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OPTIMAL DESIGN OF DMAs FOR LEAKAGES REDUCTION

Daniele B. Laucelli,

Dept. of Civil Engineering and Architecture, Technical University of Bari, *Bari, 70125, Italy,*

danielebiagio.laucelli@poliba.it

Antonietta Simone,

Dept. of Civil Engineering and Architecture, Technical University of Bari, *Bari, 70125, Italy,*

antonietta.simone@poliba.it

Luigi Berardi,

Dept. of Civil Engineering and Architecture, Technical University of Bari, *Bari, 70125, Italy,*

luigi.berardi@poliba.it

Orazio Giustolisi¹

Dept. of Civil Engineering and Architecture, Technical University of Bari, *Bari, 70125, Italy,*

orazio.giustolisi@poliba.it

ABSTRACT

The division of water distribution networks (WDNs) into district metering areas (DMAs) is a challenging issue and can be effective for analysis, planning and management purposes. This contribution proposes a novel two-steps strategy for DMA planning. The first step is the *optimal segmentation design*, by maximizing the WDN-oriented modularity index versus minimizing the number of “conceptual cuts” (i.e. not accounting for devices). The second step is the actual *optimal*

¹ Corresponding author

22 *DMA design*, returning the positions of flow meters and closed valves at the “conceptual cuts”. Since
23 closed valves change hydraulic paths of the system, the implementation of DMAs could allow
24 reducing pressure and leakages through the WDN. *Optimal DMA design* is therefore achieved by
25 solving a three-objective optimization minimizing the number of flow meters and the total unsupplied
26 customer demand while maximizing the reduction of background leakages; thus, pressure-driven
27 modelling is mandatory. The effectiveness and flexibility of the procedure is demonstrated using the
28 Apulian and Exnet networks. Results shows that DMA implementation can allow leakage reduction
29 on systems with excess of hydraulic capacity.

30

31 **INTRODUCTION**

32 The expansion of urban areas is increasing the complexity of the water distribution networks (WDNs)
33 analysis, planning and management, while the growing amount of field information for WDNs,
34 nowadays available from Information Communication Technology (ICT), could be helpful.
35 Nonetheless, this new source of information is expanding the technical tasks that water companies
36 could consider in order to increase service reliability and quality (e.g., vulnerability, performance,
37 resilience, water losses, planned and unplanned works, energy consumptions, etc.). In fact, WDNs
38 are key infrastructures, which are important in modern cities for several socio-economic reasons.
39 They are complex network structures due to factors like their size (thousands of pipes) and hydraulic
40 behaviour for the presence of non-linear devices.

41 Recently, several studies have been proposed in order to reduce the management complexity of
42 WDNs by dividing the hydraulic systems into districts for monitoring purposes.

43 This contribution proposes a novel and flexible procedure which disjoints the phase related to network
44 division in modules, named segmentation, and the engineering decision on the hydraulic system, i.e.
45 on the installation of flow meters or closed gate valves supporting the segmentation and creating the
46 actual district metering areas (DMAs). In fact, the network segmentation does not requires the
47 decision on the position of devices because it is a conceptual action on the network structure of a

48 WDN, although it can consider the devices that are already installed as existing cuts close to pipe
49 nodes (Giustolisi and Ridolfi, 2014a).

50 The community detection is the most popular approach to divide a WDN into modules, also named
51 segments or districts. The segment became district metering areas (DMAs) after installing flow
52 meters and closed gate valves. DMAs allow managing pressures, demands, leakages, rehabilitation
53 works, etc. by simplifying the hydraulic system analysis into smaller sub-networks, monitored in
54 terms of mass balance.

55 The technical literature reports several works dealing with DMA planning from various perspectives.
56 Considering WDN reliability analysis, Jacobs and Goulter (1988) proposed the division of the
57 networks into smaller sections, which can be analysed by using procedures that best exploit the
58 common features of the network and Yang et al. (1996) proposed a mechanical reliability index
59 computed using the minimum cut-set method.

60 The graph theory concepts were used for the identification of the network structure of the hydraulic
61 systems for monitoring and control purposes, as for example model calibration, metering water
62 consumption, early contaminant detection, control of pressure/leakages. Very recently, Torres al.
63 (2016) investigated the graph-based structural patterns and linkages with engineered performance
64 using a library of lattice-like pipe networks. Nonetheless, in literature, many algorithms and metrics
65 were used to define the optimal WDNs division with respect to topology and asset characteristics
66 such as pipes length and diameter, nodal elevations, leakages, etc..

67 Perelman and Ostfeld (2011) proposed a segmentation framework for topological/connectivity
68 analysis with the objective of developing and demonstrating a connectivity based algorithm for
69 WDNs analysis. Most recently, Perelman et al. (2015) proposed a strategy to decompose the system
70 into the main subsystems, approximating the network reconfiguration as a linear problem, where the
71 decision variables are the boundary valves in the edge cut and the objective function minimizes the
72 number of open boundary valves. Alvisi and Franchini (2014) suggested a procedure for the automatic
73 creation of DMAs in a WDN to identify good solutions in terms of resilience and minimum pressures,

74 accounting for the peak demand and fire-flow conditions. Ferrari et al. (2014) proposed a
75 methodology to design a given number of districts in looped WDNs considering some important
76 DMA design criteria as the maximum and minimum size recommended for a district, the
77 connectedness of each district to the water supply source and the absence of links between the
78 districts. Therefore, it allows the creation of DMAs that are independent one from each another. Di
79 Nardo et al. (2014) proposed a methodology aimed at defining the shape and dimension of network
80 DMAs based on topology using different segmentation procedures; thereafter, the location of flow
81 meters or gate valves was selected based on a partitioning technique using a real WDNs and a large
82 set of performance indices.

83 It has to remark that such literature contributions, although providing various approach, did not
84 account for all the characteristic of WDNs as infrastructure system. For example, devices are usually
85 assumed in the middle of the pipes although they are practically located close to pipe ending nodes.
86 Also such work rarely resort to hydraulically consistent pressure-driven simulation of background
87 leakages, besides demand supplied to customers.

88 Ferrari and Savic (2015) introduced the concept of leakage reduction by means of DMA definition.
89 In fact, closing gate valves changes hydraulic paths of the system and the implementation of DMAs
90 could allow reducing pressure with potential leakages reduction. It is worth noting that the
91 implementation of DMAs does not prevent from installing pressure reduction valves (PRVs) to
92 achieve larger leakage reduction. Rather, the effective planning of PRVs should account for the
93 districts in the network.

94 As mentioned above, this work proposes a novel two-steps strategy for optimal DMA design. The
95 strategy is based on the *optimal segmentation design*, as first step, aimed at achieving scenarios of
96 “conceptual cuts” dividing the network into modules (Giustolisi and Ridolfi, 2014a). “Conceptual
97 cuts” are defined as the locations of cuts that segment the WDN graph without accounting for devices
98 to be installed. In the second step, the *optimal DMA design* starts from one of the optimal
99 segmentation solutions and returns the decision on installing a flow meter or a closed gate valve in

100 each “conceptual cut”, accounting for the change of the WDN hydraulic behavior with respect to the
101 delivered customer demand and background leakages.

102 *Optimal segmentation* is here performed using a paradigm from complex network theory (Albert and
103 Barabasi, 2002; Fortunato, 2010; Newman, 2010). In fact, one possible approach to network
104 segmentation is referring to community detection strategies, while the most popular one is based on
105 modularity index (Newman, 2004). The modularity index is the most widely accepted and used metric
106 to measure the propensity of the network division into modules (or communities, consistently with
107 the earliest applications of the index) (Newman and Girvan, 2004). The modularity is a descriptive
108 measure of topology and relies strictly on the network structure. The advantage of the modularity is
109 that it is a topological index, which depends only on the identification of network adjacency matrix
110 (Steinhaeuser and Chawla, 2010) and whose assessment does not require high computational costs.
111 For a given network, a higher value of the maximum modularity index indicates a better identification
112 of communities; therefore, the maximum value of the modularity corresponds to the maximum degree
113 of segmentation.

114 Recently, Scibetta et al. (2013) and Diao et al. (2013) applied the modularity index to the
115 segmentation of a WDN using the original Newman’s formulation. Unfortunately, the original
116 formulation was proposed for immaterial networks and Barthélemy (2011), for example, pointed out
117 the strong difference between immaterial networks (e.g., food web, trade, World Wide Web) and
118 material networks (e.g., urban infrastructure networks).

119 For this reason, Giustolisi and Ridolfi (2014a) tailored the original modularity index in order to obtain
120 a WDN-oriented modularity index accounting for the features of WDNs which are infrastructure
121 systems. The modification of the original modularity index consists in considering the “conceptual
122 cuts” segmenting the network close to ending nodes (instead of the middle of pipes) and in introducing
123 pipe weights in the formulation of the WDN-oriented modularity index. Furthermore, Giustolisi and
124 Ridolfi (2014b) proposed an infrastructure modularity index, modifying the WDN-oriented
125 modularity index, in order to overcome the resolution limit of the original modularity index

126 (Fortunato and Barthélemy, 2007), which causes the non-identifiability of smaller modules depending
127 on the size of the network. Finally, Giustolisi et al. (2015) reported a comprehensive framework of
128 the WDN-oriented modularity indexes.

129 The WDN *segmentation* provides the initial step to solve the *DMA design* problem, since “conceptual
130 cuts” represent candidate locations of closed gate valves or flow measurement devices. For this reason
131 the optimal segmentation design is driven by the minimization of the number of cuts versus the
132 maximization of one of the modularity metrics proposed by Giustolisi and Ridolfi (2014a;b), which
133 is selected according to the most important technical task driving the actual DMA design (during the
134 second phase).

135 Thereafter, during the second step of the procedure, the modules identified by “conceptual cuts”
136 becomes actual DMAs establishing which “conceptual cuts” will represent the location of flow
137 measurements or closed valves.

138 Following the idea of exploiting the potentiality of DMA implementation to reduce background
139 leakages while preserving adequate water supply service, the procedure proposed herein for planning
140 DMAs is solved as a three-objective optimization problem, which minimizes the number of flow
141 meters and the total unsupplied customer demand while maximizing the reduction of background
142 leakages. This way, deciding the “conceptual cuts” where to install the closed gate valves (*vice versa*
143 where to install flow meters) contemporarily avoids the worsening of the service quality (i.e.
144 searching for solutions with null or negligible unsupplied demand) and pursues the reduction of
145 leakages (i.e. searching for solutions with significant pressure reduction through the hydraulic
146 system).

