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1 Uniformity and Heuristics Based DeNSE Method for Sectorization of Water Distribution

2 Networks

3
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17 18 **ABSTRACT**

19
20 Sectorization of a Water Distribution Network (WDN) into District Metered Areas (DMAs) is a proven
21 solution for proactive leakage control. Traditionally, WDN sectorization is done using a “trial and error”
22 approach conducted by local experts which often results in arbitrary solutions being identified. A
23 number of methods published recently tried to improve WDN sectorization by automating the process,
24 especially by using optimization. Various sectorization criteria, constraints and limitations are
25 introduced, often neglecting limited funds and shortage of water balance data often encountered in
26 poorly managed WDNs. These methods also suffer from low computational efficiency imposed by
27 optimization methods used. This paper presents a new, Distribution Network SEctorization (DeNSE)
28 method that overcomes these deficiencies. The new method is based on a heuristic procedure where the

29 WDN sectorization is driven by efficient tracking of water balance and least cost investment for
30 implementation while maintaining the same level of WDN's operational performance. Aforementioned
31 set of criteria is particularly well suited for initial sectorization of poorly managed WDNs, in which
32 great uncertainty in water balance data often leads to poor management decisions. DeNSE method is
33 validated and benchmarked against several literature sectorization methodologies on a real-sized WDN.
34 The results obtained demonstrate the ability of the DeNSE to identify set of good, realistic sectorization
35 solutions that are in some respects better than the corresponding solutions reported in the literature. The
36 new method also enables sectorization to be done in a computationally efficient manner ensuring its
37 applicability to large, real-life sized WDNs.

38

39 **Key words:** Sectorization, DMA, WDN, Uniformity, DeNSE

40 **INTRODUCTION**

41

42 Sectorization of a water distribution network (WDN) into zones (sectors, clusters or District Metered
43 Areas - DMAs) has become one of the main strategies for efficient management of WDNs. It was
44 introduced in the United Kingdom in the late 80's and since it's been implemented in many WDNs
45 worldwide. Sectorization has been done traditionally to address two main objectives: better control of
46 water losses and efficient management of pressures in the network. It is proven that sectorization can
47 be useful for other tasks such as protection against contamination (Chianese et al., 2017; Grayman et
48 al., 2009). Best definition of a DMA, given by Burrows et al. (2000), is that it is a distinct hydraulic
49 area of the WDN, separated from the rest of the supply system by isolation valves and one or more
50 metered inlets and outlets.

51

52 Sectorization of WDN into an optimal system of DMAs is a hard task to achieve, especially for the
53 existing and continuously operating WDN. Every WDN is unique in its topology and characteristics
54 and key drivers/objectives so there is no common procedure for performing its sectorization, but rather
55 a series of guidelines provided by the different water and other authorities (Butler, 2000; Farley, 2001;

56 Morrison et al., 2007; WAA & WRC, 1985; UK Water Research Industry, 1999). Ideally, planning of
57 DMAs (e.g. their number and size) should be carried out during the new WDN design phase, making it
58 much easier to come up with the solution that will be efficient both in terms of sectorization main
59 objectives and satisfaction of network's hydraulic and other requirements.

60

61 Complexity of the real life WDN results in many different alternatives in which network sectorization
62 can be done. Usually, sectorization is governed by the criteria of having zones of "manageable size" in
63 terms of number of consumers, links or network length. It can be also subjected to other criteria (e.g.
64 required number of feeds, fire flow regulations etc.) and limitations. Sectorization solutions are usually
65 obtained by the "trial and error" technique conducted by a local expert, familiar with all of the WDN
66 specifics. Practical application of such approach is illustrated in Grayman et al. (2009) where two large
67 case study networks are redesigned to implement typical DMA design as guidelines provided in Baker
68 (2007) and to allow additional control and isolation of the system in order to improve water security.
69 Need for a more formal approach to sectorization problem, that will enable investigation of alternative
70 sectorization solutions for large WDNs, is recognized early (Tzatchkov et al., 2006).

71

72 Different algorithms for automated sectorization of the WDN into DMAs have been developed and
73 presented in recent years, together with the tools that can be used to support this process (Deuerlein,
74 2008; Perelman & Ostfeld, 2012). In general, existing algorithms for automated sectorization have three
75 general steps (Perelman et al., 2015): 1) division of the WDN into clusters, 2) placement of valves and
76 flow meters on cluster's boundary pipes to define the DMAs, and 3) evaluation of solutions based on
77 the previously adopted performance indicators (PIs). For the purpose of initial division of the WDN (1st
78 Step), majority of presented methodologies rely on the Graph Theory algorithms (Alvisi & Franchini,
79 2014a; Di Nardo et al., 2013; Ferrari et al., 2014; Hajebi et al., 2016; Scarpa et al., 2016), or multi-agent
80 approach and spectral clustering (Di Nardo et al., 2018; Herrera et al., 2010; Herrera et al., 2010), while
81 others are using the modularity index (Ciaponi et al., 2016; Giustolisi & Ridolfi, 2014; Laucelli et al.,
82 2016; Campbell et al., 2016) or community structure metrics (Diao et al., 2013; Zhang et al., 2017;
83 Brentan et al., 2017), originally presented by Clauset et al. (2004) and Newman & Girvan (2004).

84 Modularity and community structure metrics are introduced from other fields of research and are based
85 on similarity between clusters based on the weights assigned to the links. Motivation for application of
86 community structure metrics comes from the fact that many complex systems, WDN being one of them,
87 have a property of higher links density within the communities than between them (Fortunato, 2009;
88 Giudicianni et al., 2018). These metrics have been tailored in different ways to be used for the WDN
89 sectorization purpose (Giustolisi & Ridolfi, 2014; Zhang et al., 2017). Although able to determine
90 DMAs, these approaches are sensitive to the selection of links weights (Ciaponi et al., 2016; Diao et
91 al., 2013). So far presented sectorization methods mainly include cluster (DMA) size range (min-max)
92 and reachability from the transmission main as the sectorization governing variables. Identifying DMAs
93 that will be also uniform in size as much as possible is aspect addressed in research presented here,
94 hypothesizing that uniformity of DMAs' sizes can be suitable variable to govern the sectorization
95 process.

96

97 A large number of possible alternatives exist for positioning the valves and flow meters in order to
98 define the DMAs (2nd Step) in a real-sized WDN. Many of those alternatives are not feasible as they do
99 not meet the basic hydraulic requirements for WDN operation. For the purpose of selecting the (near)
100 optimal alternative, sectorization algorithm is usually coupled with some type of optimization method
101 (Alvisi, 2015; Giustolisi & Ridolfi, 2014; Hajebi et al., 2016; Laucelli et al., 2016; Zhang et al., 2017)
102 which requires significant amount of computational resources. So far, computational efficiency has
103 been regarded as something of secondary importance with primary focus on the quality of the obtained
104 solution. Viable alternative to traditional optimization methods are heuristic based approaches for
105 positioning of the valves and flow meters (Alvisi & Franchini, 2014a; Ciaponi et al., 2016; Diao et al.,
106 2013) or the use of a simplified hydraulic simulator able to rapidly find near-optimal solutions (Alvisi
107 & Franchini, 2014b).

108

109 Number and type of PIs, used in 3rd Step to assess the effect of implemented interventions and evaluate
110 the sectorization solution, vary significantly in reported researches. Resilience index, as describe in
111 Todini (2000) is present in almost all researches as a measure of networks post-sectorization reliability.

112 Water age is usually used to reflect the impact on water quality in network. Some researchers added
113 various other indices to validate feasibility of obtained solutions (e.g. pressure indices are used in Di
114 Nardo et al. (2013) and entropy index is used in Scarpa et al. (2016)).

115

116 Some of the drawbacks of available methods for automated sectorization, potentially posing a question
117 of their applicability to real-life WDNs, are associated with: a) comprehensive lists of objectives and
118 constraints used in optimization, b) computational efficiency and c) resolution of sectorization solution.

119

120 In the process of developing new methods, various limitations and constraints, important for the proper
121 functioning of the WDN, were implemented in optimization procedures (Di Nardo et al., 2017; Gomes
122 et al., 2012; Zhang et al., 2019). Chronologically, only DMA size and network pressure constraints
123 were considered (Di Nardo & Di Natale, 2011), with each new method adding new sectorization
124 parameters and network's PIs to their lists of limitations and constraints. Probably the most
125 comprehensive such list is presented in Hajebi et al. (2016), having 13 objectives and 11 constraints. It
126 may be even commented that these lists have grown too much, exhausting all practical aspects important
127 for normal every day operation of the WDN. Optimization methods are computationally expensive by
128 their nature, and the addition of new objective functions by each sectorization method only highlights
129 this effect (e.g. algorithms of (Hajebi et al., 2016; Zhang et al., 2017). Solution search space
130 exponentially increases with the complexity of a network, and perhaps this is why recently presented
131 methods employing optimization are lacking results supporting their application on large-sized
132 networks (Alvisi, 2015; Laucelli et al., 2016).

133

134 Water utilities operating poorly managed WDNs, usually do not have sufficient funds to invest in large
135 number of DMAs at once, so sectorization process should be planned hierarchically and implemented
136 in phases starting with a few DMAs that can be larger than recommendations given in guidelines.
137 Establishing a few DMAs in WDN should enable tracking of water balance in the network and gathering
138 basic data about system dynamics, without significant effect on network's operational conditions. This
139 could improve operational management of WDN, as management decisions are usually made based on

140 some calculated WDN's PIs, whose values can be significantly influenced by great uncertainty of
141 available water balance data (Babić et al., 2014). With increased resolution of the sectorization, it is
142 usually required that new DMAs keep previously created boundaries of the original DMA layout. In
143 this manner economical aspect is addressed as this implies minimization of costs. Scarpa et al. (2016)
144 considered hierarchical sectorization based on progressive union of initially identified elementary
145 DMAs. This can be viewed as bottom-up approach. A top-down approach of sectorization would be
146 closer to engineering perception and more in accordance with the phased creation of DMAs. Either
147 way, hierarchy in sectorization solution should be considered.

148

149 From the previous discussion it can be concluded that, despite all recent advancements made, scope
150 exist to further improve existing water network sectorization algorithms. Aspects in which these
151 improvements can be made are: 1) implementation of practical engineering principals, relevant to the
152 WDN, to govern the sectorization process, 2) improving computational efficiency of the algorithm and
153 3) consider hierarchical sectorization.

154

155 In the method presented here, named DeNSE (Distribution Network SEctorization), first aspect is
156 addressed with implementation of a newly presented network uniformity index (Vasilic, 2018) that
157 drives WDN decomposition into clusters that are not only within predefined size limits, but also uniform
158 in size as much as possible. Uniformity index also favours sectorization in which cluster's connecting
159 links are pipes with smaller diameters, indirectly providing economically more favourable solution as
160 installation of valves and flow meters on smaller diameter pipes will be less costly. High computational
161 efficiency is achieved using common sense engineering heuristics, rather than optimization tools, to
162 position the valves and flow meters on the connecting links and define the DMAs. Network clustering
163 algorithm is evolving in a step by step manner, hence obtained sectorization solution is inherently
164 hierarchically ordered. Furthermore, algorithm presented here does not come up with a single
165 sectorization solution, but with a range of feasible solutions, giving the freedom to the decision makers
166 to select the one best suited for their needs. Algorithm is tested on large real-sized BWSN2 benchmark

167 network (Ostfeld et al., 2008) and results are thoroughly compared with other results previously
168 reported in the literature.

