341 solutions (in a reasonable amount of time/resources) for a “large size” problem like
342 this one, because for example GA is sensitive to the initial population used and
343 Genetic algorithms do not scale well with complexity.
- 344 • Hybrid evolutionary approaches that incorporate engineering experience and other
345 more deterministic methods for solving sub-problems are considered as an option.

346
347 Agent Swarm Optimization (ASO) (Montalvo *et al.*, 2010) introduced a new agent that reproduces the
348 behavior of the Louvain method for community detection (Blondel *et al.*, 2008). The Louvain method
349 maximizes a modularity index resulting in the best possible grouping of nodes:

$$350 \quad Q = \frac{1}{2m} \sum_{ij} \left[A_{ij} - \frac{k_i k_j}{2m} \right] \delta(c_i, c_j), \text{ where} \quad (4)$$

- 351 • A_{ij} represents the edge weight between nodes i and j ,
- 352 • k_i and k_j are the sum of the weights of the edges attached to nodes i and j , respectively,
- 353 • m is half the sum of all edge weights in the graph,
- 354 • c_i and c_j are the communities of the nodes i and j respectively,
- 355 • δ is a Dirac delta function that gives 1 if $c_i = c_j$, else zero.

356
357 Classic applications related to social network can use, for example, the number of messages between
358 community members for weighting edges between nodes. In the case of water network sectors, this
359 research has been using the water demand at nodes as a first weighting factor. For joining smaller
360 communities when the modularity index was not able to be increased anymore the Z coordinate (or
361 elevation) was used as weighting factor. These decisions had the intention to find sectors with
362 similar demand and with nodes located at similar altitude. The action of the agent reproducing the
363 Louvain method was combined with other type of agent reproducing the behavior of a modified Lee
364 algorithm (Lee, 1961) for finding the limits of potential sectors and deciding where to put PRV
365 valves. This behavior was also used in this research for checking solutions created just based on
366 engineering experience. ASO calculation and network visualization were done using Water-Ing,

367 software from Ingeniousware GmbH. The software is open to extensions and available for free in a
368 community edition (<https://ingeniousware.com/software/about?name=watering>).

369

370 The settings of the PRVs placed at DMA boundaries for separating sectors are not included directly in
371 the process of creating sectors. Nevertheless, the results of the objective function after the PRV
372 settings are defined is sent back to the ASO as reference in order to improve the sectors
373 created. During the time of this research, ASO was partially used to improve the sectorization
374 solution as because of limited time, it was not possible to automate the whole process of
375 creating sectors considering all the details of the objective functions. Nevertheless, the agents
376 included in ASO helped on the evaluation/verification of the ideas emerging from
377 engineering experience that were used to solve the problem.

378

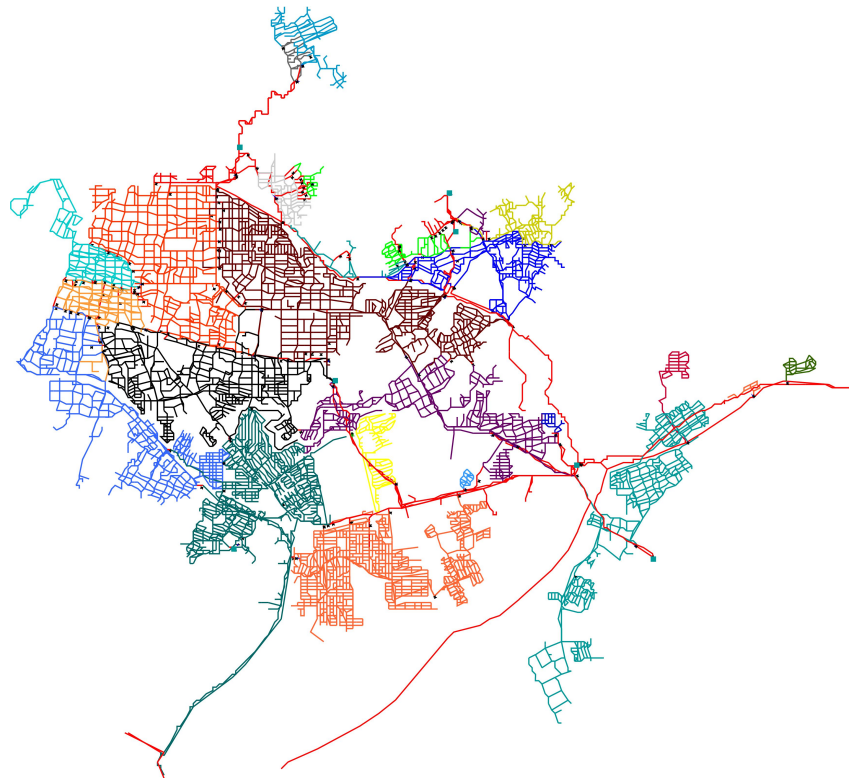
379 **SUMMARY and DISCUSSION OF RESULTS**

