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A procedure for the design of district metered areas in water distribution systems

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Abstract

A procedure for the districtualization of a water distribution system is presented. The procedure is based on the use of techniques derived from graph theory and is aimed at identifying a "near optimal solution" in terms of (a) allocating all the network nodes among an assigned number of DMAs and (b) determining which pipes should be closed to delimit such districts and which pipes should be left open and fitted with flow meters in order to maximize the resilience of the entire system after the creation of districts. The application of the proposed procedure to a real water distribution system proved its robustness and effectiveness. The results obtained show that the procedure makes it possible to identify very good solutions in terms of resilience and minimum pressures when reference to the peak water demand and fire-flow conditions is made.

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Keywords: water distribution system; district metered area; graph theory; breadth first search.

1. Introduction

District metering is a technique used to improve water distribution system (WDS) management and consists in partitioning a WDS into smaller portions called District Metered Areas (DMAs). These districts are obtained by placing and closing isolation valves along certain pipes connecting one DMA to another (closed links) and placing a flow meter in the remaining connecting pipes (open links). Based on the measured inflow and outflow of each

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DMA and taking into account storages, it is possible to determine the water balance of the DMA and monitor minimum night flows, thereby obtaining information that is useful for identifying the presence of leakage within the district. Moreover, the demand data acquired at the DMA level can be effectively used in the context of real-time system management.

Designing the DMAs of a water distribution system entails identifying how to allocate the nodes of the network among the various districts in such a way that each district is of adequate size, i.e. includes an adequate number of users/inhabitants, and determining (a) which pipes need to be closed off to delimit the DMAs and (b) which pipes need to be left open with the flow meters placed. With reference to this latter aspect, it is thus worth pointing out that while on the one hand partitioning a water distribution system into districts can bring significant benefits in terms of leakage reduction and real-time system management, on the other hand it can give rise to problems with respect to the reliability and efficiency of the system itself. District metering in fact contrasts with the approach typically adopted in the design of water distribution systems, which is based on the creation of highly looped networks which ensure high reliability. After a number of network pipes have been closed off by means of isolation valves in order to create a DMA, the network will have less of a loop structure, meaning that its reliability will be reduced; at the same time, more energy will be dissipated in the network, resulting in potential problems of ensuring minimum pressures at the nodes.

The design of DMAs thus represents a complex problem, especially in the case of real water distribution systems, which are often designed in successive stages and are typically not conceived with an eye to district metering. Several procedures have been proposed in the scientific literature to solve this problem; they are either decision support procedures (see, for example, Tzatchkov et al. 2006; Perelman and Ostfeld 2011) or automatic DMA design procedures (see, for example, Di Nardo et al., 2011; Diao et al., 2012) and are mainly based on graph theory and hydraulic simulations.

In this paper we propose an automatic procedure for the full districtualization of a water distribution system. The procedure proposed here is similarly based on the use of techniques derived from graph theory, and in particular on the Breadth First Search algorithm (BFS, Pohl,1969) and the algorithm for finding the shortest paths in a graph (Dijkstra,1959), and on hydraulic simulations of the districtualized system.

In the sections that follow, we shall describe the structure of the proposed procedure and illustrate its application to a case study of the water distribution system of Castelfranco Emilia (Modena province). After discussing the results obtained, we will compare them with those that would be obtained with a similar procedure previously proposed by Di Nardo et al. (2011) and, finally, present our conclusions.

2. The procedure

The proposed procedure for the automatic creation of district metered areas in a water distribution system has a modular structure divided into three parts. In the first part a broad set of possible solutions to the problem is identified by using graph theory-derived techniques; each of these solutions is characterized by a) a different allocation of the network nodes to form an assigned number of DMAs and b) a determination of which connecting pipes between DMA and DMA should be closed and which should be equipped with a flow meter. In the second part of the procedure a limited number of solutions that can potentially ensure good system performance is selected once again relying on graph theory-derived techniques alone. Finally, in the third part of the procedure, each of the previously selected solutions undergoes evaluation via a pressure-driven hydraulic simulation to determine its actual “goodness”, in terms of system resilience, and then the best solution is identified.