147 Therefore, the optimal DMA design approach introduced by Ferrari and Savic (2015), is here
148 expanded using a two-step optimization in order to segment first, using the findings of the complex
149 network theory, and then to introduce the hydraulic behaviour of the system using a pressure-driven
150 hydraulic modelling computing leakages and unsupplied demand in order to achieve effective
151 technical solutions. The proposed procedure proves quite flexible and general since allows selecting

152 from among the optimal segmentation solutions in the first step and to introduce any
153 technical/engineering constraint or objectives to drive the effective allocation of devices in second
154 step.

155 A small size test case, the Apulian network (Giustolisi et al., 2008), will allow presenting the
156 procedure and clarifying the concept of “conceptual cuts”, “optimal conceptual scenario” and “actual
157 DMA”. A real medium size test case, the Exnet network (Giustolisi and Ridolfi, 2014b), will allow
158 demonstrating and analysing from the hydraulic standpoint the overall DMA design strategy.

159

160 **FROM SEGMENTATION TO DMA DESIGN**

161 The concept of DMA management was first introduced to the UK water industry in the early 1980s
162 (UK Water Authorities Association, 1980), where a district was defined as an area of a distribution
163 system specifically distinct, e.g. by the closure of valves, and in which the quantities of water entering
164 and leaving the district are metered. The subsequent analysis of flow calculates the level of leakage
165 within the district, not only to plan whether works should be undertaken to reduce leakages, but also
166 to compare the level of leakages among different districts, thus assessing where it is most beneficial
167 to undertake leak location activities.

168 From such perspective, the division of WDN into districts is a common practice for multiple technical
169 purposes, generally aiming at simplifying system analysis, planning and management problems, as
170 for example, support model calibration, plan efficient metering systems, demand and leakage
171 management, etc. Walski et al. (2001) reported many technical aspects related to the installation of a
172 system for water sub-metering as well as ancillary works and activities in a real WDN, thus
173 emphasizing the need to support the effective planning of DMAs.

174 As said above, Giustolisi and Ridolfi (2014a) tailored the original modularity (Newman, 2004) in
175 order to define the WDN-oriented modularity index accounting for hydraulic networks, which are
176 infrastructure networks. To this purpose, they introduced the notion of “conceptual cuts”, which are
177 assumed close to the ending nodes of pipes where devices that create DMAs are actually installed. In

178 addition, they proposed a multi-objective segmentation design using WDN-oriented modularity
179 indexes.

180 Starting from such findings, in the proposed two-step optimal DMA design strategy, the first step
181 focuses on the structure of the hydraulic system as network, in order to segment/divide the hydraulic
182 domain, and in the second step focuses on the hydraulic behaviour, in order to define operative
183 districts. In fact, the network connectivity structure of the hydraulic system dominates the district
184 design with respect to the hydraulic behaviour. In fact, the network connectivity structure is the main
185 driver of the hydraulic behaviour.

186 It is worth noting that, searching for positions of devices (flow meters or closed gate valves), which
187 divide the network into modules and contemporarily satisfy the hydraulic requirements (service
188 quality and background leakage reduction) would be cumbersome because computationally very
189 expensive. In fact, it would be necessary to perform the extended period simulation using pressure-
190 driven analysis for all candidate segmentation alternatives during the optimization in order to compute
191 the hydraulic performance. The search space itself would increase exponentially with the size of the
192 WDN, making less and less effective the optimization.

193 On the contrary, the division of the design problem in the abovementioned two steps guarantees better
194 optimization performance and flexibility. In fact, when the segmentation solution, which is weakly
195 dependent on hydraulics, is selected, the DMA design can be simply and rapidly performed also
196 varying the hydraulic behaviour of the network (e.g. demands, installed control devices, etc.) and
197 accounting for peculiar technical objectives like, for example, system reliability.

198

199 **METHODOLOGY**

200 The subdivision of hydraulic systems into districts represents a technically structured approach for
201 several management purposes including monitoring, control and operations that might require the
202 isolation of some portion of the system (e.g. in case of planned or accidental interruptions). The
203 district design problem of WDNs has generally three drivers: (i) network structure (primarily the

204 topology, but also the hydraulic and asset characteristics), (ii) specific technical purposes (e.g.
205 monitoring water consumption) and (iii) technical constraints related to uncertainty or limitation of
206 the budget, pre-existing segmentations and devices, and/or other objectives generally related to
207 capital/operational costs. Finding a trade-off among these different goals is a complex management
208 task and is a relevant issue for water utilities to ensure adequate service for customers, increasing the
209 benefits of the planned investments. A general-purpose approach to the district design is not available
210 at date and empirical methods are generally used resorting to expertise of technicians.

211 The modularity index represents ultimately the most popular index used to divide networks into
212 modules by means of “conceptual cuts”, which are the candidate positions for installing devices
213 creating actual DMAs and even for designing isolation valve systems (Giustolisi and Savic, 2010).
214 In fact, incidentally, the segmentation problem might entail directly the optimal location of gate
215 valves only.

216 This work proposes the following district design paradigm, based on two main phases:

217 A. Two-objective optimal network segmentation, minimizing the number of “conceptual cuts”
218 versus the maximization of the WDN-oriented modularity index. Each segmentation solution
219 consists of a set of “conceptual cuts” dividing the network structure of the WDN into modules. It
220 is possible to constraint the multi-objective optimization to search for nested solutions. This means
221 each segmentation solution can be generated starting from the one having the lowest number of
222 modules by progressively increasing number of modules, so that solutions with higher resolution
223 (with more “conceptual cuts”) are nested in the more parsimonious segmentations (with less
224 “conceptual cuts”), i.e. subdividing the modules of the more parsimonious segmentation. This fact
225 provides flexibility to the segmentation design because it is possible to start from any optimal
226 scenario, depending on the preferred resolution of the districts, which is generally driven by the
227 available budget. Such feature allows the dynamic planning of the segmentation, increasing over
228 time the resolution of the districts, considering the budget uncertainty and the growing knowledge
229 of the system. Therefore, although one solution needs to be selected among the *optimal*

230 *segmentation solutions* as the basis for the actual DMA design, a “nested” segmentation design
 231 makes the procedure flexible from a technical perspective. It is to remark that the devices already
 232 installed in the system are constraints for the optimal segmentation design (Giustolisi and Ridolfi,
 233 2014a; b), therefore the proposed procedure is flexible also with respect to the applications in real
 234 hydraulic systems where DMA or devices already exist;

235 B. starting from the *selected segmentation solution*, a three-objectives optimization is performed by
 236 simultaneously minimizing the number of flow observations and the unsupplied customer demand
 237 while maximizing the reduction of leakages. The minimization of the number of flow meters
 238 instead of their total cost, which depends on diameter, represents a pressure for the optimization
 239 to install a lower number of flow meters on pipes having greater flow rates, as reported later in
 240 the text. The minimization of background leakages entails a driver towards installing closed gate
 241 valves in strategic positions, which changes the water paths resulting into reduced pressures
 242 through the hydraulic system. Finally, the minimization of the total unsupplied customer demand
 243 guarantees solutions, which are technically effective with respect to service quality.

244

245 **Optimal network segmentation (Phase A)**

246 The WDN-oriented modularity index is the basis of the optimal segmentation; its formulation is,

$$247 \quad Q(\mathbf{w}_p) = \left\{ 1 - \frac{n_c}{n_p} \right\} + \left\{ - \sum_{m=1}^{n_m} \left[\sum_{k=1}^{n_p} \frac{(\mathbf{w}_p)_k \delta(M_m, M_k)}{W} \right]^2 \right\} = Q_1 + Q_2 \quad (1)$$

248 where n_c is the number of pipes linking modules of the infrastructure network, namely the number of
 249 “conceptual cuts” in the network (i.e. the decision variables of the segmentation problem) and n_m is the
 250 number of modules. The summation inside the square brackets is related to pipe weights stored in the
 251 vector \mathbf{w}_p , whose sum is W , and Kronecker's δ function makes that the sum refers only to the weights of
 252 pipes belonging to the m -th module (i.e. $\delta = 1$ if $M_m = M_k$ and $\delta = 0$ otherwise).

253 It is worth to note that the term Q_1 of Eq. (1) decreases with the number of cuts, while Q_2 generally
 254 increases with the number of modules and, for a given number of modules, it increases with the similarity
 255 of modules to each other with respect to the assumed pipe weights.

256 The modularity index measures the similarity of the segments/modules with respect to selected pipe
 257 weights (e.g.; in the case of lengths the similarity of segment lengths) for a given number of “conceptual
 258 cuts” dividing the network in n_m segments. Therefore, its maximization provides the maximum number
 259 of modules, which are similar with respect to pipe weights, obtained with the minimum number of cuts.

260 The formulation of the two-objective optimal segmentation is,

$$\begin{cases} [M, n_c, n_{act}] = \text{Connectivity}(I_c, |\mathbf{A}_{np}|) \\ f_1 = \max \{Q(\mathbf{L}_p)\} = \max \left\{ \left(1 - \frac{n_c}{n_p} \right) - \sum_{m=1}^{n_{act}} \left[\sum_{k=1}^{n_p} \frac{(\mathbf{L}_p)_k \delta(M_m, M_k)}{L} \right]^2 \right\} \\ f_2 = \min \{n_c\} \end{cases} \quad (2)$$

262 where \mathbf{A}_{np} is the incidence matrix, I_c is the set of n_c cuts in the network, decision variables of the
 263 optimization, the $\text{Connectivity}(I_c, |\mathbf{A}_{np}|)$ stands for component analysis of the undirected graph for the
 264 given cuts, and n_{act} indicate the cuts that are *actually* used to separate modules (Giustolisi and Ridolfi,
 265 2014a). Note that being the decision variables related to “conceptual cuts”, the already existing flow
 266 measurements corresponding to control valves, pumps, tank and reservoir, could be considered as
 267 constraints, i.e. already existing “conceptual cuts”, which are the initial basis of the network segmentation.
 268 Similarly, closed valve or pressure reduction valves locations can be considered as constraints, i.e. already
 269 existing “conceptual cuts”.