380 In Figure 5, we show DMA configurations of the main North part of the network where the colors
381 were chosen from a library by the Porteau software to distinguish each DMA. It can be observed that
382 there is a large variation of elevation within small distances in the North. As a result, it was necessary
383 to sectorize the areas into smaller DMAs so that the pressure can be controlled within the given limit
384 of (15m-60m pressure) using PRVs, each DMA acting like an “irrigation terrace” used in agriculture
385 as we go uphill. Although one of the objectives by the battle organizers was to have the smallest
386 number of DMAs possible (but above 15 in number), this also explains the relatively large number of
387 DMAs in this area, which has resulted in some DMAs having relatively smaller average volume
388 demand compared to bigger DMAs with higher volume of consumption. Therefore, the demand
389 similarity objective DS was increased to maximum to make sure the conflicting pressure similarity
390 objective is reduced, and pressure constraints were satisfied.

391

392 For the south part (see Figure 6) and in our sectorization solution, the water is coming from
393 Tank 15 (depicted with the dark-blue square in the center bottom). It is important to highlight the

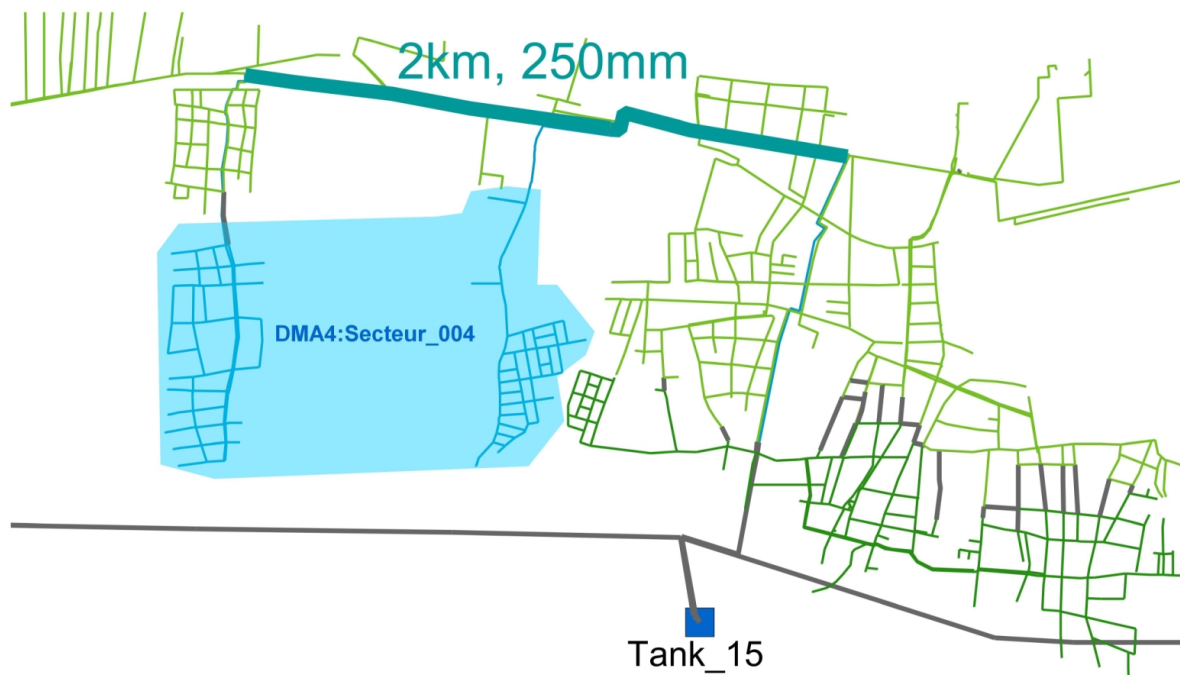
394 necessary reinforcement/reorganization is the most important intervention we have done in
395 term of implementation costs. It consists of pipe reinforcement with roughly 2km of pipes (top
396 thick green line) to limit the head loss at the lower elevation and satisfy pressure constraints at the
397 high altitude in the ends of DMA 4. Because of the large variation in elevation in in this area, we
398 created three DMAs to sectorize this area into three areas of more homogeneous elevation.
399