More in details, given the network to be subdivided in district meters (see, for example, Fig. 1), let $N0$ be the number of supply points and NN the number of remaining nodes for each of which the number of connected users U_i is known (with i=1:NN); furthermore, let $Utot$ be the total number of network users (e.g. $Utot=4000$) and n_{DMA} the number of DMAs we want to partition the network into (e.g. n_{DMA}=2); the procedure can then be broken down into the steps described below:

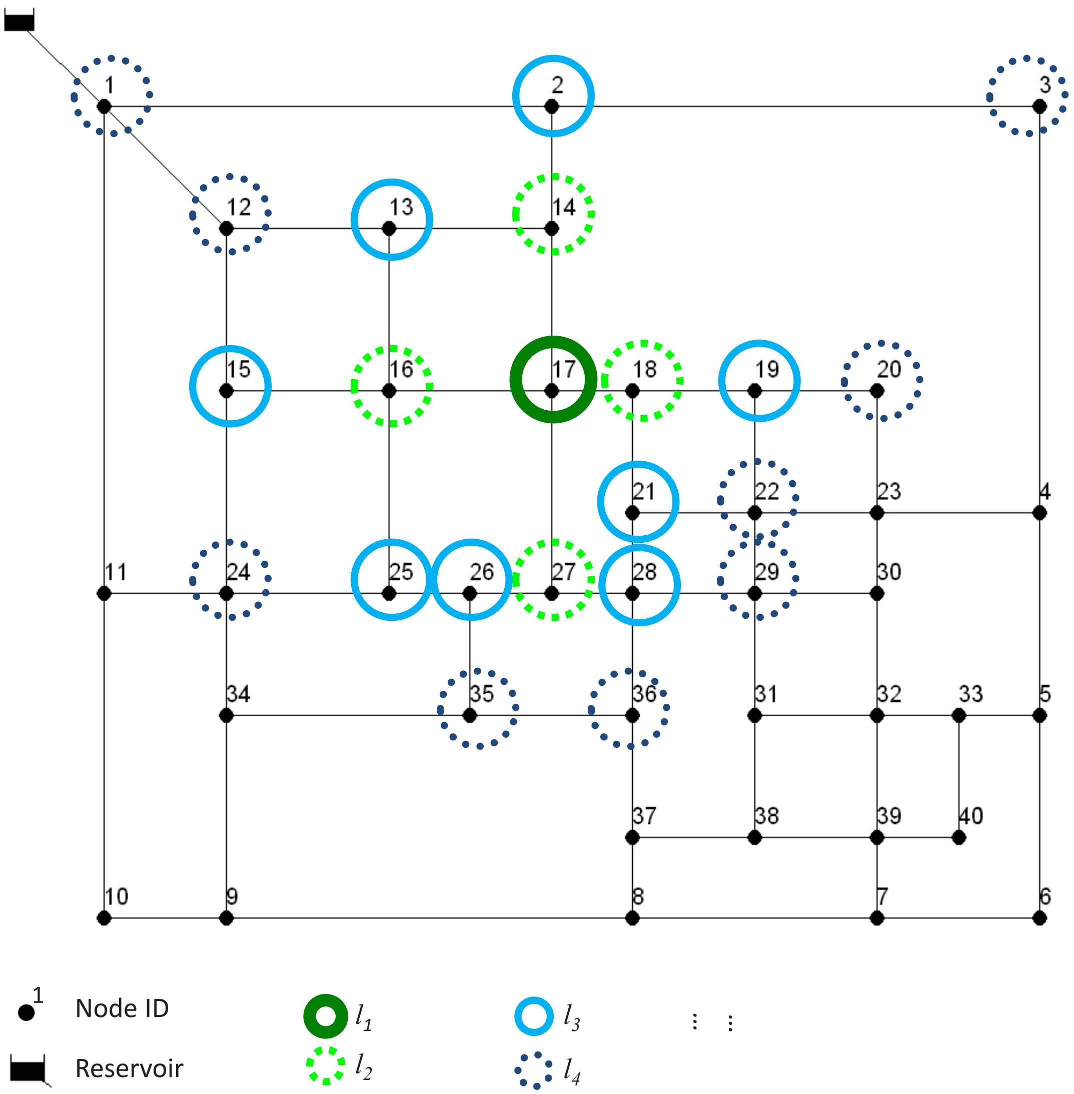

Fig. 1. Example of a simple water distribution system to be district metered and sequence of nodes visited in a BFS carried out starting from node 17.

Part I – Generation of a broad set of solutions for the creation of DMAs

1. Assuming the total number of network users *Utot* to be uniformly allocated among the n_{DMA} districts the number of reference users $Uref=Utot/n_{DMA}$ that each DMA should contain is computed (in the case of the example we would have *Uref*=4000/2=2000 users).
2. We set a tolerance ΔU, in percentage terms relative to *Uref*, for the number of users actually includable in each DMA (for example ΔU=5%). For a given ΔU we will consider acceptable all of the solutions in which the number of users actually included in each DMA falls within a neighborhood $Uref \pm \Delta U$,
3. We consider the *NN* network nodes *one by one*. For each node *i*, where *i*=1:*NN*, we carry out the following steps 3.1 to 3.3:

3.1. We carry out a breadth first search (BFS, Pohl, 1969). The breadth first search enables us, starting from the *i*-th node considered, to "visit" all the other network nodes; first of all we visit the nodes adjacent to the starting node and then visit all of the nodes adjacent to them which have *not yet been visited,* and so on until there are no longer any unvisited adjacent nodes. In practical terms, with reference to the network in Fig. 1 and assuming for example the node 17 as the starting node first we visit nodes 14, 18, 27 and 16, then, starting from node 14, we visit nodes 2 and 13, starting from node 18, we visit nodes 19 and 21, etc..