270 Although several formulation of the WDN-oriented modularity index have been developed (Giustolisi et
 271 al., 2015) the use of a specific index does not impair the generality of the multi-objective optimization
 272 described in Eqs. (2). In this work the length of pipes stored in the vector \mathbf{L}_p , is reported in Eqs. (2),
 273 therefore L is the sum of pipes lengths. Actually, this selection is consistent with the main purpose of
 274 reducing leakages while guaranteeing adequate water supply in next DMA design. In fact, pipe lengths

275 significantly influence the WDN hydraulic behavior having a technical meaning also with respect to
276 background leakages for a given deterioration of the system (Giustolisi et al., 2008).

277 Solving the optimization problem in Eq. (2) returns a Pareto front of *segmentation solutions* that are
278 *optimal* with respect to the number of “conceptual cuts”, thus generating modules that are similar to each
279 other in terms of total length for a given number of cuts. As said, the optimal segmentation could be
280 constrained to search for nested solution providing flexibility to the entire procedure. At the end of this
281 first phase, the selected optimal segmentation solution, for example based on available budget, will be the
282 basis for the second phase related to the actual design of DMAs.

283

284 **Optimal design of the network DMAs (Phase B)**

285 The optimal DMA design procedure aims at determining the position of flow meters and closed gate
286 valves in the “conceptual cuts” dividing the network structure of the WDN in modules. Therefore, the
287 optimization problem has binary decision variables, one for each “conceptual cut”, corresponding to the
288 decision of installing a flow meter or a closed gate valve. It is worth noting that the procedure could be
289 constrained by existing flow meters (e.g. close to tanks, reservoirs, pump installations, etc.) and existing
290 closed gate valves, (i.e. considered as constrained “conceptual cuts” during the first phase) are assumed
291 as fixed variables during the second phase. In addition, between the first and second phase, a connectivity
292 analysis is performed to check whether the closure of each candidate isolation valve would determine the
293 disconnection of some WDN portions; unfeasible locations of gate valves are then automatically removed
294 from the set of candidates assuming flow meters.

295 As said above, the installation of closed gate valves alters the original flow paths reducing the pressure
296 status into the WDN due to the increase of head losses along other flow paths. In other words, the
297 procedure is conceived to obtain a double effect, the design of districts in the hydraulic system and the
298 leakage reduction (Ferrari and Savic, 2015).

299 The formulation of the three-objective optimal segmentation problem is,

$$\begin{cases}
f_1 = \min \{n_{fm}\} \\
f_2 = \max \left\{ 1 - \frac{V_T^{leak}(\mathbf{v})}{V_T^{leak}} \right\} \\
f_3 = \min \left\{ 1 - \frac{V_T^{cust}(\mathbf{v})}{V_T^{cust}} \right\}
\end{cases}
\quad \text{subject to:} \quad (3)$$

$$\begin{cases}
\left[\begin{array}{l}
\mathbf{A}_{pp} \mathbf{Q}_p(t) + \mathbf{A}_{pn} \mathbf{H}_n(t) \\
\mathbf{A}_{np} \mathbf{Q}_p(t) - [\mathbf{d}_n^{leaks}(\mathbf{H}_n, t) + \mathbf{d}_n(\mathbf{H}_n, t)]
\end{array} \right] = \begin{array}{l}
-\mathbf{A}_{p0} \mathbf{H}_0(t) + \mathbf{H}_p^{pump}(t) \\
\mathbf{0}_n
\end{array}
\end{cases} \quad \forall t=1, \dots, T$$

and *Technical Constraints*

301 where n_{fm} is the number of flow meters; V_T^{cust} and V_T^{leak} are namely the total customer demand and
302 leakages over T -steps extended period simulation (EPS), in the original WDN configuration (i.e. without
303 accounting for devices); $V_T^{cust}(\mathbf{v})$ and $V_T^{leak}(\mathbf{v})$ are the same figures, but referred to the set \mathbf{v} of closed gate
304 valves located at “conceptual cuts” (i.e. representing the implementation of the DMAs). \mathbf{d}_n and \mathbf{d}_n^{leaks} are
305 the vectors of water demand and background leakages (lumped at nodes) which depend on time and
306 current pressure status. Further details on the hydraulic model used for the following case studies are
307 reported in Giustolisi et al. (2008).

308 In order to account for the emptying/filling process of tanks during optimal DMA design the following
309 constraints have to be added to the formulation (3),

$$\begin{cases}
H_s^{ini} \leq H_s^{final} \\
H_s(t) \geq H_s^{\min}
\end{cases} \quad (3a)$$

311 where s is the subscript of the s th tank node; H_s^{\min} is the minimum head level at the s th tank node;
312 H_s^{ini} is the initial head level at the s th tank node varying over time t and H_s^{final} is the final level at the
313 s th tank node. The constraints in (3a) guarantee system reliability because the first equation states that
314 the initial level (i.e. volume) in each tank should be lower than the final of the EPS, while the second
315 states that the tank level cannot be lower than the minimum during EPS.

316 The minimization of the number of flow meters does not account for their cost of purchasing, which
317 depends on pipe diameter, for two main reasons: (i) the flow meters management cost is much higher than

318 the initial cost of purchasing; and (ii) it drives the search towards a lower number of flow meters installed
319 on pipes with greater flow rates. In other words, it drives towards the installation of closed gate valves on
320 pipes with lower flow rates, whose interruption that does not impair the service quality while allowing
321 leakage reduction.

322 The reduction of the background leakages is formulated as the fraction of saved water volume with respect
323 to the original WDN configuration (i.e. without closing the valves). The maximization of the leakages
324 volume reduction, obtained through the positioning of closed valves, is assessed by means of extended
325 period simulation of the hydraulic system behavior, i.e. during a selected operative cycle. It is relevant to
326 note that pressure-driven analysis is compulsory for hydraulic modelling (Giustolisi et al., 2008; Giustolisi
327 and Walski, 2012).

328 Finally, the minimization of the total unsupplied customer demand is formulated as fraction of the water
329 volume unsupplied to customers with respect to that required during a selected operative cycle. This
330 objective function is relevant in order to obtain the leakage reduction with null or negligible unsupplied
331 demand, i.e. without decreasing service quality. Once again, pressure-driven analysis represented with the
332 matrix equations in (3) is compulsory to compute the unsupplied demand, e.g. using the Wagner model
333 (Wagner et al., 1988).

334 It has to remark that the abovementioned pressure-demand model permits also to consider the pressure
335 requirements of hydrants when the WDN serves for fire protection. In the case of accounting for fire
336 protection, in the hydraulic model of Eqs. (3) the component of hydrants in demands is added, i.e. \mathbf{d}_n
337 + \mathbf{d}_n^{leaks} + \mathbf{d}_n^{hydr} , and a scenarios of fire protection based on specific national regulation should be
338 considered (Giustolisi and Walski, 2012). Another possible approach is to increase the pressure for a
339 correct service considering the pressure requirement for hydrant and an excess of pressure in order to
340 consider the increased flow in the network during a fire event.

341 However, it is to remark that fire protection is not an issue for all water distribution networks,
342 depending on the specific national regulations and on the leakage rate, which can suggest renouncing
343 to the higher pressure required for fire protection. For this reason, the case study, without loss of

344 generality, will be performed to discuss and demonstrate the two steps for DMA design methodology
345 considering the requirements for customer demands only.

346 Finally, phase B allows introducing any *Technical Constraint* (last Eq. (3)) in order to drive DMA design
347 towards engineering sound solution as, for example, excluding transmission mains (i.e. diameters larger
348 than a given threshold) from candidate location of closed gate valves.

349 Accordingly, the proposed strategy shows two levels of flexibility to support DMA design.

350 In phase A segmentation can be driven to return segments that are nested, thus permitting flexibility in
351 the selection of the conceptual cut that are candidate for the next step or to account for existing devices.

352 In phase B, it permits to introduce any technical/practical constraints entailing engineering considerations
353 or even other objective functions to match peculiar technical purposes, even different from those reported
354 in this work (e.g. minimize the possible spread of contaminants (e.g. Grayman et al., 2016) while
355 minimizing background leakages and matching the required demand).

356

357 **CASE STUDIES**

358 All tests were performed by means of a specific function for WDN segmentation implemented as part of
359 WNetXL system integrating a genetic algorithm, named OPTIMOGA (see Acknowledgements). The
360 methodology is presented on three different case studies, Apulian network, Apulian oversized network
361 and Exnet network.

362

363 **Apulian Case study**

364 The proposed design strategy is here presented on a simple network in order to show and discuss its main
365 features. The Apulian network (Giustolisi et al., 2008) is a small network having one reservoir feeding by
366 gravity 23 nodes and 34 pipes, whose layout is reported in Figure 1. The parameters of the leakage model
367 (Germanopoulos, 1985; Giustolisi et al., 2008) are set as $\alpha = 1.2$ and $\beta = 1.06 \times 10^{-7} \text{ m}^{2-\alpha} \text{ s}^{-1}$ for all the pipes,
368 which leads to a leakage rate of about 24% of the total WDN inflow. The pressure assumed to get a correct
369 water supply service is 10 m at every demand node. The first optimization procedure (phase A) returned

370 a Pareto front of optimal segmentations by solving the problem of Eqs. (2). The optimal configurations
371 are characterized by a number of cuts ranging from three to nine. It is to remark that all configurations
372 share a common “conceptual cut” close to the unique reservoir of the network, which should be candidate
373 to be flow meter in the final DMA solutions/configurations.

374

375 **Results and discussion - Apulian case study**

376 The solution with the maximum number of cuts, reported in Figure 2, corresponds to the maximum value
377 of the WDN-oriented modularity index. This last solution is here selected as the basis for the second phase
378 (phase B), the actual DMA planning.

379 As reported in Table 1, the phase B returned several “DMA configurations”, i.e. location of flow meters
380 and closed valves, resulting into different leakage reduction rates and total unsupplied customer demand.
381 Table 1 shows that the number of closed gate valves for different “DMA configurations” ranges from 5
382 (i.e. 4 flow meters) to 2 (i.e. 7 flow meters). Due to the hydraulic capacity of the original network (i.e.
383 optimized for normal working conditions without closed valves), few solutions in Table 1 (i.e., 1, 10, 11,
384 17, 20, 30 and 35) show null or negligible unsupplied demand in spite of closed gate valves. Those “DMA
385 configurations” are characterized by a small leakage reduction of about 4% on average. Therefore, the
386 optimization provides information about the actual possibility of reducing leakages by installing closed
387 valves, accounting also for the residual hydraulic capacity of the system.