400

401

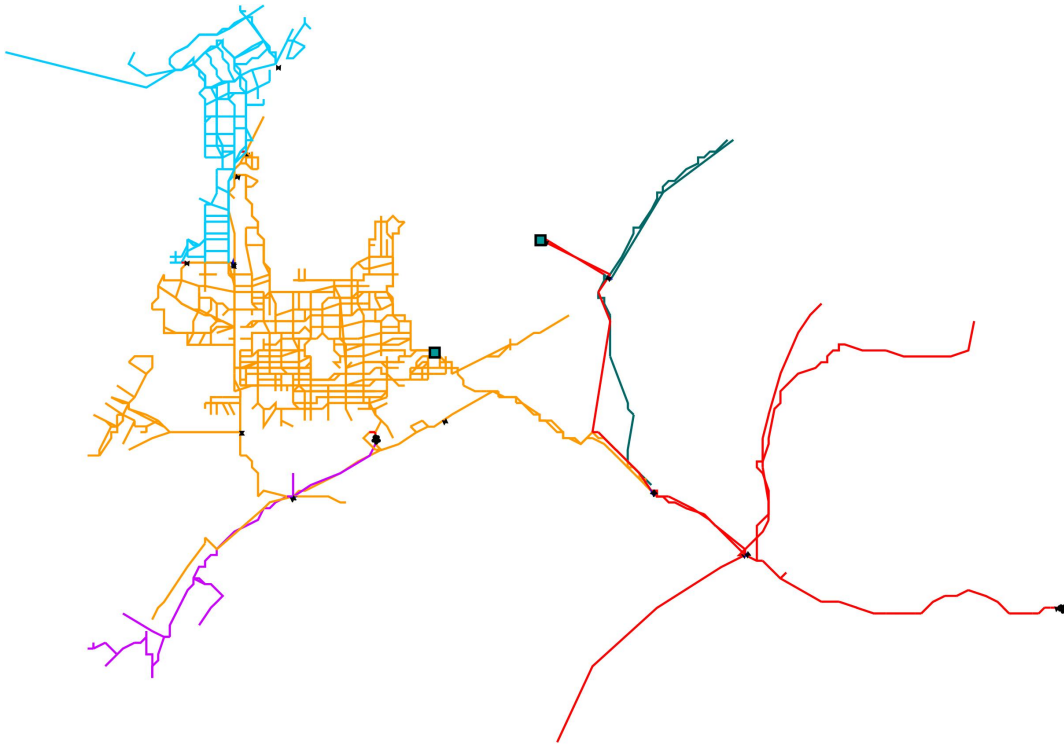
Figure 5: Final DMA splitting result for the main North part of E-Town network



402

403 Figure 6: Final DMA 4 for the South part of E-Town network

404 We show in Figure (7) the center part of the network, where in the rainy season, the water comes
 405 mainly from Bachue (the very right of Figure 7). In the dry season, this supply is halved in capacity
 406 and so was complemented by Mohan pumping station. In this competition, the pumping stations are
 407 specified to contain only fixed-speed pumps. To increase redundancy and flexibility in supply, we
 408 recommend the pumps (to have higher head specifications) and introduce variable speed pumps,
 409 which can be operated more efficiently with resultant savings of energy (Wu et al. 2011). This can be
 410 exploited even further if the water resources (aquifers) at Mohan have capacity to supply more water.