169

170 **METHODOLOGY**

171

172 This paper presents uniformity and heuristics based method for water Distribution Network
173 SEctorization into DMAs (DeNSE), also able to address hierarchical sectorization. Algorithm is based
174 on the Graph Theory for identification of Strong Connected Components (SCCs) and their aggregation
175 into clusters based on newly presented network uniformity index (U). As discussed in Introduction,
176 sectorization process should start with the definition of key sectorization objectives and design criteria,
177 followed by the identification of PIs that will be used to assess impact of interventions made in the
178 network. Tracking the water balance in the network is main sectorization objective adopted in DeNSE
179 method. Designing the sectorization solution that requires least investment in the equipment necessary
180 for creation of DMAs (flow meters and isolation valves), while keeping the same level of network's
181 operational efficiency are main design criteria. Such set of design criteria is most appealing to many
182 water utilities, especially in the developing countries, which operate highly inefficient WDNs with
183 significant amount of water and revenue losses. Two PIs are adopted to evaluate the effects of the
184 sectorization on network's operational performance: 1) Resilience Index (Res), reflecting post-
185 sectorization reliability of WDN (Todini, 2000) and 2) Water Age (WA), surrogate metrics for water
186 quality reflecting water retention rate in the WDN.

187

188 The new method requires hydraulic model of WDN as an input, like many other methods relying on it
189 to prove hydraulic feasibility of sectorization solution. The quality of the adopted solution will be better
190 if calibrated hydraulic model is used, and required interventions in the network can be taken with more
191 assurance in preservation of networks hydraulic performance. The method runs through 3 stages to
192 identify the best sectorization solution, as shown in Figure 1. First stage is a pre-processing stage in
193 which all the relevant network data is obtained from the WDN model and prepared for the follow run

194 of the clustering algorithm. WDN decomposition into clusters is done in the second stage, based on the
195 uniformity index. Third stage involves selection of the narrow set of solutions that will be hydraulically
196 analysed. Heuristic, engineering based positioning of the valves and flowmeters on clusters connecting
197 links in order to define DMAs, extended period hydraulic analysis of the solutions and evaluation of
198 adopted PIs, are all part of the third stage. Finally, feasible solutions are ranked and preferable solution
199 is selected. Each of the three stages will be explained in details in the following text.

200

201 **Input Data**

202

203 The new sectorization method requires the following input data:

204 1. Calibrated WDN network model in the form of EPANET input file, which contains all relevant
205 data (topology, hydraulic characteristic, demand data, etc.).

206 2. Minimum (n_c^{\min}) and maximum (n_c^{\max}) number of property connections per DMA, as well as
207 total number of connections in the network (n_c), since number of connections per node is usually
208 not available with mathematical model. Recommendations about these values can be found in
209 number of available guidelines for DMA creation, and usually it is considered that number of
210 connections should be in the range of 500-5,000 (Farley, 2001; Morrison et al., 2007). It is
211 considered that having DMAs larger than 5,000 connections is not practical as it becomes
212 difficult to distinguish leakages from the night flow data, while taking more time to allocate
213 them. It should be noted that the preferable DMA size is network specific, influenced by many
214 factors and should be determined based on a thorough analysis of the specific data relevant to
215 the network in consideration.

216 3. Transmission main threshold diameter (D_{main}). Large diameter pipes connected in series,
217 running from the network's main source(s) are considered a transmission main. These are the
218 pipes that convey water between the reservoirs and tanks and serve as main supply paths in the
219 network. In this methodology they are excluded from any interventions. As with the DMA size,
220 value of D_{main} is network specific, usually being 300-350 mm (Ferrari et al., 2014).

- 221 4. Pipe closure threshold diameter (D_{tr}). Pipes having diameter equal or larger than this diameter
222 will not be considered for possible closure for positioning the valves and flowmeters (part of
223 the 3rd stage). By default, algorithm uses first class of diameter lower than the D_{tr} (e.g. if D_{main}
224 is 350 mm, D_{tr} will be 300 mm), but user can specify a different value. However, this will affect
225 the number of isolation valves and flowmeters required to create the DMAs and consequently
226 the solution cost.
- 227 5. Minimum required and maximum allowed pressures in the network, p_{min} and p_{max} , as well as
228 the maximum Water Age (WA_{max}) allowed in the network as a water quality indicator.
- 229 6. Desired number of sectorization solutions (N_{sol}). It is considered that 10 to 15 solutions is large
230 enough set to make representative multi-criteria ranking, however user can opt for a larger set
231 of solutions to compare.

232
233

234 **Pre-processing (STAGE 1)**

235

236 In the first stage, there are two phases (Figure 1). In the first phase, transmission mains are defined,
237 based on the D_{main} value, and excluded from the sectorization process. For this purpose, network is
238 explored using slightly modified Breadth First Search (BFS) algorithm (Jungnickel, 2005),
239 simultaneously starting from all main source nodes (reservoirs). BFS algorithm is modified to prioritize
240 propagation through the links with diameters equal or greater than D_{main} . In the second phase, 24-hour
241 Maximum Day Demand (MDD) hydraulic simulation of the analysed WDN is performed to determine
242 the orientation of pipes (based on water flow directions obtained in the simulation). As a result,
243 directional graph (DIGRAPH) G is defined with two sets $G = \langle N, C \rangle$, set of network nodes N and set
244 of network links C , where each link is presented with ordered pair of nodes. Network links with
245 changing flow directions are identified as non-oriented (or links that can have both flow directions),
246 and are represented with the addition of fictitious link in the opposite direction. This network
247 representation is used only for identification of SCCs in Stage 2, and original network topology is used

248 for hydraulic simulations. Both of these phases are illustrated on a simple example network shown in
249 Figure 2.

250

251 The example network consists of 16 nodes, two of which are reservoirs, and 21 links. Links connecting
252 reservoirs are identified as transmission mains and are excluded from further analysis. Remaining part
253 of the network, connected to the transmission main with one link in node 9 should be partitioned into
254 DMAs. Illustrated orientations of the remaining links are determined based on the results of the
255 hydraulic analysis. Two of those links are identified as not oriented, and putting that in the context of
256 water networks, those are usually pipes (links) that are connecting tanks with the rest of the network.
257 So in an example network, two fictitious links are added (2-3 and 8-7) and nodes 8 and 2 could be tanks.

258

259

260

261 **Network clustering (STAGE 2)**

262

263 In the second stage of the DeNSE method, partitioning of the WDN into clusters is performed. It is done
264 in three phases (see Figure 1).

265

266 **Phase 1.** First step is to identify the Strongly connected components within the previously created
267 DIGRAPH. Strongly connected component (SCC) is a term from Graph Theory, and it is defined as a
268 subgraph in which each node can be reached from any other node within that subgraph (Gabow, 2000).
269 Essentially, a SCC is a directed cyclic component in which flow direction within that component can
270 reverse (Perelman & Ostfeld, 2012). Therefore, SCCs are parts of network where water is circulating
271 during the simulation (Vasilić et al., 2016). Due to that fact, control of the water balance and/or water
272 pressure regulation in SCC parts of the network could be difficult to achieve, so the idea is to detect
273 SCCs and treat them as aggregated nodes in further network analysis and clustering. Algorithms for the
274 extraction of SCCs from digraph are well known in the Graph Theory. The Gabow algorithm (Gabow,
275 2000) is used in the methodology shown here. It is chosen due to its' linear computational time, which

276 makes it more efficient compared to the others. This is significant as algorithm has to be able to deal
277 with large networks efficiently. Gabow's algorithm requires only one pass through the network
278 (DIGRAPH) with recursive call of the Depth First Search (DFS) algorithm (Tarjan, 1971) with arbitrary
279 selection of the starting node.

280

281 For illustration purposes, a simple digraph shown in Figure 2 is used. Starting the DFS search from the
282 node 2, nodes 3, 4, 6, 1 and 5 are visited (Figure 3-a). During the DFS search, a check is made whether
283 the selection of the next node forms a cyclic path or not. If yes, nodes forming the cyclic path are
284 identified as a SCC. The algorithm continues until no further propagation is possible. In example shown
285 in Figure 3, the first SCC component identified is composed of nodes 2, 3, 4, 6, 5 and 1. No further
286 propagation is possible, so the DFS starts again from randomly selected node, chosen from the set of
287 nodes that were not visited during the first search. Assuming that the randomly selected node is node 9,
288 and after nodes 11 and 10 are visited, the second SCC composed of these three nodes is identified. DFS
289 search is repeated again starting from node 8, and third SCC composed of nodes 8 and 7 is detected
290 (Figure 3-b). At the end, aggregated digraph is composed of three identified SCCs. The digraph can
291 also be viewed as set of aggregated nodes and two remaining connected to transmission main with one
292 link (Figure 3-c). The most important property of new aggregated digraph is its acyclicity, indicating it
293 is a digraph without cycles. Such graph is referred to as Directed Acyclic Graph (DAG), and in terms
294 of water network is very important, because it clearly separates source from the demand nodes and
295 hence, makes the sectorization of network easier.

296

297 **Phase 2.** In the second phase topological sorting of the identified DAG is conducted. DAG nodes,
298 represented with SCCs, are sorted from the downstream end, and this order will be used to drive
299 aggregation of the DAG from the most peripheral SCCs. Again, simple implementation of recursive
300 DFS algorithm, as explained in Sedgewick & Wayne (2011), is used for this purpose. In an example
301 shown in Figure 3-c, topological sorting yields following list of SCCs: SCC1, SCC2 and SCC3.

302

303 **Phase 3.** In this phase aggregation of the sorted DAG, composed of the SCCs connected between each
 304 other and connected to the transmission main, is conducted based on the newly presented network
 305 uniformity index (U). Network uniformity index (Vasilic, 2018) is defined as follows:

$$306 \quad U = u_{net} u_v w_{agg} \quad (1)$$

307 where u_{net} is network uniformity in terms of cluster size, u_v is uniformity of the DMAs size vector and
 308 w_{agg} is relative weight of aggregated links. Each of these variables are explained in the following
 309 paragraphs, followed by the explanation of the aggregation algorithm itself.

310

311 Each cluster is characterized with its size (S_i), calculated as sum of all nodal demands within that cluster

$$312 \quad - S_i = \sum_{j=1}^{N_n^i} q_j, N_n^i \text{ being number of nodes in } i\text{-th cluster. Network uniformity } (u_{net}) \text{ measures average}$$

313 deviation of clusters size from the preferred DMA size (S_{pref}). Ideally, all clusters should have size equal

314 to S_{pref} but, obviously, this is not possible in real networks. Preferred DMA size is calculated based on

315 minimum and maximum DMA size, S_{min} and S_{max} , as $S_{pref} = \frac{S_{min} + S_{max}}{2}$. Minimum and maximum

316 DMA size are calculated based on the daily average total demand in the WDN (Q_{tot} , available from the

317 WDN hydraulic model), the number of minimum and maximum connections in the DMA (n_c^{\min} and

318 n_c^{\max}) and a total number of connections in the WDN (n_c), given as an input data:

$$319 \quad S_{min} = \frac{Q_{tot}}{n_c} n_c^{\min} \quad (2)$$

$$S_{max} = \frac{Q_{tot}}{n_c} n_c^{\max}$$

320 Network uniformity is calculated based on the triangular function f that quantifies “quality” of cluster

321 size in the range $[0,1]$ (Figure 4). If a cluster i has a size $S_i = S_{pref}$, its value of f will be the best, i.e. $f_i=1$.

322 If a cluster has a different size (larger or smaller than S_{pref}) it will have the value of $f_i < 1$. Since the

323 function f is equilateral, both larger and smaller cluster are equally penalized. Extremely large clusters

324 (larger than S_{pref}), are scored with the lowest value of $f_i=0$. Potentially, other types of function f , that

325 will penalize small and large clusters in different rates, could be used, but triangular one currently
 326 implemented provided the most consistent results. Finally, network uniformity is calculated as:

$$327 \quad u_{net} = \frac{\sum_{i=1}^{N_{cl}} f_i}{N_{cl}} \quad (3)$$

328 where N_{cl} is number of clusters for a given sectorization. Note that maximum value of u_{net} is 1 if all
 329 clusters are equal to S_{pref} , and minimum value is zero.