388 It is worth noting that the maximum percentage of leakage reduction (70%) is achieved with five closed
389 gate valves and that, in general, the reduction of background leakages involves the increase of unsupplied
390 demand, consistently with the reduction of pressure due to the change of water paths in the network.

391 From management perspective, accepting values of unsupplied demand lower than 1% (e.g. equal to
392 0.35%), it is possible to achieve about 4% of leakage reduction.

393 Figure 3 reports two optimal DMAs configurations corresponding to solutions number 12 and 13 in Table
394 1 having three closed valves and six flow meters. It is evident that to a high value of leakage reduction
395 corresponds a high value of unsupplied demand, while the unsupplied demand value grows up when a

396 configuration with a higher leakage reduction is considered as solution. In fact, pipe sizes in Apulian
397 WDN were optimally designed (Giustolisi et al., 2008) in order to provide sufficient hydraulic capacity
398 without closing any valve. This, in turns, leaves little room to reduce losses without increasing the
399 unsupplied demand.

400 Furthermore, the two configurations of Figure 3 differ for a closed valve installed on pipe 7 and 1 (see
401 Figure 1) having the similar diameters (i.e. 327 mm and 368 mm,). Despite this fact, the configurations
402 returns different technical conditions. This observation hints that an important driver of an effective DMA
403 design is the network topological structure of the hydraulic system. In other words, given a diameter, i.e.
404 a cost of valve installation, the hydraulic effect on the WDN can be greatly influenced by the topological
405 position of that valve as well as the position of the other valves, thus changing the flow paths in the system.
406 In order to prove further this point, the only phase B of the procedure was performed on an oversized
407 version of the Apulian network. Such oversizing was obtained by assuming internal diameters equal to
408 184 mm for all pipes in bold in Figure 1 in place of the optimized diameters equal to 100 mm for all such
409 pipes except for pipes 15 and 27, whose optimized diameters were 164mm. This way, the network is
410 assumed to represent real systems, which are generally oversized with respect to the customer water
411 requests.

412 Table 2 reports the three Pareto efficient solutions returned for the optimal DMA design of the oversized
413 Apulian WDN. It is evident that the increased hydraulic capacity due to pipe oversizing allows finding
414 solutions with null or negligible unsupplied demand with respect to the previous case, although showing
415 sensible leakage reduction.

416 Indeed, Figure 4 shows that the leakage reduction values are similar even if the positions of the closed
417 valves change among different solutions. Each solution creates different flow paths inside the hydraulic
418 network and for this reason the WDN functioning needs to be considered globally and not looking at a
419 single closed valve.

420 It is worth remarking that, for the oversized Apulian, the same segmentation configuration (i.e.
421 “conceptual cuts”) used for the original Apulian is the basis of the optimal DMA design. This fact

422 demonstrates the flexibility of the procedure that does not require repeating the optimal segmentation
423 design (phase A) when the network topology does not change.

424

425 **Exnet Case study**

426 Exnet network (Giustolisi et al., 2008) is a real medium size network composed of 1.894 nodes and 2.471
427 pipes. Figure 5 reports the network layout. Actually, for the sake of the example all valves in the original
428 Exnet data were eliminated, while five reservoirs were added at original inflow nodes 3003, 3004,
429 3005, 3006 and 3007; the head of all such new reservoirs and the original reservoir 3001 were
430 assumed equal to 70 m. Finally, the elevation of junctions 1107, 1084, 726, 55, 41, 186, 1092, 120
431 and 5555 (i.e. close to reservoirs 3001 and 3002) was put equal to 10 m. All such changes guarantee
432 hydraulically consistent simulation of inlet flow using pressure-driven analysis.”Also, it is assumed a
433 leakage model with parameters $\alpha = 1.1$ and $\beta = 10^{-8} \text{ m}^2\text{-}\alpha\text{s}^{-1}$ for all the pipes (Germanopoulos, 1985;
434 Giustolisi et al., 2008), which leads to a leakage rate of about 28% with respect to the total water inflow.
435 The hydraulic system was analyzed during a daily operating cycle using the same daily pattern of
436 customer demands reported in Figure 1, because the original real pattern was not available.

437 Without loss of generality for the following discussion, as explained in the section entitled “Optimal
438 design of the network DMAs (Phase B)”, the fire protection is not here considered.

439 Figure 6 shows the Pareto front of *optimal segmentations* returned by the first optimization procedure of
440 the methodology (phase A) for Exnet network. The maximum value of the WDN-oriented modularity
441 corresponds to ninety-nine “conceptual cuts” dividing the network in 32 modules, as reported in Figure
442 7, while the minimum number of “conceptual cuts” is constrained by the eight pipes delivering water
443 from the seven reservoirs. The segmentation scenario of Figure 7 was used as basis for the second phase
444 (phase B) in order to design the actual DMAs.

445 It is to remark that the selected solution for phase B has some cuts, which are either close to the reservoirs
446 or separate branched portions from the rest of the WDN. For these cuts, the installation of a flow meter is
447 mandatory, because otherwise one or more reservoirs or network portions would be disconnected.

448 Moreover, for the sake of the example, the optimal DMA design of Exnet was constrained to pipes with
449 diameters no higher than 500 mm. From hydraulic standpoint, this constraint avoid closing major
450 transmission mains that would result into massive reduction of system hydraulic capacity for which the
451 WDN was originally designed, although oversized.

452 Therefore, considering that all abovementioned technical constraints results into 31 mandatory flow
453 meters, the DMA design phase will provide the decision about installing a closed gate or a flow meter for
454 68 out of 99 “conceptual cuts”.

455

456 **Results and discussion - Exnet Case study**

457 The optimization procedure returned 12 solutions (Figure 8), all characterized by null unsupplied demand.
458 In fact, as for the oversized Apulian case, Exnet hydraulic system is oversized and the returned solutions
459 dominate the technically unfeasible ones.

460 The twelve solutions shows a number of flow meters ranging from 16 to 27 (i.e. closed gate valves
461 decreasing from 52 to 41), that correspond to a leakage reduction between about 11% and 15% with
462 respect to the original configuration.

463 Figure 9 shows the percentage of times that each candidate “conceptual cuts” is selected for installing a
464 closed valve, over the twelve optimal DMA design solutions. Consistently with previous constraints, the
465 maximum pipe diameter in Figure 9 is 500 mm. 33 out of 68 “conceptual cuts” are selected in all solutions
466 (i.e. 100% of times) for installing closed gate valves. This means that such “conceptual cuts” are in
467 strategic topological position to change water paths in the WDN, irrespectively on their diameter.

468 Figures 10 and 11 show the pressure drop, with respect to the original pressure status, of the solutions 1
469 and 12, which are obtained with a different number of flow meters, 27 and 16 respectively (corresponding
470 to 41 and 52 closed valves). The leakage reduction is about 15.4% and 11%, respectively. Therefore, a
471 significant difference between the reported solutions exists in terms of ratio valves/meters and positioning
472 at “conceptual cuts”. This generates a different hydraulic behaviour of the WDN, as shown by pressure
473 drop in Figures 10 and 11. In other words, each solution generates a different distribution of flow paths

474 with respect to the original ones of the hydraulic system (i.e., without DMAs definition), which need to
475 be carefully simulated considering a pressure-driven analysis and a consistent background leakages
476 model. Figures 12 and 13 show the significant difference in terms of diameters of closed valves with
477 respect to flow meters of the solutions 1 and 12. In terms of leakage reduction, it can be observed that a
478 solutions with a larger number of closed valves installed on smaller diameter pipes (i.e. up to 319 mm)
479 (solution 12) is less effective than a solution with a lower number of valves installed on larger diameter
480 pipes (solution 1).

481 Therefore, bearing in mind that none of the solutions have unsupplied demand, the trend of increasing
482 leakage reduction as the number of closed valves decreases indicates that a lower number of valves can
483 be more effective for leakage reduction, because installed in strategic topologic positions (i.e., more
484 important flow paths) with respect to the original flow paths of the hydraulic system. *Vice versa*, a greater
485 number of valves can be less effective for leakage reduction, if their positioning is driven only by the need
486 of topological division of the network structure, i.e. they are installed in positions that do not change
487 significantly the original system configuration. From this perspective, it is worth noting that a realistic
488 hydraulic modelling is strategic in order to predict the WDN behaviour. Thus, leakage and pressure-driven
489 analysis are compulsory. In the opposite case, considering pressure drops in demand-driven analysis as
490 surrogate of their actual effect on leakage reduction might result in a solution with many closed valves
491 driven by the topologic division of the network structure, because negative pressures returned by demand-
492 driven modelling need to be avoided, with the result of a negligible actual leakage reduction.

493 Finally, considering that all the proposed solutions are optimal as resulting from the solution of problem
494 in Eqs.(3), the best selection among the DMA design solutions depends on constraints/options of the
495 decision maker, e.g. the number of flow meters versus leakage reduction, DMA configuration, etc.
496 Therefore, consistently with results, the authors' opinion is that DMA design should be accomplished on
497 the base of a decision support tool providing Pareto efficient solutions, which are all effective with respect
498 to the objective functions explicitly accounted in the problem definition. Such solutions could be
499 significantly different from a more comprehensive technical standpoint when additional criteria are

500 adopted, that are not considered while solving in the problem statement. Our procedure, thanks to the
501 flexibility, see e.g. problem formulation in Eqs. (3), allows designing technically consistent DMAs.

502

503 **CONCLUSIONS**

504 The paper presents a two-phase design strategy for *optimal DMAs design*. The first phase entails a multi-
505 objective optimization, where the network is segmented by maximizing the infrastructure modularity
506 index (Giustolisi and Ridolfi, 2014b) against the minimization of the number of “conceptual” pipe cuts.

507 The second phase starts from an *optimal segmentation* solution returned by the first phase, and searches
508 for the actual DMAs of the network by establishing the position of flow meters and closed valves among
509 the “conceptual cuts”, accounting for the reduction of the number of flow meters, background leakages
510 and unsupplied demand to customers, within a multi-objective optimization. Moreover, the second phase
511 is able to incorporate any technical constraint driven from engineering or management needs.

512 An advanced pressure-driven modelling approach to predict leakage reduction and unsupplied demand
513 (Giustolisi et al., 2008) is embedded in both phases.

514 The procedure proves able to deliver many district metering solutions, taking into account of various
515 technical and management aspects, as well as those related to the hydraulic functioning of the network
516 (leakages, unsupplied demand, pressure deficit, etc.) and engineering insight as technical constraints. In
517 particular, from the background leakages reduction perspective, results from the case study related to a
518 real WDN, highlighted the different impact of placing closed valves in few strategic positions rather than
519 in many locations as obtained looking at network topological division only.