411

412

Figure 7: Final DMA splitting for the central part of E-Town network

413

In summary, the following were also achieved in the final configuration and optimized operational

414

settings:

415

- In Table 1, we show the decomposition of PU_{net} into the first and second elements of the sum in Equation (3), labelled PU_{net_Pmin} PU_{net_Pav} , respectively. We note that some DMAs have high deviation from the minimum pressure because they are either in a sector of low elevation near the sea ('Secteur_005', 'Secteur_010' in NW) or possess high variation in elevation and are close to a source supplying other DMAs ('Secteur_012' and 'Secteur_020' at the entrance of the Northern part, see also Figure 8). Note also that 'Secteur_012' is close to 'Tank_16' with nodal pressures close to the 60m upper limit at times).

416

417

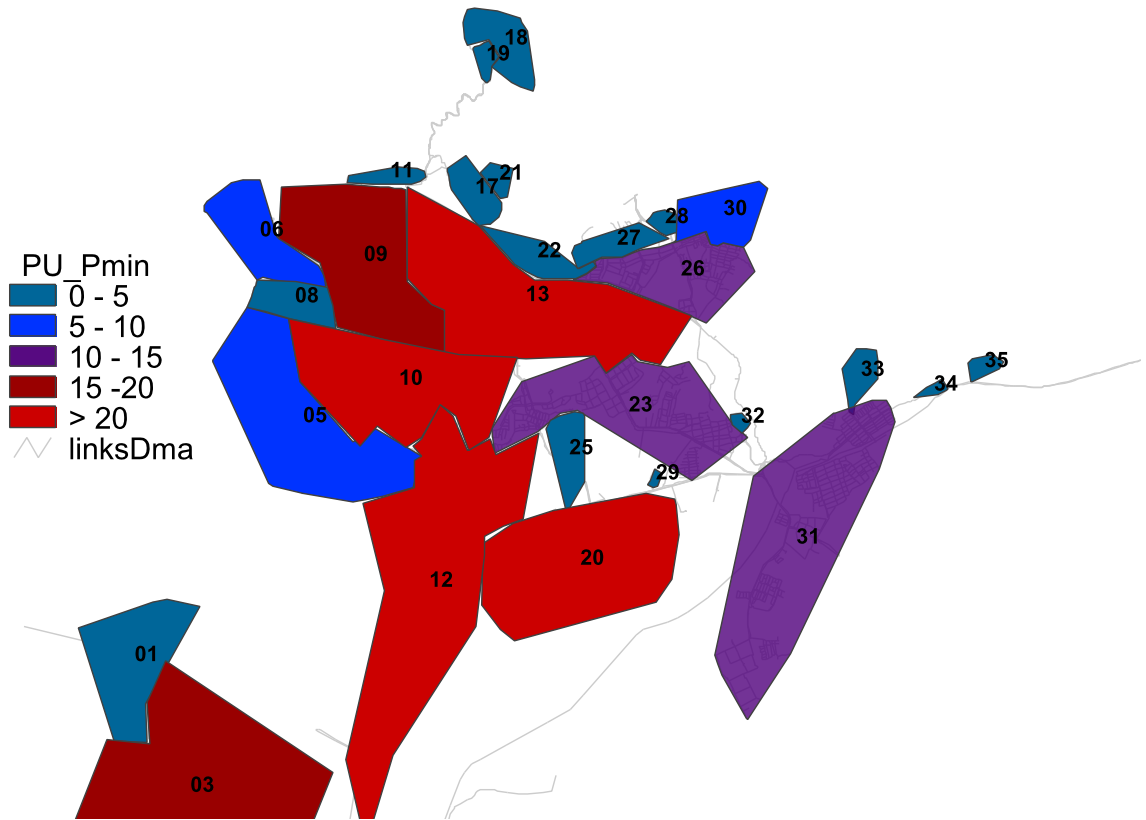
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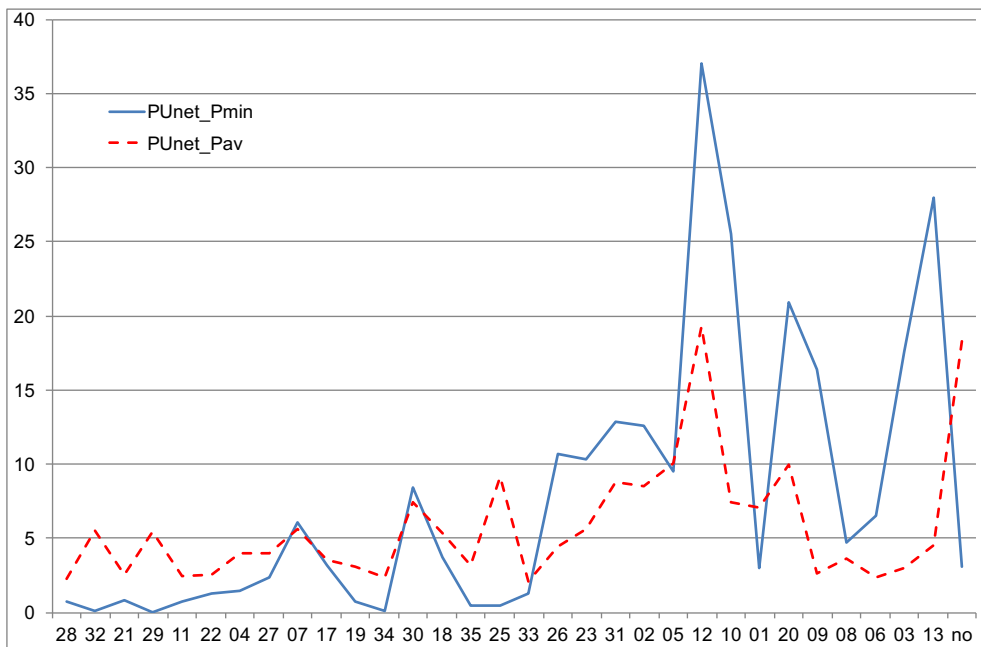
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423