330

331 Sizing clusters in the range S_{min} – S_{max} , and as much as possible close to S_{pref} , is one sectorization
 332 objective. Sizing them equally is the other one. Sizes of all clusters form the normalized size vector of

333 specific sectorization into N_{cl} clusters – $\mathbf{S}^n = \{S_1^n, S_2^n, S_3^n \dots, S_{N_{cl}}^n\}$, where $S_i^n = \frac{S_i}{\sum_{i=1}^{N_{cl}} S_i}$. Uniformity

334 of this vector is calculated as its Euclidean norm (L2 norm):

$$335 \quad u_v = \sqrt{\sum_{i=1}^{N_{cl}} (S_i^n)^2} \quad (4)$$

336 If all clusters are equal in size (e.g. $S_1=S_2=S_3=\dots=S_{pref}$), which is the most preferable case, uniformity
 337 of the size vector is:

$$338 \quad u_v^{best} = \sqrt{\left(\frac{S_1}{N_{cl}S_{pref}}\right)^2 + \left(\frac{S_2}{N_{cl}S_{pref}}\right)^2 + \dots} = \sqrt{\frac{N_{cl}(S_{pref})^2}{N_{cl}^2(S_{pref})^2}} = \sqrt{\frac{1}{N_{cl}}} \quad (5)$$

339 If all nodes are part of the same cluster, meaning worst case scenario in which there is no clustering,

340 uniformity of the size vector is $u_v^{worst} = 1$. To be consistent with the ranging values of network

341 uniformity metrics (u_{net}), where 0 is the minimum value and 1 is maximum, uniformity of the size vector

342 is scaled to the same range to yield final form of equation for its calculation:

$$343 \quad u_v = \begin{cases} 1 - \frac{u_v \sqrt{N_{cl}} - 1}{\sqrt{N_{cl}} - 1}; & N_{cl} > 1 \\ 0 & ; N_{cl} = 1 \end{cases} \quad (6)$$

344 Relative weight of aggregated links is calculated as:

$$w_{agg} = \frac{\sum_{i=1}^{n_l^{agg}} D_i}{\sum_{i=1}^{n_l} D_i} \quad (7)$$

346 where n_l is total number of links, n_l^{agg} is number of links within the clusters, and D_i is links diameter. In
347 case of large number of clusters there will be more unaggregated connecting links than in the case of a
348 small number of clusters. Hence, the value of w_{agg} will be smaller in the former than in the latter case.
349 Minimum value of w_{agg} is zero, if no aggregation is done, and 1 if all SCCs are aggregated into one
350 cluster.

351
352 Aggregation of SCCs into clusters, based on uniformity index metrics described above, is done in a step
353 by step manner, propagating upstream through topologically sorted DAG made of SCCs (obtained in
354 Phase 2) and aggregating in each step SCCs whose aggregation will contribute the most to the network
355 uniformity (Vasilic, 2018). Initially, all identified SCCs are considered as individual clusters, meaning
356 that initial number of clusters corresponds to the number of identified SCCs. Aggregation is iteratively
357 carried out through three steps: 1) identification of candidates SCCs for aggregation, based on
358 topologically sorted DAG; 2) selection and aggregation of the candidate with highest uniformity gain
359 (ΔU_{max}); 3) aggregation of remaining downstream SCCs with positive uniformity gain ($\Delta U > 0$). Third
360 step in this iterative aggregation procedure is implemented to avoid the scenario in which small
361 peripheral SCCs remain unaggregated until the late stages of aggregation. This could happen as such
362 SCCs usually have relatively small uniformity gain and aggregation would continue past them further
363 upstream.

364
365 Uniformity index metrics that drives clustering process is made of three components as given with the
366 eq. (1). Since the aggregation process is driven with the highest uniformity gain (ΔU_{max}), it is of interest
367 to maximize all three components of network uniformity index (u_{net} , u_v and w_{agg}). Maximizing w_{agg} ,
368 implies that the links with the larger weights (diameters) are aggregated first. In this manner, links with

369 smaller diameters will be left as connecting links between the clusters which in turn provides
370 economically more favorable sectorization solution.

371

372 The aggregation algorithm presented here is essentially a Greedy optimization method, in which
373 aggregation direction is determined based on the highest uniformity index gain (ΔU_{\max}). This is similar
374 to greedy optimization, based on highest modularity gain, used to maximize network's modularity index
375 presented in Clauset et al.(2004). As with all similar type algorithms, it is not guaranteed that the global
376 optimum solution will be found. However, the benefit is that generally a good sub-optimal solution can
377 be found with significant computational time savings when compared to other optimization algorithms.
378 The algorithm is deterministic in nature, and it will always provide the same results as long as the same
379 input parameters are given.

380

381 Application of described aggregation algorithm is illustrated on a simple example shown in Figure 5.
382 The example is derived from Figure 3-c, adding 6 more SCCs for illustration purposes. For the sake of
383 simplicity, total demand of 20 L/s is assigned to all 9 SCCs. Diameters of the links connecting SCCs
384 are shown in Figure 5 in millimetres. Minimum (S_{\min}) and maximum (S_{\max}) DMA size are set to 40 and
385 80 L/s respectively, which yields preferred DMA size (S_{pref}) of 60 L/s. Figure 5 shows evolution of
386 network uniformity index through aggregation process of this simple example. Uniformity index (U) is
387 plotted against the number of clusters corresponding to each aggregation step (secondary horizontal
388 axis).

389

390 Highest uniformity index value (U_{\max}) corresponds to network sectorization into 3 clusters with total
391 demands of 40, 60 and 80 L/s. Sizes of all three clusters are within predefined DMA size limits (40 –
392 80 L/s). Clusters are connected with three links between them. Next aggregation step leads to the
393 solution with 2 clusters, having total demands of 80 and 100 L/s. Obviously, this solution does not meet
394 DMA size constraints, as one cluster is larger than S_{\max} . However, there are now two links connecting
395 2 clusters which requires less isolation valves and flow meters to isolate them and create DMAs than in

396 the case with 3 clusters. Figure 5 also illustrates hierarchical ordering of the sectorization solutions,
397 embedded in the clustering algorithm. Solution with 3 clusters is lower in hierarchical order, and is
398 easily derived from the solution with 2 clusters.

399

400 **Heuristic device placement and solutions' evaluation (STAGE 3)**

401

402 At the end of the Stage 2 the clustering of DAG, made out of identified SCCs, based on network
403 uniformity index is finished. As described above, clustering is done in a step by step manner, preserving
404 data about clusters' structure at each aggregation step (Figure 5). Note that number of aggregation steps
405 corresponds to the number of identified clustering solutions. Obviously, not all of the solutions obtained
406 are of interest, only the ones with high value of network uniformity index are.

407

408 Prior to execution of the Stage 3 itself, selection of solutions that will be hydraulically analysed and
409 evaluated for satisfaction of initially adopted PIs is made. Number of solutions (N_{sol}) for the Stage 3
410 analysis is specified by the user as an input parameter. Selection of solutions is made based on the
411 network uniformity index values obtained at each aggregation step. Solution with the highest uniformity
412 index is selected (best solution), together with additional $N_{sol}-1$ solutions from succeeding aggregation
413 steps. Additional solutions are on the descending part of uniformity index plot (Figure 5), characterized
414 by the lower value of uniformity index (than the best solution) but also by the smaller number of
415 clusters. Described strategy for selection of solutions is adopted here as it is particularly well suited for
416 the application at the initial stages of the DMA design process. For coarser sectorization, solutions can
417 be chosen from the ascending part of uniformity index plot as well. Clusters connected only to the
418 transmission main, and having size smaller than S_{min} are removed from each solution and excluded from
419 further analysis. Such clusters are below minimum DMA size limit and will not be considered as a
420 DMA.

421

422 After the selection of solutions for evaluation has been made, main part of the Stage 3 is evoked. There
423 are two main phases in the Stage 3: 1) Conversion of clusters into DMAs (Phase 1) and 2) Evaluation
424 of solutions' PIs (Phase 2).

425

426 **Phase 1.** To convert clusters into DMAs (i.e. define DMAs), flow meters and isolation valves have to
427 be positioned on clusters' boundary edges. Positioning of the flow meters and valves is done based on
428 engineering heuristics. Continuing from the simple example used to describe aggregation algorithm
429 (Figure 5), consider the solution with the highest value network uniformity index. This solution has 3
430 clusters and 4 boundary edges to be considered for installation of flow meters/valves. For methodology
431 illustration purposes, another branch of transmission main and 4 boundary edges are added to this
432 solution (Figure 6-a).

433

434 Boundary edges are labelled as L1 through L8, and numbers are showing links' diameters in
435 millimetres. Flow orientations during 24-hour MDD hydraulic simulation, obtained in Phase 1 of the
436 Stage 1, are indicated with arrows. Pipes with a changing direction (non-oriented) are indicated using
437 dashed lines without arrows. Non-oriented pipes are only those connecting clusters with the
438 transmission main, as identified clusters resulted from the DAG analysis (i.e. all other non-oriented
439 pipes are already aggregated with the identification of SCCs in STAGE 2-Phase 1). In this case, there
440 is only one such pipe (L2). The heuristic procedure is comprised of the following three steps:

- 441
- 442 • Non-oriented pipes are identified, and all such pipes in which absolute difference between the
443 maximum and minimum flow rate is less than 0.2 L/s are marked for closure, as this is
444 considered as negligible flow rate (hypothetically, let L2 be such pipe in this example).
 - 445 • All links connecting clusters with the transmission main, oriented from the clusters to the
446 main, are closed (L3 and L8 in the example shown). These are the pipes always returning the
447 water from the demand nodes into the main, hence it is considered that they are not supply
448 pipes and can be closed without negative effects on system's hydraulics.

448 • Supply pipes of each cluster (oriented towards cluster) are analysed independently. It is
449 sufficient to analyse only supply pipes as graph in consideration is a DAG and one clusters'
450 output pipes are others' supply pipes. Supply pipes for a cluster are identified and pipe with
451 the largest maximum inflow to the cluster (Q_{max}) is considered as main supply pipe, and will
452 not be considered for closure. Maximum capacity of this pipe (C_{max}) is calculated based on
453 maximum allowable velocity of 2.0 m/s, and its remaining capacity is $C = C_{max} - Q_{max}$. All
454 remaining supply pipes having diameter larger than threshold value, given as an input (D_{tr}),
455 are candidates for closure. Their maximum capacities are calculated in the same manner (c_{max}),
456 and they are analysed one by one, starting from the link with the lowest maximum flow rate
457 (q_{max}). When a pipe i is considered for closure, resulting residual input capacity (C_{cl}) is
458 calculated subtracting i -th pipe capacity as $C_{cl} = C + \sum c_{max} - c_{max}(i)$. If reduced capacity is
459 still larger than the maximum flow rate carried by the i -th pipe ($C_{cl} \geq q_{max}(i)$), pipe is closed
460 by setting its capacity to zero ($c_{max}(i) = 0$). Iterating through this procedure, candidate pipes
461 are closed until input capacity is fully exhausted. Hypothetically, applying this to the simple
462 example in Figure 6 would result in closure of supply pipe L4 for cluster CL 1 and pipe L5
463 for cluster CL 2. Cluster CL 3 has only one supply link, so it remains opened.

464

465 Another approach for positioning flow meters and valves is the optimization method (e.g. Genetic
466 algorithm - (Ivetić et al., 2013)) which considers each boundary pipe as closed or open. Since it is not
467 uncommon that number of boundary edges exceeds several tens in case of real WDNs, the optimization
468 method could be very time consuming hence it was not implemented here. At the end of the Phase 1,
469 flow meters and isolation valves are positioned on the clusters boundary edges converting them into
470 DMAs (Figure 6-b).