520 The proposed approach, based on separating the segmentation of the WDN from the planning of devices
521 at DMA boundaries allows great flexibility to provide technically feasible alternatives. Besides the
522 possibility of including prior “conceptual cuts” or selecting among “nested” segmentation solutions in the
523 phase A, the DMA design optimization problem in phase B can be easily extended including other
524 objective functions and/or technical constraints.

525

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529 water losses in urban aqueducts” and “Tools and procedures for an advanced and sustainable
530 management of water distribution systems”.

531 The case studies reported herein has been accomplished by means of the WNetXL Design Module,
532 which implement the proposed optimal DMA design strategy. The system tool WNetXL can be
533 requested free of charge for students and research purposes at www.idea-rt.com. The network data
534 used in WNetXL can be obtained contacting Prof. Orazio Giustolisi (orazio.giustolisi@poliba.it).

535

536 **Notations list**

537 *The following symbols are used in this paper:*

538 \mathbf{A}_{pn} = general topological matrix of the network ($\mathbf{A}_{pn} = \mathbf{A}_{np}^T$);

539 F_i = objective function;

540 I_c = set of n_c cuts in the network;

541 K_i = node degree of the i -th node;

542 \mathbf{L} = connectivity matrix of the edges/pipes;

543 $(\mathbf{L}_p)_k$ = vector of pipe length values in module k ;

544 L = sum of pipes length values;

545 M_i = identifier of network modules;

546 N = network;

547 n_{act} = actual number of modules satisfying the constraints;

548 n_c = number of pipes linking modules of the infrastructure;

549 n_m = number of network modules;

550 n_p = number of network links/pipes;

551 Q = WDN-oriented modularity index;

552 \mathbf{w}_p = vector of pipe weights;
553 W = sum of pipe weights;
554 α = exponent of the leakage model;
555 β = coefficient of the leakage model;
556 δ = Kronecker's delta function;

557

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639

640 **List of Tables**641 **Table 1.** List of forty-two DMA optimal solutions for Apulian case study.

Solution	Closed Valves	Leakage Reduction [%]	Unsupplied Demand [%]
1	1	3,58	0,33
2	1	27,27	7,60
3	2	3,56	0,33
4	2	29,83	11,05
5	2	31,27	13,77
6	2	27,08	7,93
7	2	45,55	29,70
8	2	36,22	19,68
9	2	27,08	7,95
10	3	3,91	0,33
11	3	1,09	0,00
12	3	34,55	19,14
13	3	47,78	34,28
14	3	36,24	19,70
15	3	29,56	11,81
16	3	40,07	29,24
17	3	7,70	0,90
18	3	48,80	37,87
19	3	36,64	19,70
20	3	4,78	0,35
21	3	30,93	14,76
22	3	31,07	19,11
23	3	40,44	29,26
24	3	39,66	20,22
25	3	26,78	8,46
26	3	68,52	50,94
27	4	17,53	13,60
28	4	50,92	44,98
29	4	36,75	19,76
30	4	4,78	0,34
31	4	40,50	29,26
32	4	69,84	57,33
33	4	47,26	40,78
34	4	39,82	20,23
35	4	8,66	0,91
36	4	29,95	16,88
37	4	45,46	30,55
38	4	43,84	29,77
39	4	70,48	61,54
40	4	70,35	61,53
41	4	66,91	53,70
42	4	26,25	13,67

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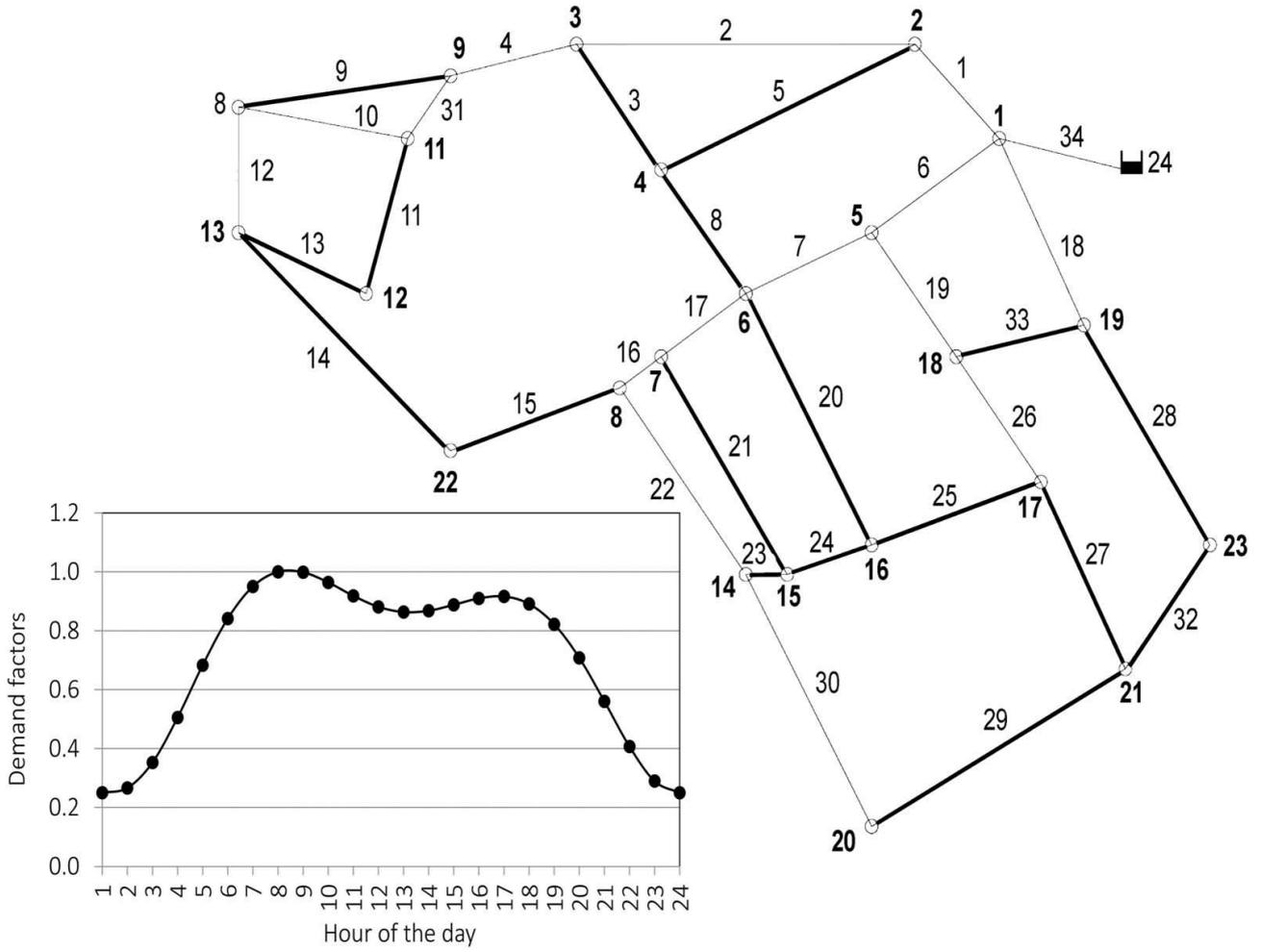
644 **Table 2.** List of three DMA optimal solutions for Apulian oversized case study.

Solution	Closed Valves	Leakage Reduction [%]	Unsupplied Demand [%]
1	5	18.23	0.02
2	5	17.23	0.00
3	4	17.22	0.00

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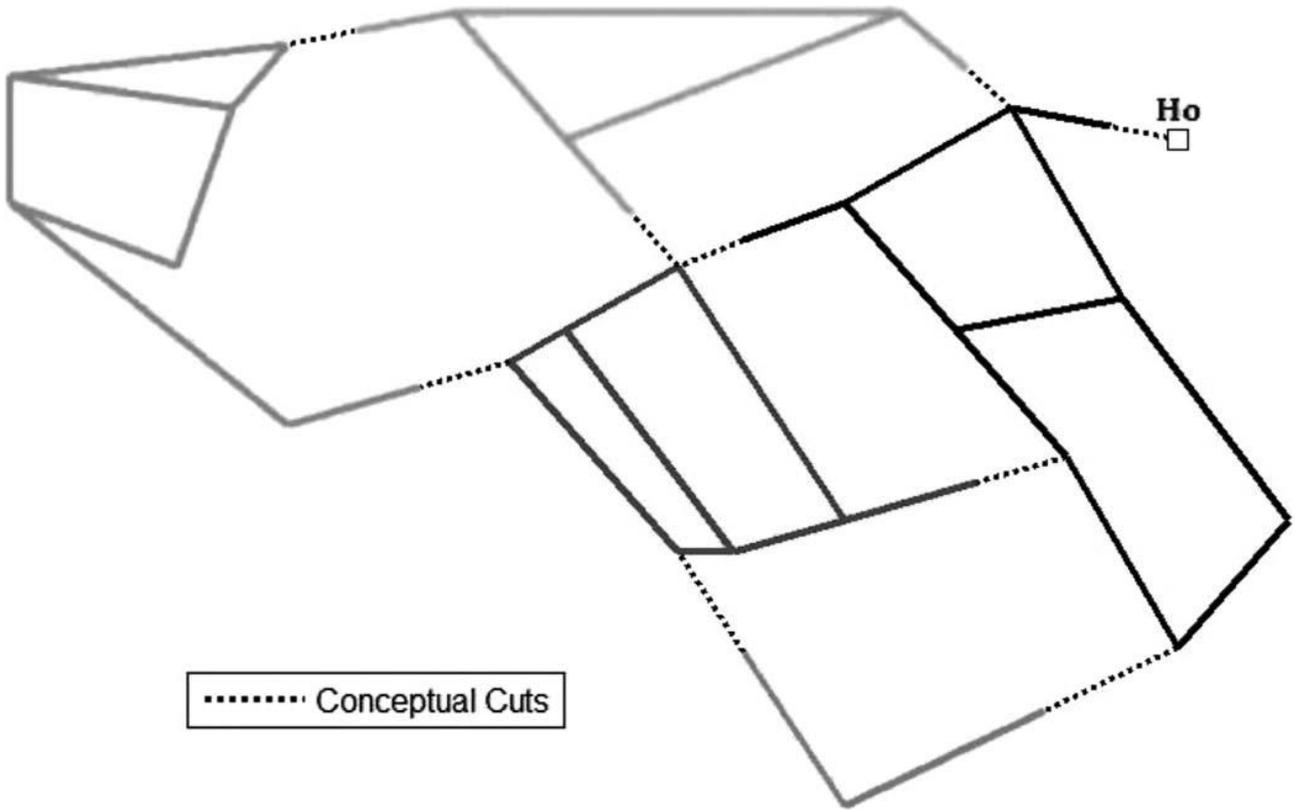
647 **Fig. 1.** Apulian network layout and daily pattern of customer demands.