424 Figure 8: Mean pressure deviation from PUnet_Pmin for the North part of E-Town network

425



426

427 Figure 9: The two PU contributions for all DMAs contributions of E-Town network; the DMAs are

428 sorted by total demand.

- 429
- The water age objective (WA_{net}) is close to zero (0.005 hours) in both seasons, as
430 there are only 20 violations of the 60-hour maximum limit.
 - By making use of a graph simplification tool and engineering judgement, it was
431 possible to identify the main flows and bottlenecks. This has allowed changing the
432 network with minimal pipe interventions (11 in total but with only 5 with significant
433 lengths). Similarly, the operational changes from one season to another have been
434 kept to only 14 (with five main pipes status changes, eight FCV setting changes and
435 three PRV setting changes). The details of all these are summarised in the Excel files
436 submitted as supplementary material together with the optimized network models in
437 EPANET INP format.
 - Similarly, we have tried to minimize the capital cost of intervention with valves (see
438 Table 2). Although we use 52 valves in the network, 13 of the PRVs located at entry
439 point of the DMAs are completely open and not doing any regulation. They only
440 represent water meters at their respective DMA entry point, where we are required to
441 measure the volume of water going through. EPANET does not offer the possibility
442 to include water meters and that's why they are represented in our solution as totally
443 open PRV without any regulation.

446

447 **SUMMARY AND PERSPECTIVES**

448 The objective of this paper is to share our experience with the civil engineering and academic
449 community in facing the challenging Battle of Water Networks District Meter Areas problem.

450 We have adopted three main strategies:

451

452 The first one consists of using our experience and skills in network modeling as much as possible. For
453 that, it was very important to understand how the supply of tanks and demand nodes may work in
454 rainy and dry seasons. The steps taken included:

- model validation,

- 456 • supply route and altimetry analysis,
- 457 • use of a deterministic and stochastic hydraulic model to test the pressure constraints for each
- 458 candidate DMA configuration,
- 459 • tuning the setting of the FCVs and of the PRVs.

460 This strategy has allowed the derivation of a feasible solution with regards to the pressure and tank
461 level-range constraints. It was the most time consuming and has required inventiveness. Our
462 experience was also used to simplify the problem in terms of the number of variables and
463 objectives and to help the ASO with appropriate rules.

464
465 The second strategy was to use a metaheuristic agent-swarm method to explore other solutions that
466 are not intuitive and so were not exploited in engineering judgment. The method moves some
467 elementary pieces of network and analysis the different combinations. A single hydraulic
468 steady state was run to check the pressure constraint feasibility and water age constraints. No
469 substantial improvement was achieved due to the lack of automation of the overall
470 sectorization process with ASO.

471
472 The third and last strategy was to solve the operational optimization problem for the setting of PRVs
473 and FCVs, and for the pump working point by sequential convex programming method. Further
474 studies are needed to guarantee significant decreases in the objective or use relaxation approaches for
475 global optimality studies (Pecci et al. 2017).