471

472 **Phase 2.** After definition of its' DMAs boundaries, each solution is subjected to the extended period
473 hydraulic simulation to investigate the effects of modifications made to the network. Firstly, feasibility
474 of solution is considered through evaluation of pressure constraints in each node:

475
$$P_{i,t} \geq P_{\min} ; P_{i,t} \leq P_{\max} \quad (8)$$

476 where $p_{i,t}$ is pressure in i -th node in simulation time step t , and p_{\min} and p_{\max} are minimum and maximum
 477 allowable pressures in network. If solution does not meet pressure constraints it is considered unfeasible
 478 and it is excluded from further analysis.

479

480 For each feasible solution, cost and two adopted PIs are calculated as follows:

481 1. *Cost* – Cost of the solution calculated based on the unit cost of devices installed to create the
 482 DMAs (flow meters and isolation valves). Unit cost functions are taken from De Paola et
 483 al. (2014).

484 2. Average network resilience index (Todini, 2000), calculated as mean value over the simulation
 485 time period (T). Resilience index is represented as the ratio of residual amount of power in the
 486 network after satisfaction of nodal demands and maximum amount of power that can be
 487 dissipated in the network internally, while satisfying nodal demands and minimal pressure
 488 constraints:

489
$$Res = \underset{T}{mean} \left(\frac{\sum_{i=1}^{n_j} q_i (h_i - h_i^*)}{\sum_{j=1}^{n_r} Q_j H_j + \sum_{k=1}^{n_p} \frac{P_k}{\gamma} - \sum_{i=1}^{n_j} q_i h_i^*} \right) \quad (9)$$

490 where n_j is number of junctions, n_r is number of reservoirs, n_p is number of pumps, q_i is nodal
 491 demand at node i , h_i is nodal head at node i , h_i^* is minimum nodal head at node i , Q_j is discharge
 492 from the reservoir j , H_j is head in reservoir j , P_k is the amount of power introduced in the
 493 network by pump k and γ is specific weight of the water.

494 3. Average Water Age in the network over the last 24 hours of extended period simulation (WA):

495
$$WA = \frac{\sum_{i=1}^{n_j} \sum_{t=T-24}^T WA_i^t}{24n_j} \quad (10)$$

496 Where WA_i^t is Water Age in junction i at time t . Water age is also often calculated as demand-
 497 weighted water age to give more significance to nodes with larger demands. In this research,

498 equation (10) is used for WA calculation instead, in order to be comparable with other
499 methodologies available in literature.

500

501 Above listed indicators are calculated and used to evaluate solution based on initially adopted
502 sectorization criteria in this research. However, other PIs can be calculated to address other set
503 sectorization criteria (e.g. some type of leakage index).

504

505 **Selection of preferable sectorization solution**

506

507 After the Stage 3, WDN sectorization is completed resulting in a set of feasible solutions. This is one
508 of the main advantages of presented methodology, as it gives an array of alternative DMA designs to
509 the decision maker. One can opt for a solution with large number of small DMAs or for a solution with
510 small number of large DMAs, or anything in between. This is especially convenient for the analysis of
511 large WDNs without previously established DMAs, where DMAs strategic planning should be
512 addressed carefully. It is up to a decision maker to select sectorization solution best suitable to his
513 preferences, based on calculated PIs and other parameters.

514

515 **CASE STUDY**

516

517 **Description**

518

519 Methodology presented in this paper has been tested on a large water distribution network. The analysed
520 network was originally presented as second case study network in the Battle of the Water Sensor
521 Networks competition (BWSN2 - Ostfeld et al. (2008)). It is a real life WDN slightly modified to
522 preserve its anonymity. This network has been used as a case study for number of other DMA design
523 algorithms (Diao et al., 2013; Ferrari et al., 2014; Grayman et al., 2009; Hajebi et al., 2016; Zhang et
524 al., 2017). Network consists of 12,523 nodes, 14,822 pipes, two reservoirs, two tanks, four pumps and

525 five valves. Total demand in the network is $Q_{tot} = 1,243$ L/s and total number of connections in the
526 WDN is $n_c = 77,916$.

527

528 The input data for DeNSE sectorization method (see Methodology section) are carefully set to allow
529 meaningful comparison with previously published methods in the literature where the same network
530 was used. The input data are as follows: 1) network's EPANET input file is downloaded from Exeter
531 Centre for Water System (<http://emps.exeter.ac.uk/engineering/research/cws/downloads/benchmarks/>);
532 2) minimum number of connections per DMA $n_c^{min} = 500$, maximum number of connections per DMA
533 $n_c^{max} = 5,000$; 3) transmission main diameter threshold is $D_{main} = 350$ mm; 4) pipe closure diameter
534 threshold is $D_{tr} = 300$ mm; 5) minimum and maximum operating network pressures are set to
535 $p_{min} = 20$ m and $p_{max} = 75$ m, maximum allowable water age is $WA_{max} = 48$ h; desired number of
536 sectorization solutions $N_{sol} = 15$.

537

538 Based on total demand in the network (Q_{tot}), minimum (n_c^{min}) and maximum (n_c^{max}) number of
539 connections in a DMA, and total number of connections in the network (n_c), minimum and maximum
540 DMA size are calculated using equation (2) as $S_{min} = 8$ L/s and $S_{max} = 80$ L/s. For hydraulic modelling
541 24 hours MDD simulation is used, while for water quality modelling (WA calculation) extended period
542 simulation of 192 hours is used.

543

544 **Network clustering (STAGE 2)**

545

546 Figure 7 shows the evolution of network uniformity index (U) through network clustering process done
547 in the Stage 2, with maximum uniformity index value corresponding to 43 clusters ($U_{max}=0.5112$).
548 Minimum number of clusters is 23 which is in accordance with research of Ferrari et al. (2014), in
549 which the same transmission main diameter was used (350 mm) and 23 independent districts, connected
550 to the main, were identified. Figure 8 shows the evolution of all three components constituted in the
551 network uniformity index (U) - u_{net} , u_v and w_{agg} , in the last 77 aggregation steps (in total there are 11708
552 steps and all three components start from zero). Results illustrate that until maximum uniformity index

553 value is reached, u_{net} is the main parameter driving the clustering process. After that point large clusters
554 are created, which impacts both u_{net} and u_v causing them to decrease (seemingly at comparable rate). As
555 the plot suggests, w_{agg} constantly increase as aggregation proceeds, and changes only slightly in the
556 final 77 steps as most of the links are already aggregated.

557

558 **DMAs definition and evaluation (STAGE 3)**

559

560 After the Stage 2, 15 solutions are selected for further analysis having between 43 and 29 clusters. In
561 the Stage 3 flow meters and isolation valves are positioned to create DMAs and each solution is
562 hydraulically analysed. First solution (Sol-1), with 43 DMAs, does not satisfy the pressure constraints
563 and it is excluded from further analysis as unfeasible.

564

565 Beside adopted PIs used to evaluate the solutions, the following additional indicators are calculated to
566 aid the evaluation of solutions using the methods proposed here, but also to enable a comparison with
567 other literature methods (see corresponding section below):

- 568 1. Number of DMAs (N_{DMA}), number of meters (N_M) and number of valves (N_V),
- 569 2. NL – Number of DMAs larger than maximum DMA size (S_{max}),
- 570 3. NS – Number of DMAs smaller than minimum DMA size (S_{min}),
- 571 4. A_{com} – Average number of connections per DMA.

572 Cost, adopted PIs (Res and WA) and above listed additional indicators for the remaining 14 feasible
573 solutions are shown in Table 1.

574

575 As it can be seen from Table 1, all solutions have relatively similar values of two PIs, WA and Res . As
576 the number of DMAs in the solution decreases, average number of connections per DMA increases,
577 meaning that DMAs are larger in size. Consequently, for creation of smaller number of larger DMAs
578 requires less flow meters and isolation valves resulting in lower solutions' cost. Solution Sol-2 has one
579 DMA which is smaller than minimum size S_{min} . In solutions Sol-3 to Sol-9 all DMAs are within

580 specified $S_{min} - S_{max}$ range, while in the solutions Sol-10 to Sol-15 there are one or two DMAs that are
581 larger than S_{max} .

582

583 **Selection of preferable sectorization solution**

584

585 The preferable solution is identified by analysing the solutions that fully satisfy the DMA size
586 constraints, i.e. solutions Sol-3 to Sol-9. As noted earlier, all feasible solutions have similar impact on
587 network's resilience ($Res = 0.880 - 0.885$) and water age ($WA = 33.88 - 34.13$ h). Therefore, Sol-9 is
588 preferred solution over the Sol-5, as it is the less costly.

589

590 Figure 9 shows the preferred solution Sol-9 where the analysed WDN is sectorized into 35 DMAs,
591 together with the detail of DMA #23 with the position of valves and flow meters. These positions are
592 identified using heuristic approach described in Phase 1 of the Stage 3. Originally, the cluster that this
593 DMA belongs too had 6 boundary pipes. Three of them were identified as links that always return water
594 to the transmission main, and as such are marked for closure (V2, V3 and V4). Other three boundary
595 pipes are "always-input to the zone" pipes, and using described methodology pipe V1 ($D = 203.2$ mm)
596 is selected for closure, while other two pipes with larger diameters ($D = 304.8$ mm) are left opened and
597 equipped with flow meters (M1 and M2).

598

599 To provide further insight into the selected solution and the effects of network interventions required to
600 create DMAs, in addition to PIs and other indicators characterizing solution listed above (see Table 1),
601 for each DMA in a solution following PIs are calculated:

- 602 1. p_{DMA}^{av} – mean average pressures over the 24 hours in a DMA, as a good indicator of network
603 interventions' impact on pressure distribution, calculated as:

$$604 \quad p_{DMA}^{av} = \frac{\sum_{i=1}^{n_j} \sum_{t=1}^{24} p_j^t}{n_j} \quad \forall n_j \in DMA \quad (11)$$

- 605 2. Res_{DMA} – Average resilience index for a DMA, calculated per equation (9), only this time
606 accounting for nodes within considered DMA and
- 607 3. WA_{DMA} – Demand weighted WA for a DMA, averaged over the entire extended period
608 simulation (192 h). Demand weighting is used to account for difference of size between DMAs
609 in terms of demand.

$$610 \quad WA_{DMA} = \frac{\sum_{i=1}^{n_j} \sum_{t=1}^T WA_i^t q_i^t}{\sum_{i=1}^{n_j} \sum_{t=1}^T q_i^t} \quad \forall n_j \in DMA \quad (12)$$

611

612 Figure 10 and Figure 11 show results for each of 35 created DMAs in selected solution Sol-9. Figure 10-
613 a shows average consumption in DMAs, with highlighted minimum and maximum size constraints. As
614 it can be seen from the graph, identified 35 DMAs vary in size considerably but always within the
615 design limits imposed. Figure 10-b shows relative changes in mean average pressure in DMAs,
616 compared to mean average pressures in nodes that are part of that DMA in the original non-sectorized
617 network (Δp_{DMA}^{av}). For most DMAs the mean average pressure has slightly decreased (up to 4%), whilst
618 slight increase occurs in six DMAs (up to 1%). Therefore, network sectorization had very limited impact
619 on re-distribution of pressure within the WDN. Significant decrease of pressure is observed in DMA #8
620 (by 13%), but all pressures are still within the required range of $p_{min} - p_{max}$.

621

622 Figure 11-a illustrates relative changes in water age in the DMAs, again compared to the original
623 network layout (ΔWA_{DMA}). Maximum decrease of WA is 20%, while increase is almost 30%. While
624 decrease of WA is desirable, increase of 30% may seem a bit high at first. However, plotting absolute
625 values of WA for DMAs in which increase is induced by network interventions (Figure 12) it is easy to
626 conclude that WA is still well below set maximum WA_{max} of 48 h. Figure 11-b shows relative changes
627 in DMAs resilience index (ΔRes_{DMA}). Changes in resilience index range from -3.5% to +2.2%,
628 indicating very limited impact of sectorization on the resilience of the WDN.