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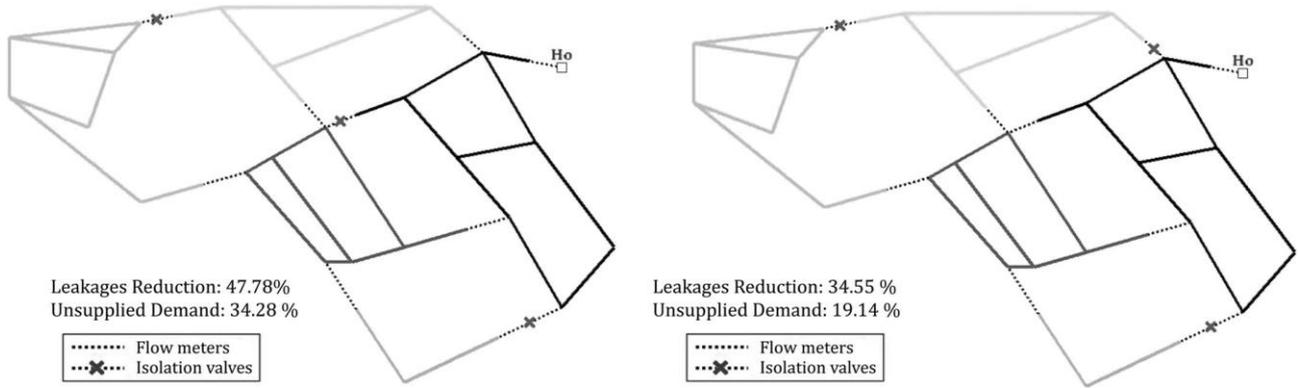
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650 **Fig. 2.** Segmentation with nine “conceptual cuts” dividing the network structure of the hydraulic
651 system in five districts (coloured).



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655 **Fig. 3.** Two solutions of optimal DMAs design with three valves and six flow measurements.

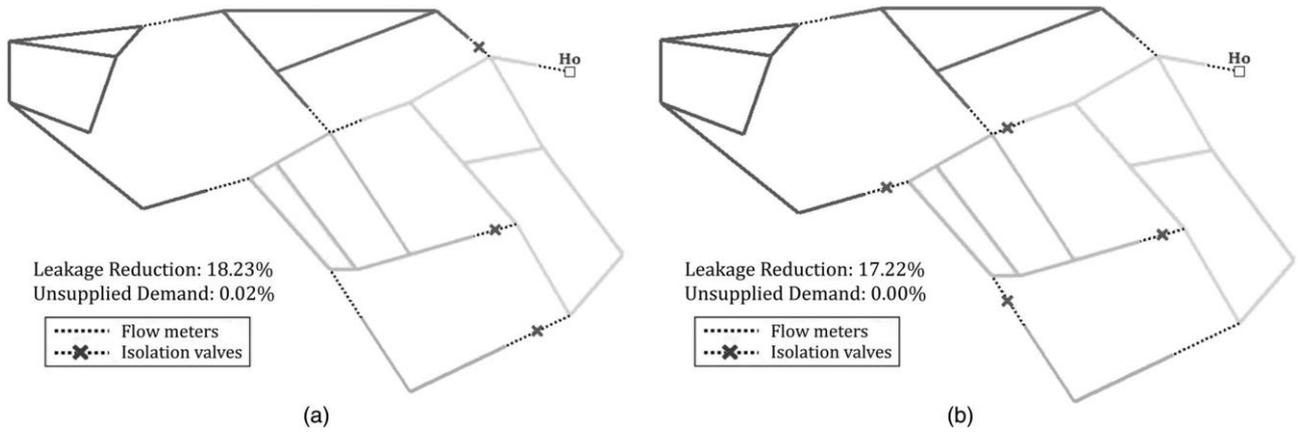


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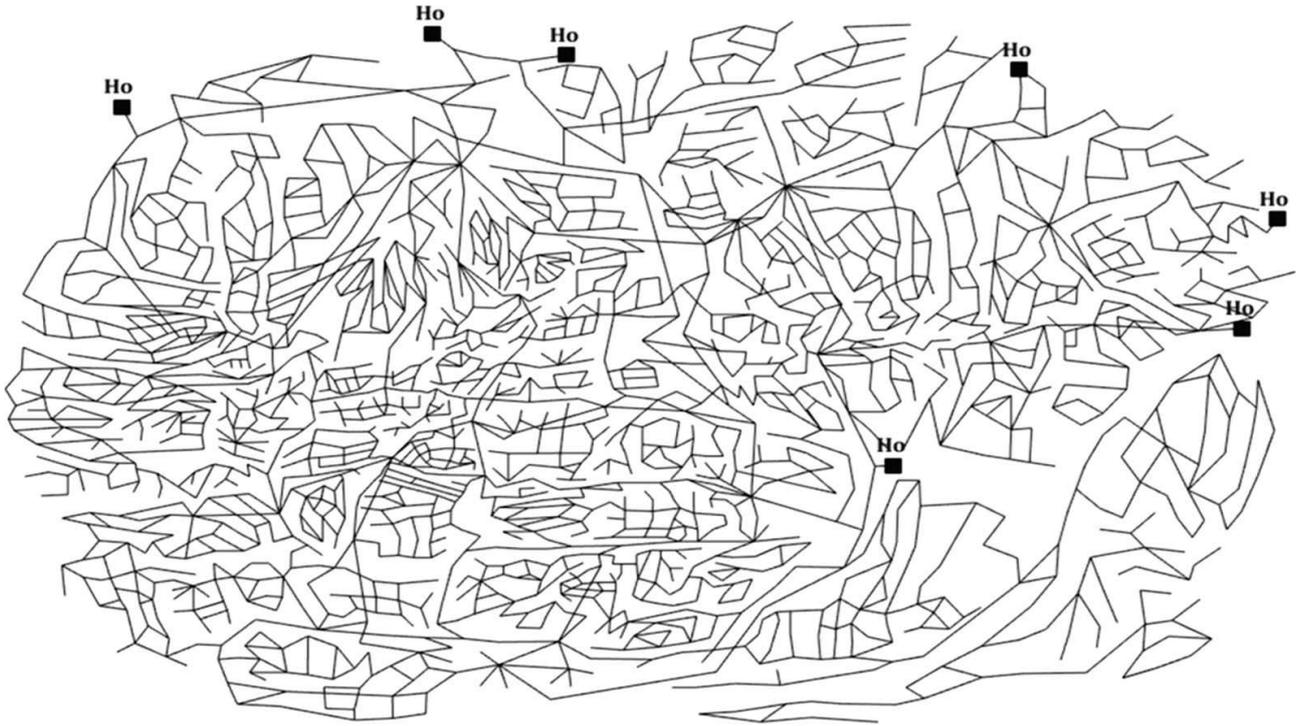
659 **Fig. 4.** Two solutions of optimal DMAs design with three valves and four closed valves.



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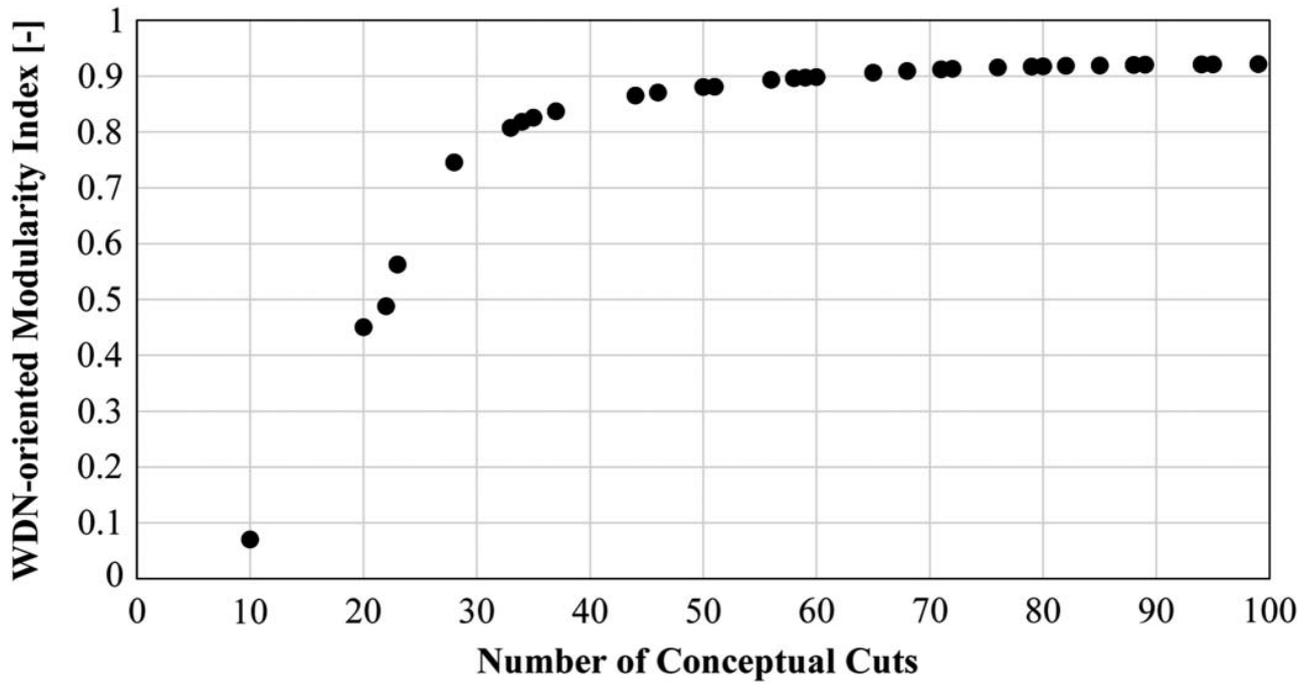
662 **Fig. 5.** Layout of Exnet network.