476
477 The final solution consists of a reinforcement with 3km of pipes at a cost of 141 k\$. In sectorizing the
478 network, we placed three kinds of control and metering devices: PRVs that are regulating the DMAs
479 are placed at the sector entrances, metering devices that we represent by open PRVs, and open PRVs
480 at the outlets for metering what is leaving the DMAs. The valves cost 208 k\$ in total. There is no tank
481 cost since we do not recommend new tanks or increasing the capacity of existing ones; the total cost is
482 only approximately 349 k\$. The water age is lower than 60 hours at almost all nodes so that our

483 solution is optimal for this objective, with only insignificant violations of 0.05 hours aggregated over
484 all nodes over seven days. Satisfying the objectives to the average pressure and increasing the
485 pressure uniformity in each and across the DMAs has led to the creation of additional smaller sized
486 DMAs compared to the solution derived at the first stage. Finally, we have 31 DMAs in total.

487

488 Future research will study further the use of ASO and deterministic optimization tools, as well as their
489 efficient coupling to further explore the space of possibilities. We have also provided as
490 supplementary material to this paper, the INP files of our results and a summary of the results in Excel
491 files containing the scores of the objective functions set, the definition of the sectors, nodal pressures,
492 the tank level at each time-step, and all these for the two seasons.

493

494 It should be noted that, although the algorithms and software tools used have were vital in solving a
495 large-scale problem that is too complex to tackle manually, they were complimentary to sound
496 engineering judgement rather than completely substituting it. An essential core of the solutions was
497 also the result of applying experience and engineering knowledge. Visual Basic and C codes for
498 running EPANET and generating the analysis on the networks are available on request.

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559

560 **TABLES**

561

Table 1. Comparison of *PUnet* objective function elements for all the 31 DMAs.

DMA	demand m3/7 days	nbNode	nbDemandNode	PUnet_Pmin	PUnet_Pav
Secteur_028	1549.31	25	25	0.6987	2.2601
Secteur_032	1759.63	29	29	0.0691	5.4905
Secteur_021	2006.85	31	26	0.8269	2.5155
Secteur_029	2301.72	26	26	0.0235	5.4707
Secteur_011	4908.42	44	37	0.7508	2.4374
Secteur_022	5191.81	48	36	1.3208	2.5766
Secteur_004	5383.49	118	62	1.4741	4.0094
Secteur_027	7897.8	88	74	2.3604	4.0048
Secteur_007	9387.84	193	162	6.1162	5.6021
Secteur_017	9578.36	100	94	3.2133	3.5324
Secteur_019	10279.01	50	39	0.7096	3.1027
Secteur_034	10739.73	14	12	0.1432	2.3412
Secteur_030	11089.48	246	224	8.4334	7.414
Secteur_018	12335.58	145	115	3.7259	5.3124
Secteur_035	14782.33	34	30	0.4497	3.1806
Secteur_025	15004.06	103	97	0.4734	9.1526
Secteur_033	15567.98	38	34	1.2717	2.1086
Secteur_026	23114.2	448	377	10.6525	4.4648
Secteur_023	54159.39	514	440	10.3694	5.6524
Secteur_031	54601.91	498	410	12.8299	8.7903
Secteur_002	57795.21	557	409	12.5499	8.492
Secteur_005	71648.25	572	507	9.5529	10.0936
Secteur_012	73703.9	934	773	37.0166	19.2645
Secteur_010	77886.19	852	713	25.5174	7.4012
Secteur_001	81519.5	249	186	3.0262	7.093
Secteur_020	83853.16	1055	898	20.8845	9.9377
Secteur_009	84905.37	606	501	16.4216	2.6549
Secteur_008	85158.52	250	198	4.678	3.6356

Secteur_006	87365.95	338	217	6.5152	2.3366
Secteur_003	88830.7	708	567	17.5792	3.0187
Secteur_013	90513.91	1045	891	27.9382	4.5598
noDma	9112.37	1164	41	3.0443	18.2869

562
563
564

Table 2. Intervention types and associated cost.

Intervention type	Implementation cost in \$
Pipes	141188
Tanks	0
Valves	208142
Total	349330

565