629

630 To summarise, from the results discussed above it can be concluded that: 1) all DMAs are within
631 required size limits in terms of consumption, 2) network's hydraulic performance is not endangered as
632 changes in zone pressures are negligible, 3) water quality requirement, expressed through the WA is
633 satisfied, as for all DMAs WA is still below maximum allowed threshold of 48 h and 4) Network
634 reliability is sustained as changes in resilience index are almost insignificant.

635

636 **Comparison of results with other methods**

637

638 Finally, a comparison of results obtained here is made to the corresponding results obtained using five
639 previously published approaches that addressed the WDN sectorization problem and by using the same
640 case study (Table 2). Comparison is made in terms of number of DMAs (N_{DMAs}), DMAs that are larger
641 (N_L) and smaller (N_S) than predefined size constraints, number of flow meters (N_M) and isolation valves
642 (N_V), added pipes (P_{add}), average number of connections per DMA (A_{conn}), computational time
643 ($Comp.Time$) and PIs adopted in this research to evaluate the solutions – Water Age and Resilience
644 Index (WA and Res). Direct comparison with other methods in terms of $Cost$ could not be made because
645 the cost was not explicitly reported in other papers. Reported values of PIs in the Table 2 refer to best
646 sectorization solutions reported by each research. Computational times are given only as a qualitative
647 metric, to illustrate differences in magnitudes between different methods. Table 2 also provides an
648 overview of sectorization methods used in each method for: a) partitioning the WDN and b) positioning
649 the flow meters and isolation valves.

650

651 As it can be seen from Table 2, only the methodology presented in Hajebi et al. (2016) and DeNSE
652 method, presented here, produce a set of feasible solutions. A total of 78 feasible solutions are identified
653 in Hajebi et al. (2016) with solutions having between 28 and 48 DMAs. Regarding the DMA size
654 constraints, solutions presented by Grayman et al. (2009) and Diao et al. (2014) have DMAs that are
655 both larger and smaller, while in the solution presented by Ferrari et al. (2014) all DMAs fulfil size
656 constraints. In Hajebi et al. (2016) all 78 feasible solutions meet size constraints, while in methodology
657 presented here this is case for 7 out of 14 feasible solutions.

658

659 Methodologies using MO optimization to position flow meters and isolation valves (Hajebi et al. 2016,
660 Zhang et al. 2017) require significant amount of computational time (15 hrs and 278 hrs respectively).
661 Substantially lower computational time of Hajebi's method, compared to the method of Zhang, can be
662 attributed to the use of shorter extended period simulation time (48 h compared to 192 h) used to
663 calculate WA. Issue of high computational time, as a consequence of using MO optimization, is
664 addressed in Diao et al. (2013) in which two stage heuristic procedure for device placement is applied,
665 resulting in acceptable running time of around 20 min. However only one solution with 41 DMAs is
666 reported with three DMAs out of required size limits. Engineering based heuristic procedure used in
667 methodology presented here takes similar amount of time (about 20 min), but produces a set of feasible
668 solutions compared to the research of Diao et al. (2013). Computational efficiency of DeNSE method
669 is even more emphasized when compared to the method of Hajebi et al (2016). Both methods are able
670 to produce a set of feasible solutions, but DeNSE takes only 20 min (compared to 15 hrs) and yet it uses
671 a longer extended period analysis for WA calculation (192 hrs compared to 48 hrs).

672

673 Methodologies of Ferrari et al. (2014) and Hajebi et al. (2016) ensure connectedness of each DMA to
674 the transmission main (direct access to water source) and their isolation from other DMAs (so called
675 isolated DMAs – iDMAs). While methodology presented here does not create iDMAs, preferable
676 solution presented earlier (Sol-9) fulfils condition of direct access to water source. All 35 DMAs are
677 directly connected to the transmission main: 20 DMAs with 1 pipe, 4 with 2, 6 with 3, 4 with 4 and 1
678 with 6 pipes.

679

680 Table 2 also gives comparison of main performance indicators values for best reported solutions,
681 obtained with different methods – water age (WA) and resilience index (*Res*). Presented results show
682 that DeNSE method achieves slightly better value of resilience index and slightly worse value of water
683 age. Reported results are only indicative as different input parameters, affecting values of compared
684 indicators, are used. For water age calculation Grayman et al. (2009), Diao et al. (2014) and
685 methodology presented here use 192-h extended period simulation, while Hajebi et al. (2016) uses 48-h

686 simulation. Furthermore, water age value is highly dependent on the adopted time step for water quality
687 simulation and those papers do not supply this information. Grayman et al. (2009) reported increase of
688 2.61% in *WA* for the DMA system, when compared to the original network (from 30.71 h to 31.51 h).
689 In the case of DeNSE method *WA* is increased by 3.31 % for the DMA system (from 32.91 h to 34 h)
690 which is regarded as insignificant increase and same order of magnitude as achieved in Grayman et al.
691 (2009). Reported resilience indices are influenced by the adopted minimum allowable pressure in the
692 network and time period over which they are averaged. Grayman et al. (2009) adopted minimum
693 pressure of 30 psi (20 m) and 51-h time period. Hajebi et al. (2016) uses 28 m minimum pressure and
694 48-h time period, while Diao et al. (2013) does not report values of this indicator. Grayman et al. (2009)
695 reported decrease of resilience index of 4.07 % for the DMA system, when compared to the original
696 network (from 0.836 to 0.802), while the DeNSE method achieves lower decrease of 2.55 % (from
697 0.903 for the original network to the 0.88 for the DMA system). As noted above, due to the different
698 input parameters, values of PIs presented in Table 2 are not directly comparable, but illustrative and
699 show that in terms of water age and resilience all methods perform similarly.

700

701 **CONCLUSIONS**

702

703 The new DeNSE sectorization method is introduced in this paper. It was tested and validated on a large,
704 real-life sized water distribution network BWSN2 (Ostfeld et al., 2008). The results obtained were
705 compared to several other literature sectorization methods that used the same case study network. Based
706 on this the following conclusions are drawn:

- 707 1. The DeNSE method is able to identify a set of good, feasible network sectorization solutions
708 for a large water distribution network such as the one used in the case study here. The method
709 is able to do this in a computationally efficient manner which, in turn, enables exploring
710 alternative sectorization strategies by changing the method input parameters. High
711 computational efficiency comes mainly from the new heuristic methodology for positioning the
712 flow meters and isolation valves. The advantage of this approach is noticeable especially when

713 DeNSE algorithm is compared with other, optimization based sectorization methods (Hajebi et
714 al., 2016; Zhang et al., 2017).

715 2. The DeNSE method ensures that sectorization interventions are identified in a way that does
716 not worsen the operational performance of the WDN prior to its sectorization. The method
717 ensures that minimum and maximum network pressures before and after sectorization stay
718 within the same range. The method also ensures that water quality (measured by water age) is
719 not worsened by WDN sectorization.

720 3. The DeNSE method estimates explicitly the costs involved in WDN sectorization as opposed
721 to other literature methods where costs are assessed indirectly, e.g. via a number of installed
722 new devices or summarized diameters (e.g. Hajebi et al., 2016) Even though the proposed
723 method does not make use of optimization, this explicit assessment of costs enables the
724 identification of realistic sectorization solutions that can be compared with budgets available.

725 4. The DeNSE method seems particularly well suited for the application at the initial stages of the
726 DMA design process and in low efficient WDNs (i.e. WDNs with higher water losses). This is
727 because the method enables: (a) alternative DMA sizes (both small and large) to be considered
728 and analyzed and (b) preservation of network hydraulic performance and reliability which, in
729 turn, enables tracking the network water balance more easily, as opposed to other literature
730 methods which seem to focus more on controlling the pressures in the network (Zhang et al.,
731 2017).

732
733 Future DeNSE development will address adding sectorization criteria such as design for fire flows,
734 specific water quality parameters (e.g. Chlorine), design for security etc.

735

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906 **Table 1.** Evaluation indicators for 14 feasible solutions

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<i>Sol ID</i>	N_{DMAs}	NL	NS	A_{conn}	WA	Res	$Cost$	N_M	N_V	u_{net}	u_v	U
[-]	[-]	[-]	[-]	[-]	[h]	[-]	[€]	[-]	[-]	[-]	[-]	[-]
Sol-2	42	0	1	1655	34.13	0.881	557,405	81	178	0.538	0.967	0.5073
Sol-3	41	0	0	1696	34.11	0.881	551,215	80	177	0.552	0.943	0.5070
Sol-4	40	0	0	1738	34.11	0.881	545,870	79	177	0.545	0.943	0.5013
Sol-5	39	0	0	1783	33.98	0.882	542,210	79	176	0.537	0.944	0.4943
Sol-6	38	0	0	1830	34.02	0.880	537,920	77	176	0.537	0.931	0.4872
Sol-7	37	0	0	1879	34.02	0.880	534,500	76	175	0.528	0.925	0.4767
Sol-8	36	0	0	1931	34.01	0.880	530,995	76	169	0.534	0.910	0.4744
Sol-9	35	0	0	1987	34.00	0.880	523,685	75	166	0.530	0.895	0.4633
Sol-10	34	1	0	2045	34.00	0.881	522,565	75	164	0.522	0.882	0.4496
Sol-11	33	1	0	2107	34.01	0.881	516,375	74	163	0.516	0.855	0.4318
Sol-12	32	2	0	2173	33.98	0.881	515,815	74	162	0.505	0.839	0.4145
Sol-13	31	2	0	2243	33.98	0.881	510,470	73	162	0.482	0.840	0.3957
Sol-14	30	2	0	2318	33.96	0.880	497,205	71	153	0.481	0.840	0.3956
Sol-15	29	2	0	2398	33.88	0.885	490,470	71	138	0.466	0.818	0.3736

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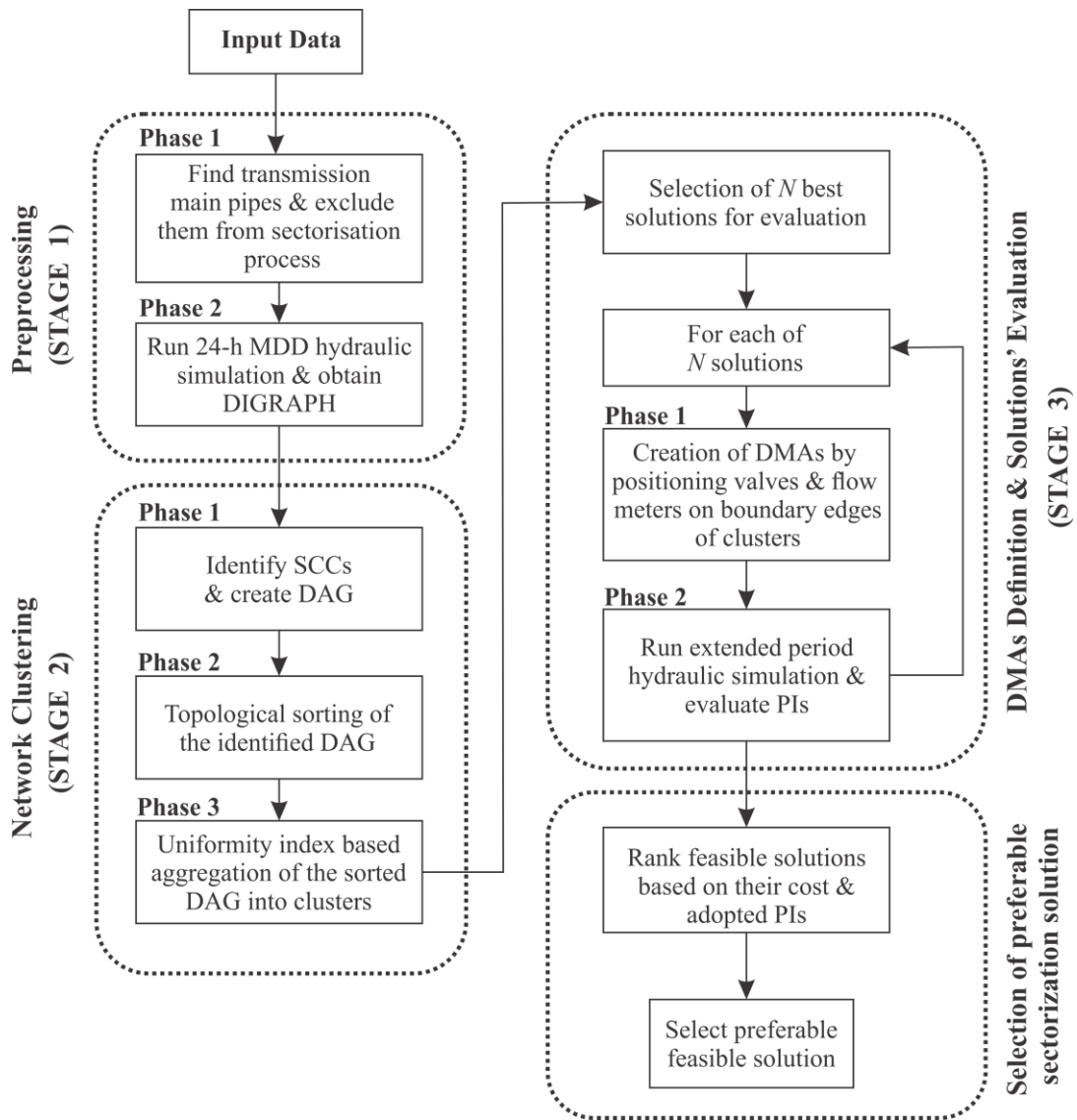
910 **Table 2:** Comparison of results with other methods