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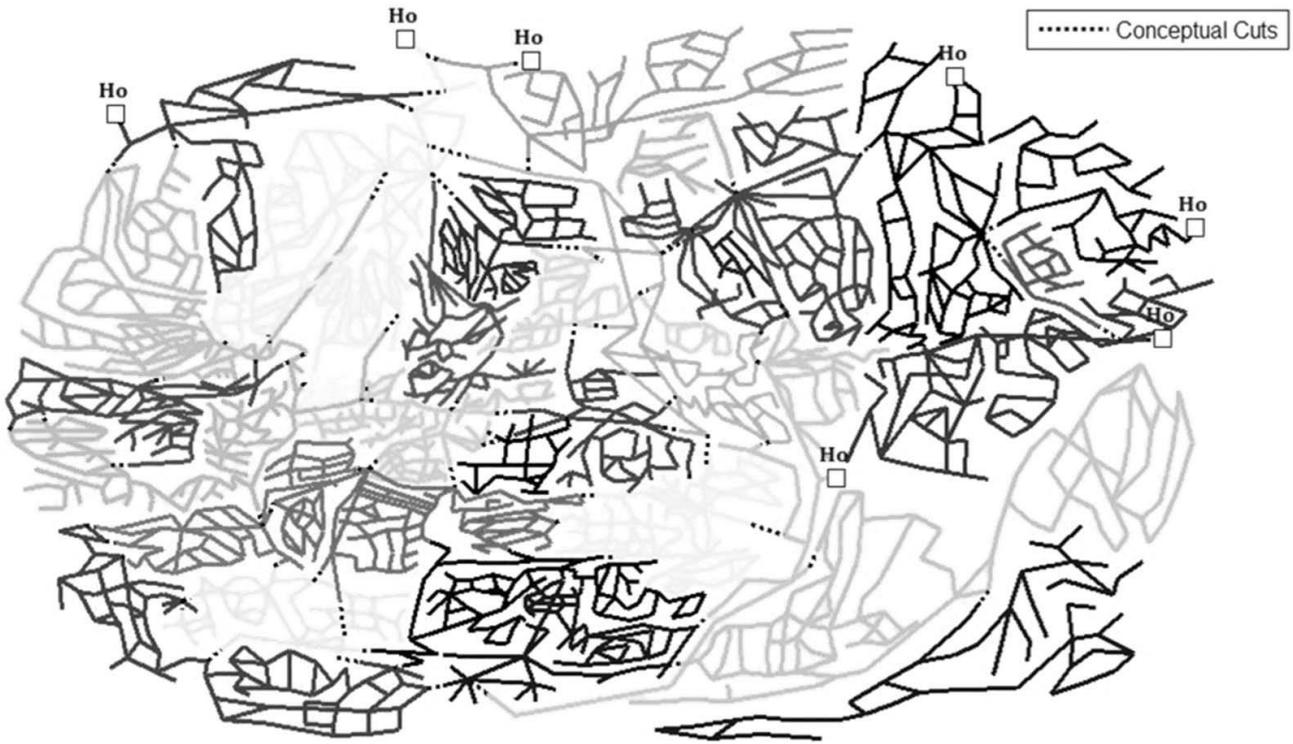
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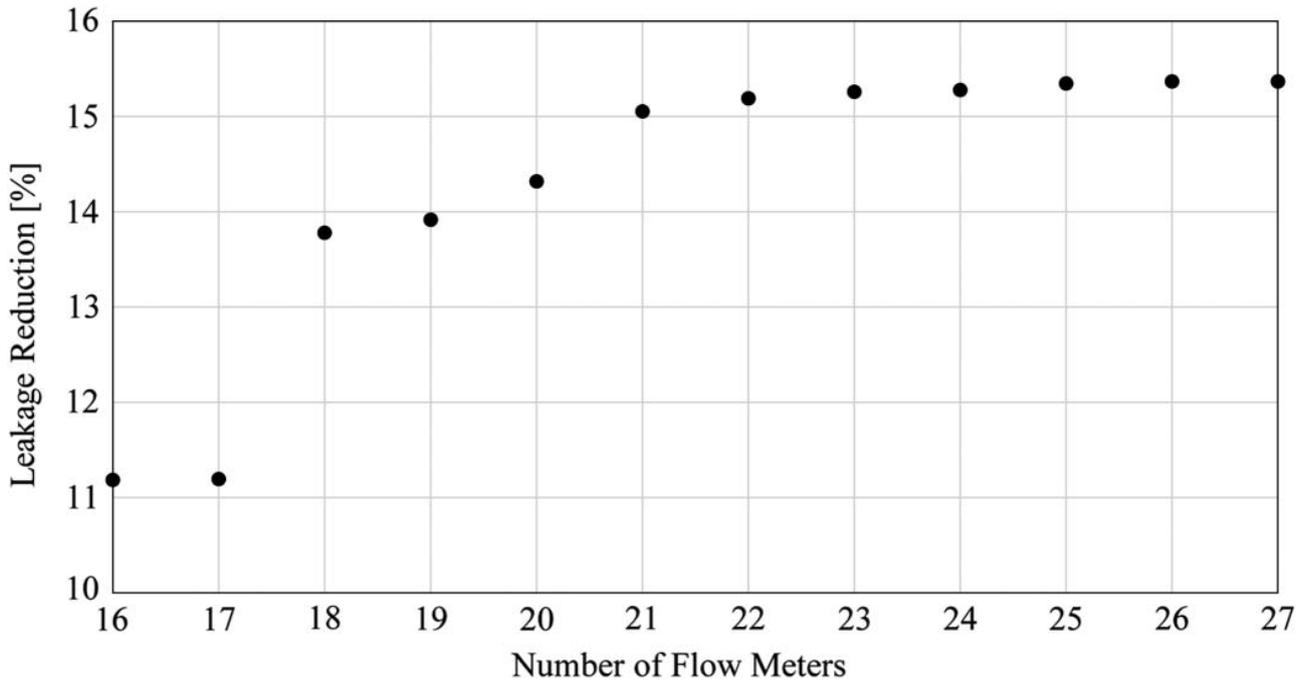
668 **Fig. 7.** Optimal segmentation for Exnet with 32 modules and 99 cuts, corresponding to maximum
669 value of modularity.



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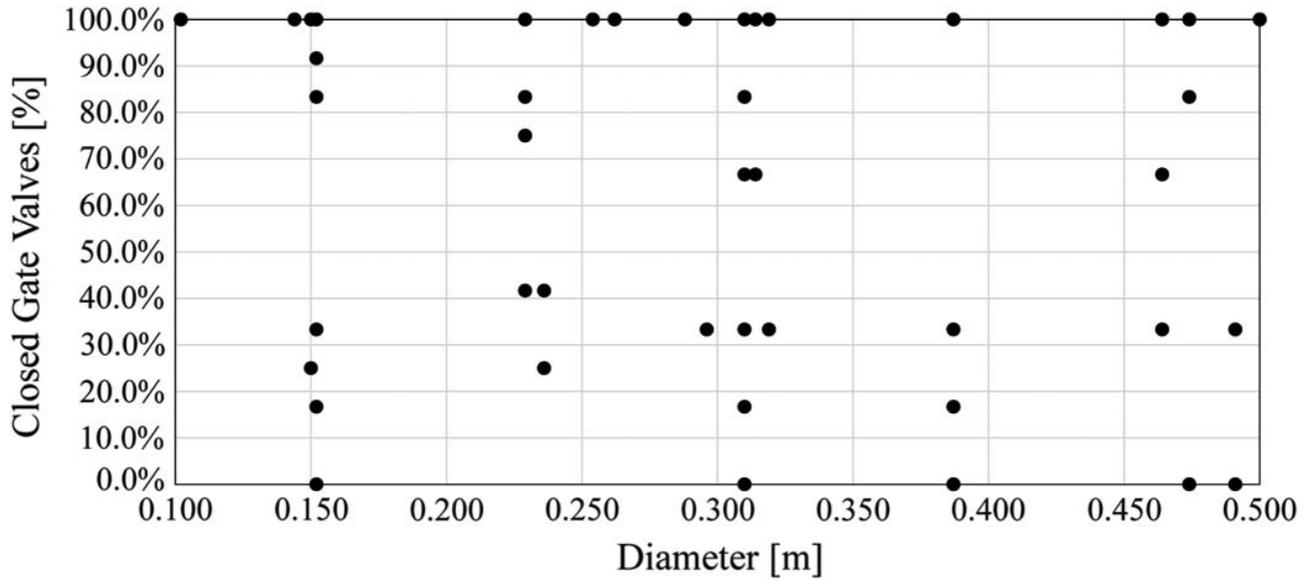
672 **Fig. 8.** Twelve DMA design solutions with null unsupplied water



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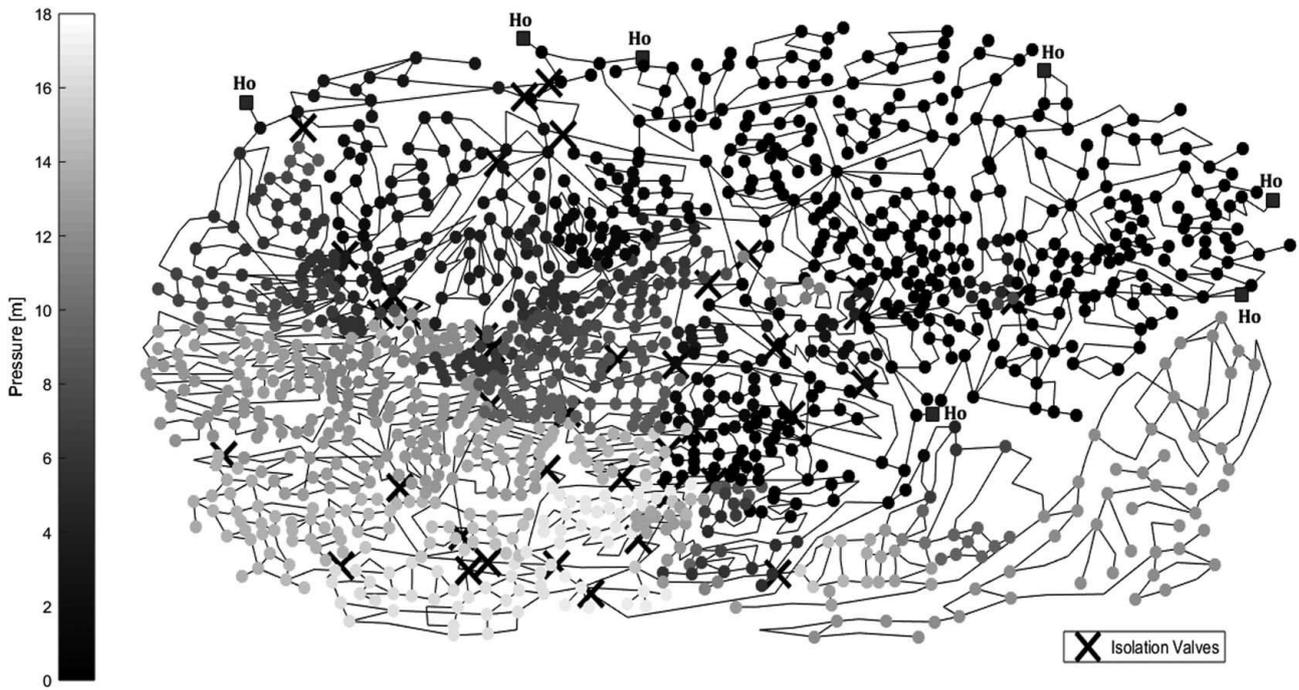
675 **Fig. 9.** Average use of closed valves in the 68 candidate positions versus diameter.