911

Published in	Method for		N_{DMAs}	NL	NS	N_M	N_V	P_{add}	A_{conn}	<i>Comp. Time</i>	WA	Res
	WDN partitioning	Device placement	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[min/h]	[h]	[-]
Grayman et al. (2009)	Manual		43	1	3	53	163	11	1996	NA	31.51	0.802
Diao et al. (2013)	Comm. detection	2 stage heuristic method	41	2	1	NA	NA	0	2044	20 min	32.01	NA
Ferrari et al. (2014)	Graph based recursive bisection algorithm		36	0	0	181	152	0	2317	NA	NA	NA
Hajebi et al. (2016)	Heuristic graph partitioning	MO optimization	28-48	0	0	56-78	66-161	0	1415-2423	15 h	31.01	0.830
Zhang et al. (2017)	Comm. detection	MO optimization	43	NA	NA	103	33	0	NA	278 h	NA	NA
DeNSE Algorithm	Uniformity based clustering	Engineering based heuristic	29-42	0-2	0-1	71-81	138-178	0	1656-2398	20 min	34.00	0.880

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913 * NA – not available; WA – Water Age for best reported solution; Res – Resilience Index for best reported solution

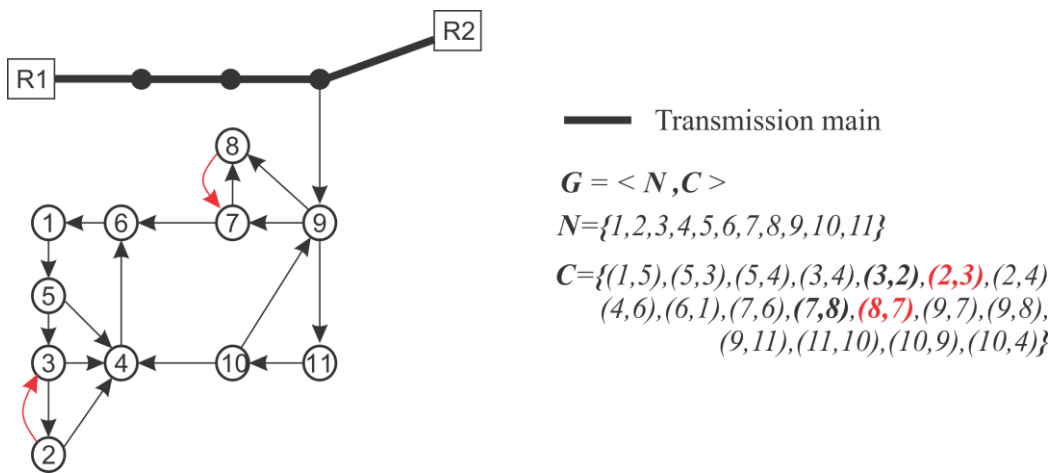


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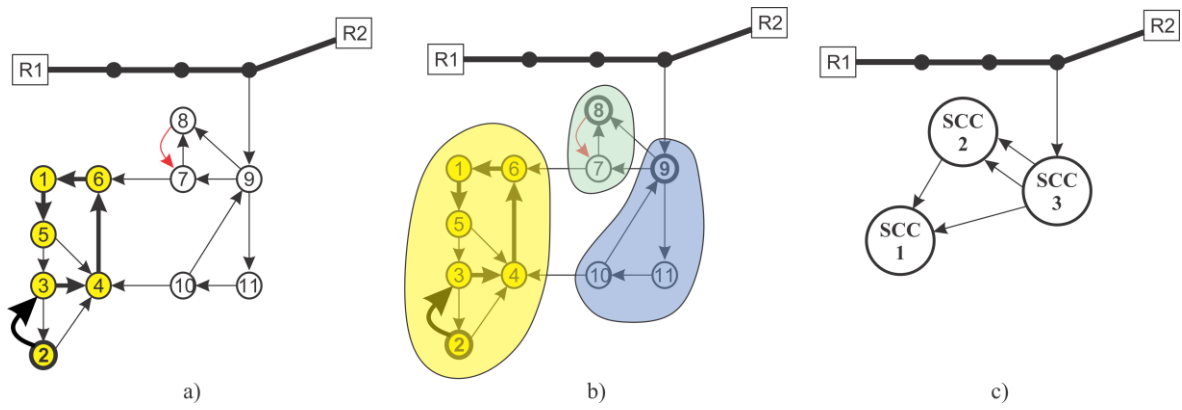
Fig. 1. Flow chart of the DeNSE sectorization method



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Fig. 2. Digraph presentation of a simple network with 2 sources and 2 undirected links



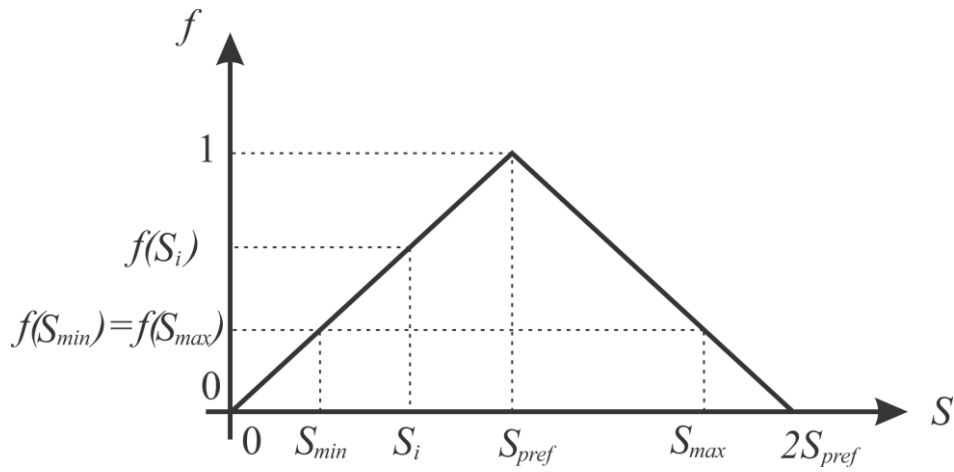
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Fig. 3. DIGRAPH transformation to DAG: a) Start the DFS; b) Detected SCCs; c) Newly formed DAG

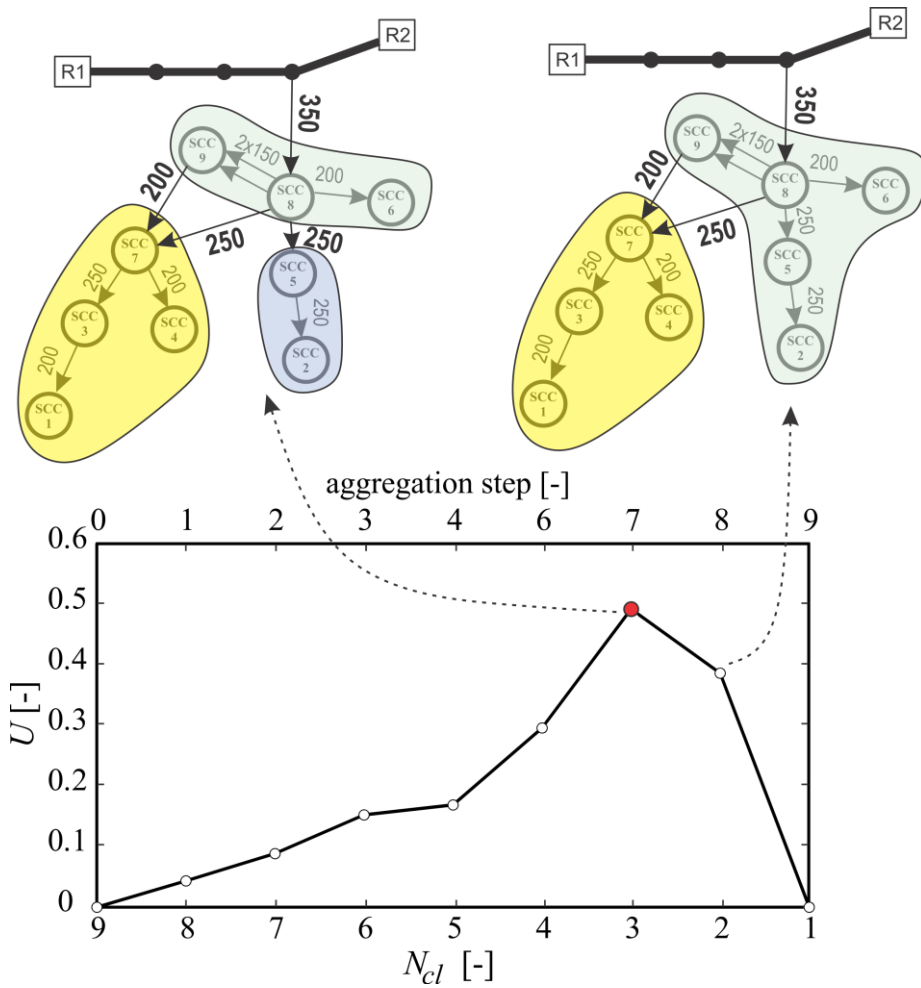


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Fig. 4. Triangular function f quantifying cluster size “quality”

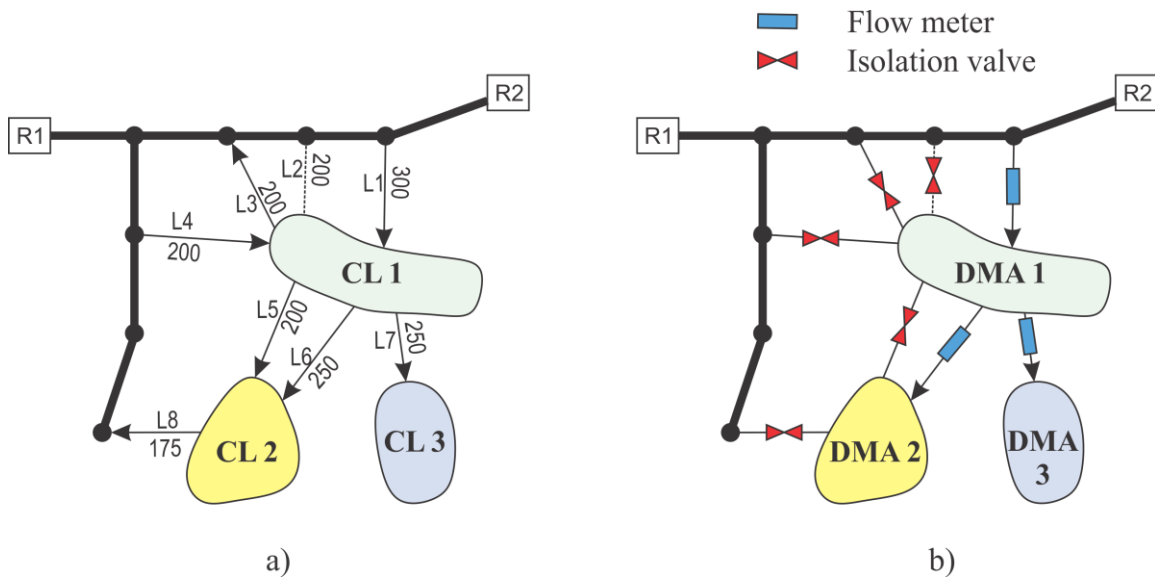


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Fig. 5. Evolution of network uniformity index during aggregation process

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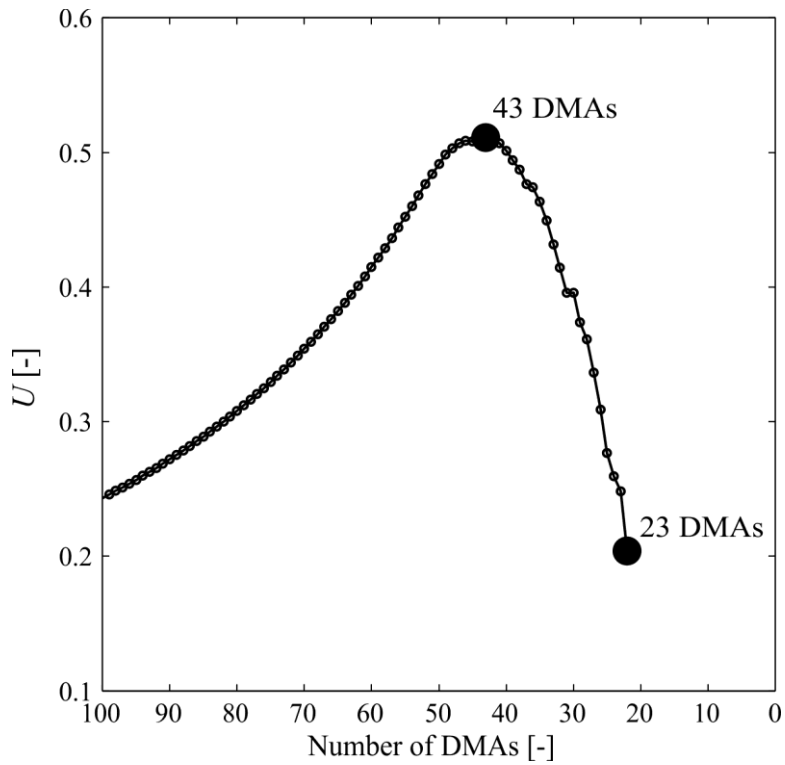


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Fig. 6. Heuristic based placement of flow meters and isolation valves (Stage 3 – Phase 1)

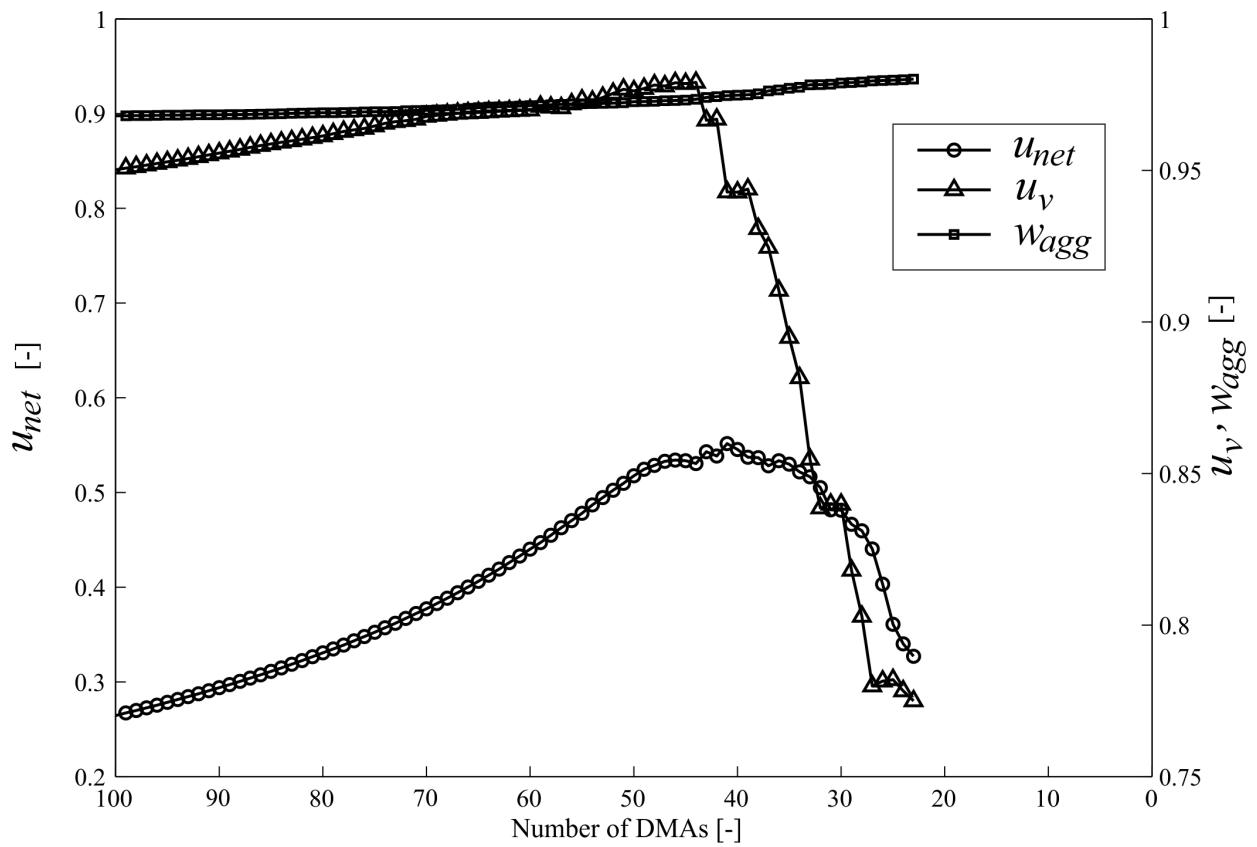
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Fig. 7. Evolution of Uniformity Index during clustering of BWSN2 network



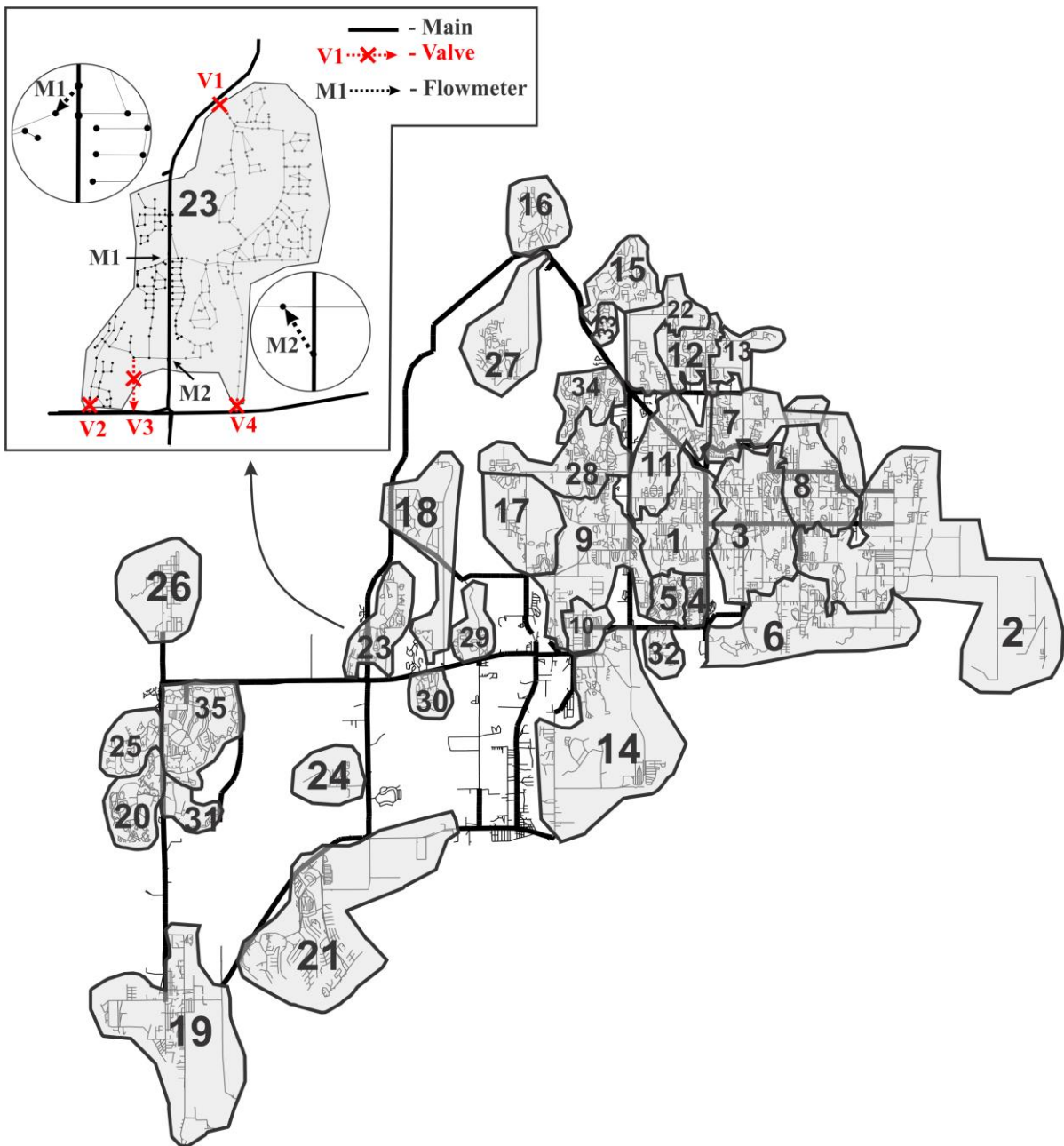
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Fig. 8. Evolution of all three components (u_{net} , u_v and w_{agg}) constituted in the network uniformity index (U) in the last 77 aggregation steps