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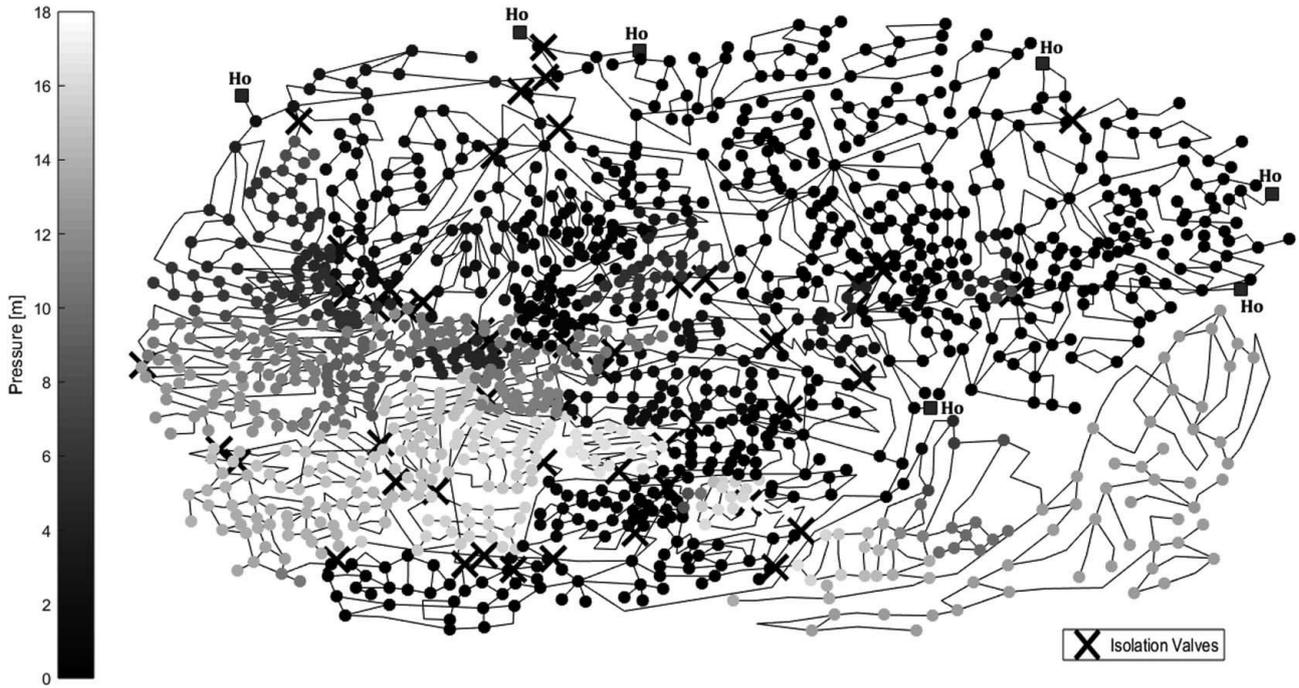
678 **Fig. 10.** Pressure drop of the solution 1 causing a leakage reduction of 15.4% using 27 meters and 41
679 valves.



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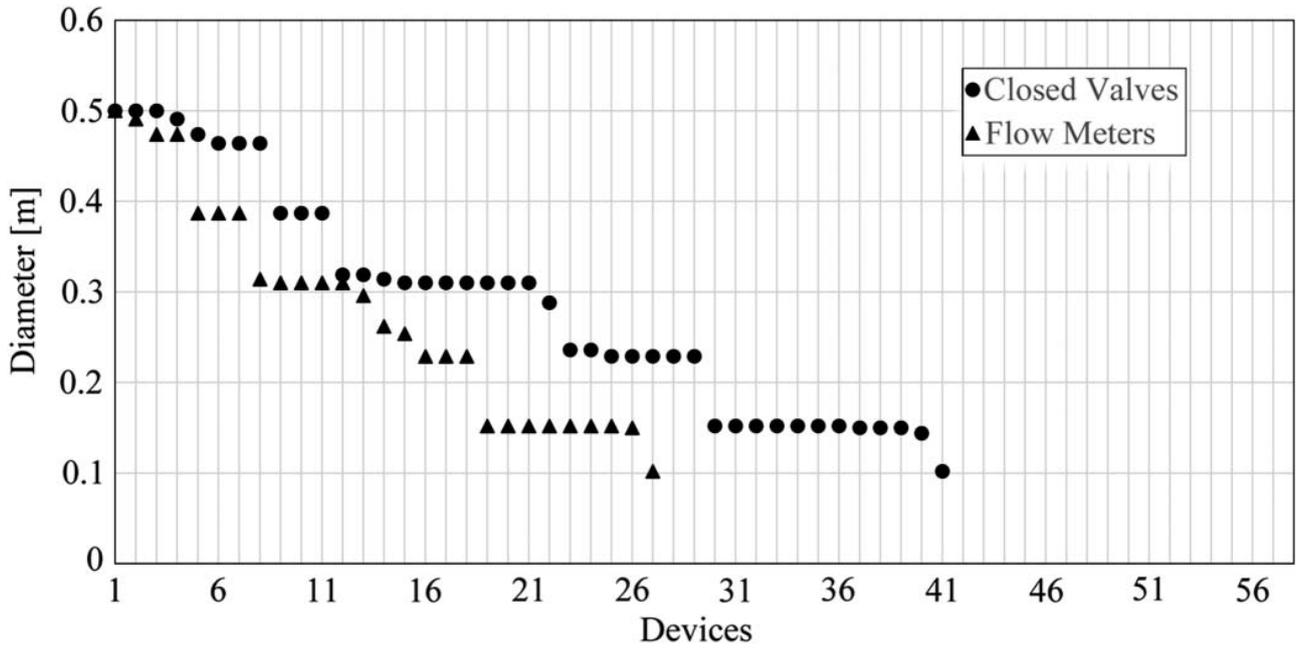
682 **Fig. 11.** Pressure drop of the solution 12 causing a leakage reduction of 11.2% using 16 meters and 52
683 valves.



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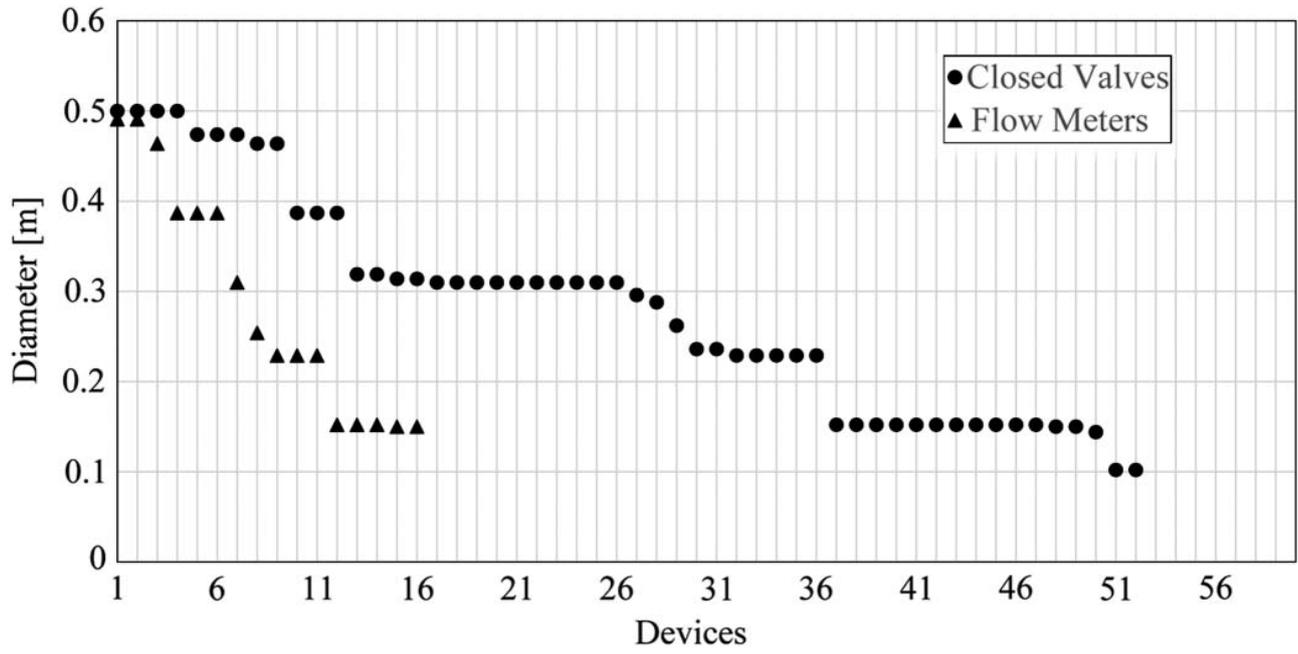
686 **Fig. 12.** Diameter of devices (closed valves and flow meters) for the solution 1 (15.4% leakage
687 reduction).



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690 **Fig. 13.** Diameter of devices (closed valves and flow meters) for the solution 12 (11.2% leakage
691 reduction).



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