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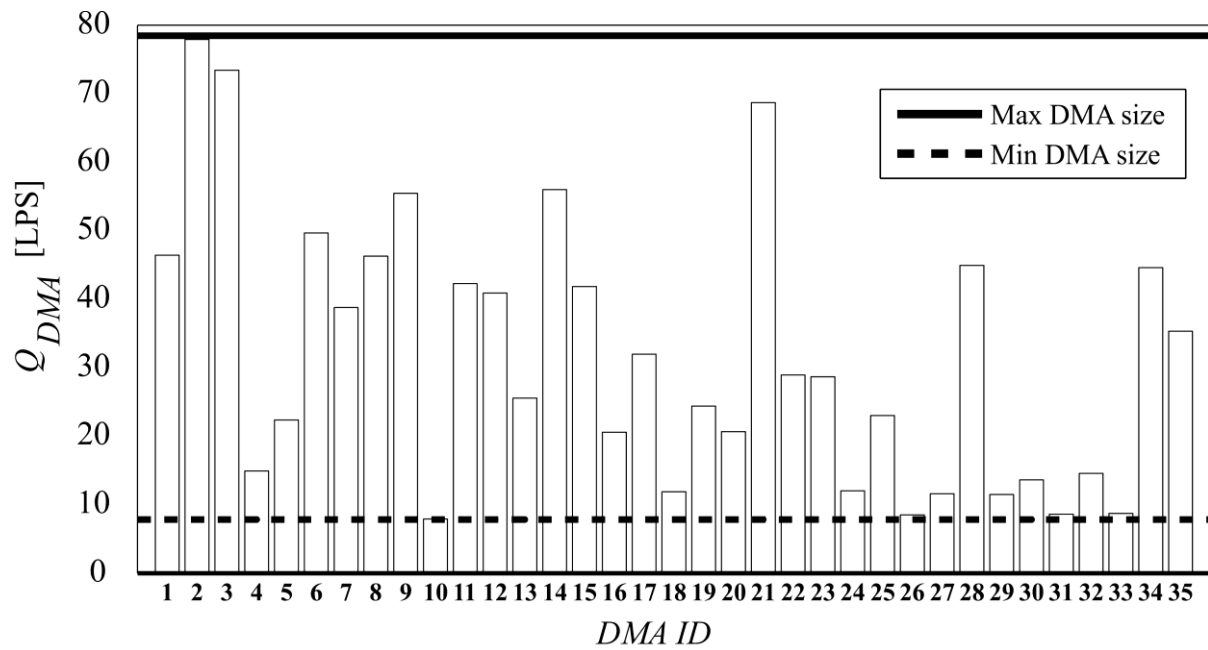


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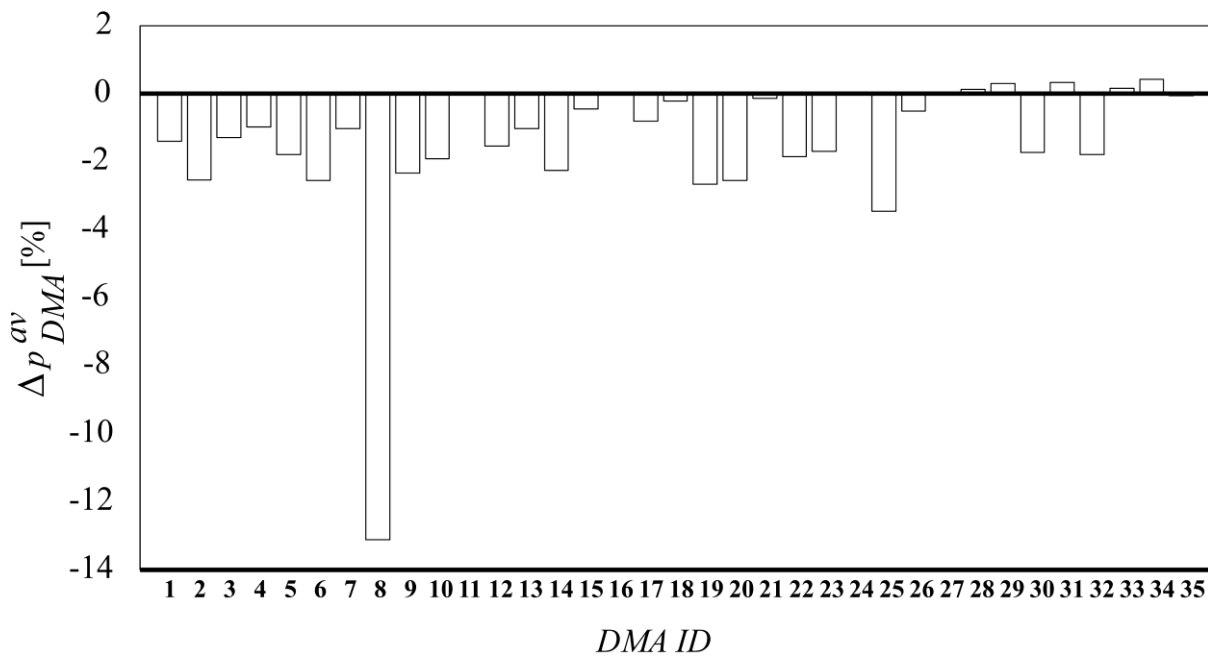
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Fig. 9. Preferred sectorization solution (Sol-9) with 35 DMAs and detail of DMA #23

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a)



b)

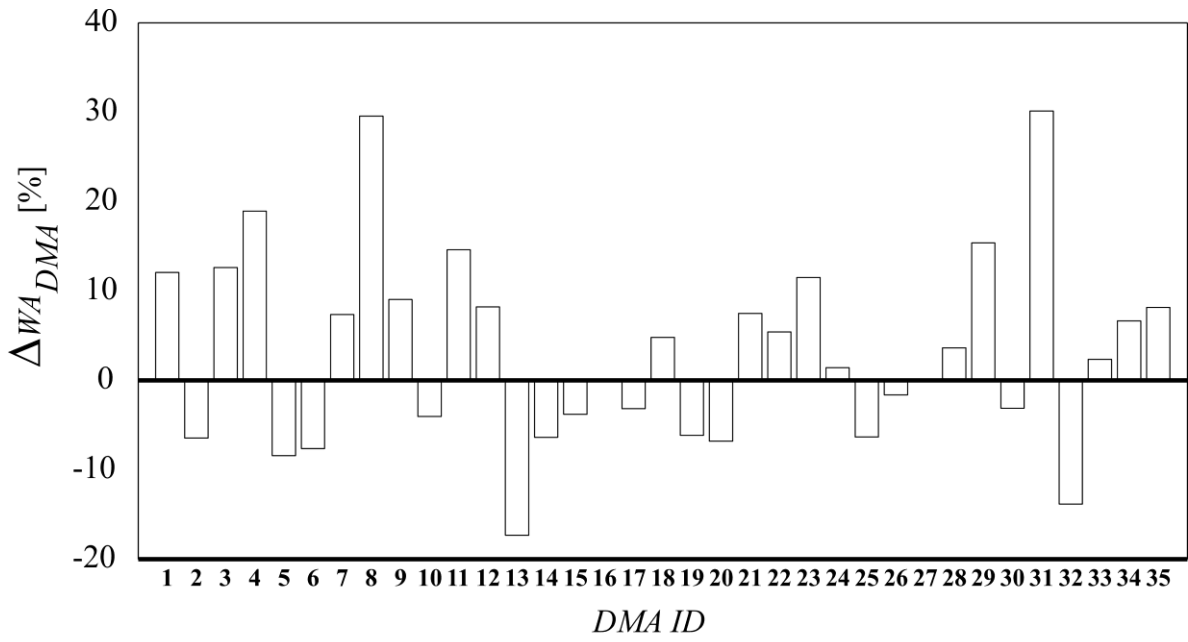
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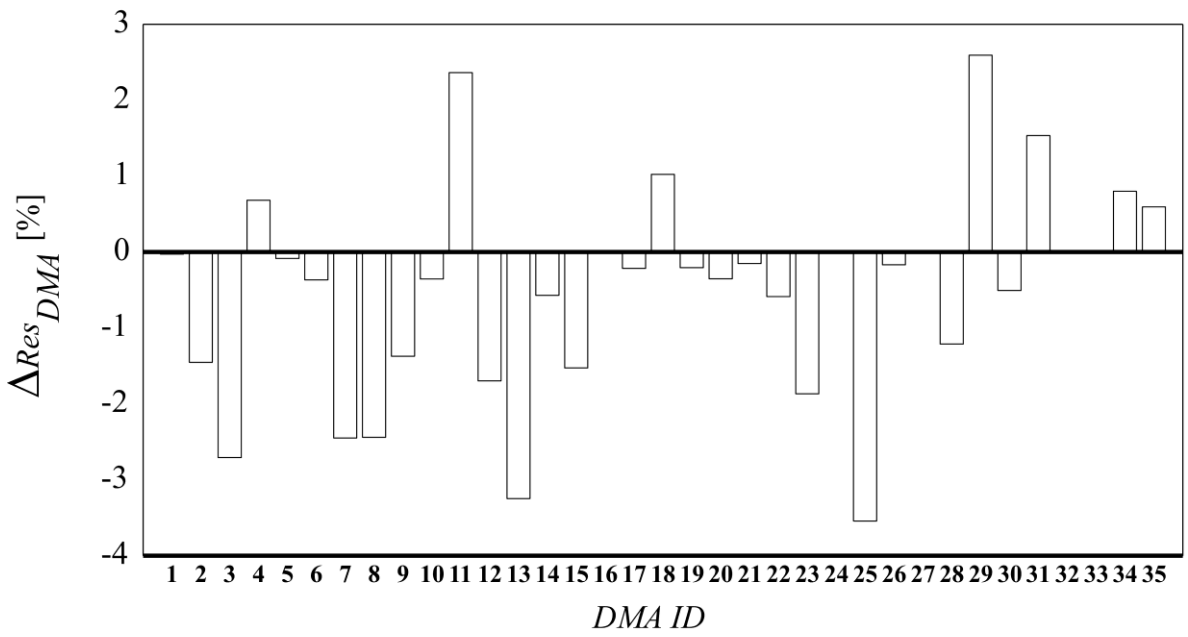
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Fig. 10. Results for each DMA in selected preferable solution (Sol-9): a) average DMA consumption; b) relative change of mean average pressure



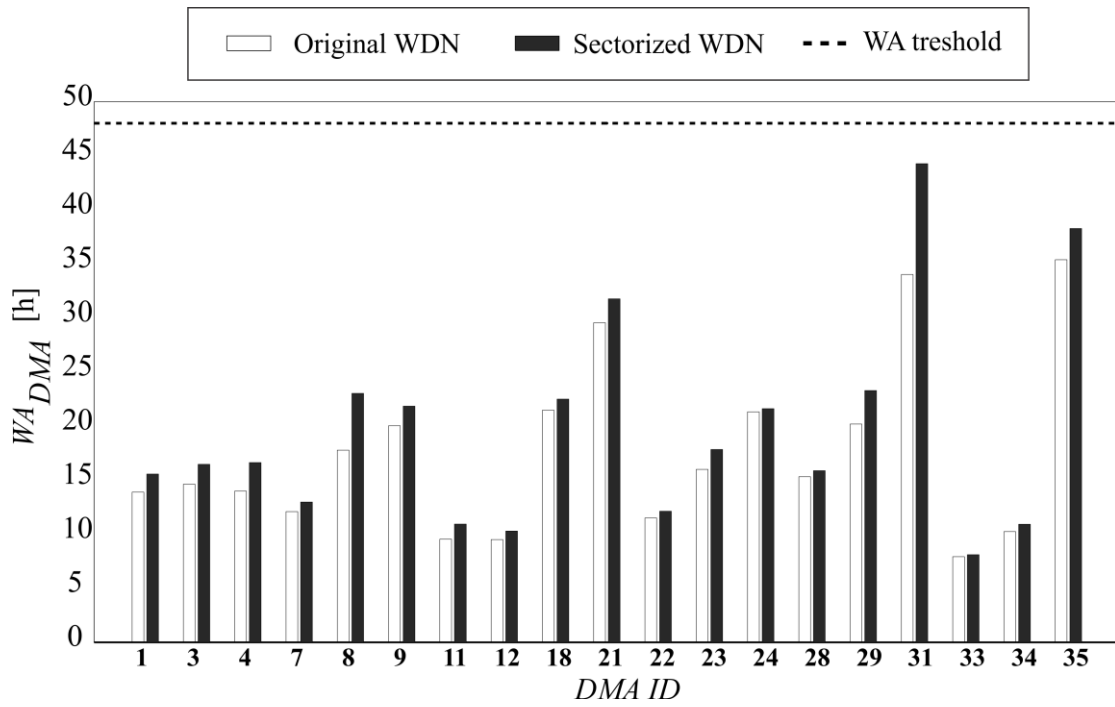
a)



b)

Fig. 11. Results for each DMA in selected preferable solution (Sol-9): a) relative change of Water Age; b) relative change of Resilience Index

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Fig. 12. Values of water age, before and after sectorization, for DMAs with increased water age

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