3.2. We allocate the network nodes in layers l_j (with j=1:nl) (see Table 1), where l_1 indicates the layer consisting solely of the starting node, the layer l_2 indicates the set of nodes directly linked to the starting node (l_2={14,16,18,27}), the layer l_3 the set of nodes directly linked to the nodes of the layer l_2 (l_3={2,13,15,19,21,25,26,28},) etc.; for each layer l_j we calculate the total number of users Ul_j included, i.e. the sum of the users corresponding to the nodes included in the layer (see Table 1, column 4) and the cumulative sum Ul_j^{cum} of the numbers of nodal users included in the preceding layers and in the layer j itself (see Table 1, column 5).

3.3. Let l_{thr} be the "threshold" layer, that is the first layer that has a corresponding number of cumulative users Ul^{cum} that is greater than $Uref$ and let NNl_{thr} be the number of nodes making it up (in the example, being $Uref$=2000 users, $l_{thr} = l_4$ and NNl_{thr} =9, see Table 1, column 3); we consider all the possible combinations of NNc=1, 2,.., NNl_{thr} of these nodes (i.e. of the nodes of this latter layer). For each combination it is assumed that the nodes making it up constitute a DMA *together* with all the nodes belonging to the layers which precede the threshold layer, i.e., in the example, together with the nodes of layers l_1, l_2 and l_3. In particular, only the solutions corresponding to a number of users included in the DMA that falls within the neighborhood $\pm\Delta U$ of $Uref$ are selected.

The operations described in steps 3.1 to 3.3, to be repeated for each node i=1:NN of the entire network, enable us to identify a large number of possible solutions for attributing network nodes to form DMAs of the desired size. In particular, in the case considered in the example illustrated here, where n_{DMA}=2, once nodes have been attributed to a (first) DMA, the second DMA will also be automatically defined, since it will be made up of all remaining network nodes. If the number of the DMAs n_{DMA} we want to create is greater than 2, we will iteratively repeat steps 3.1 to 3.3 for *each of the* combinations obtained at the end of step 3.3 for the first DMA (associable with the *i*-th node selected in step 4), but in this case we will consider each time only the nodes not yet included in the previously created DMA(s).

4. The operations described thus far make it possible to identify a large number n_{sol} of different possible solutions for allocating the network nodes to form n_{DMA} DMAs, while ensuring that the DMAs are always of a size falling within the set margin of tolerance. For *each* of these solutions, assuming that at least one meter is placed in each DMA to measure inflow (or outflow from the contiguous DMA), we identify its location in the following manner. For the DMAs directly connected to the supply point(s) and for each supply point we place a meter in the outlet pipe leading from the supply point itself (see Fig. 2).

For the remaining DMAs we identify the pipes connecting them to the preceding DMAs (in turn directly connected to the supply points) and each *of these connecting pipes* is assigned a weight w defined as:

$$w=\left(\frac{\lambda}{D2gA^2}L\right)^{-1} \tag{1}$$

where D, A and L are respectively the diameter, cross section size and length of the pipe and λ is the resistance coefficient.

For each DMA not directly connected to a supply point, it is assumed that a meter will be placed in the connecting pipe having the greatest weight (see Fig. 2). It is worth noting that this weight represents a sort of conductance of the pipe and thus placing the meters in the connecting pipes with the greatest weight is equivalent to selecting the pipes associated with the lowest head losses given the same flow discharge.

Table 1. Allocation of the nodes in layers and calculation of the number of users connected to each layer based on the BFS carried out on the network of Fig. 1, assuming node 17 as the starting point.

layer	node ID	NNl_j # nodes per layer	Ul_j # layer users	Ul_j^{cum} # cumulative users
l_1	17	1	160	160
l_2	14, 16, 18, 27	4	480	640
l_3	2, 13, 15, 19, 21, 25, 26, 28	8	1040	1680
l_4	1, 3, 12, 20 ,22, 24, 29, 35, 36	9	1160	2840
l_5	…	…	…	…
…	…	…	…	…

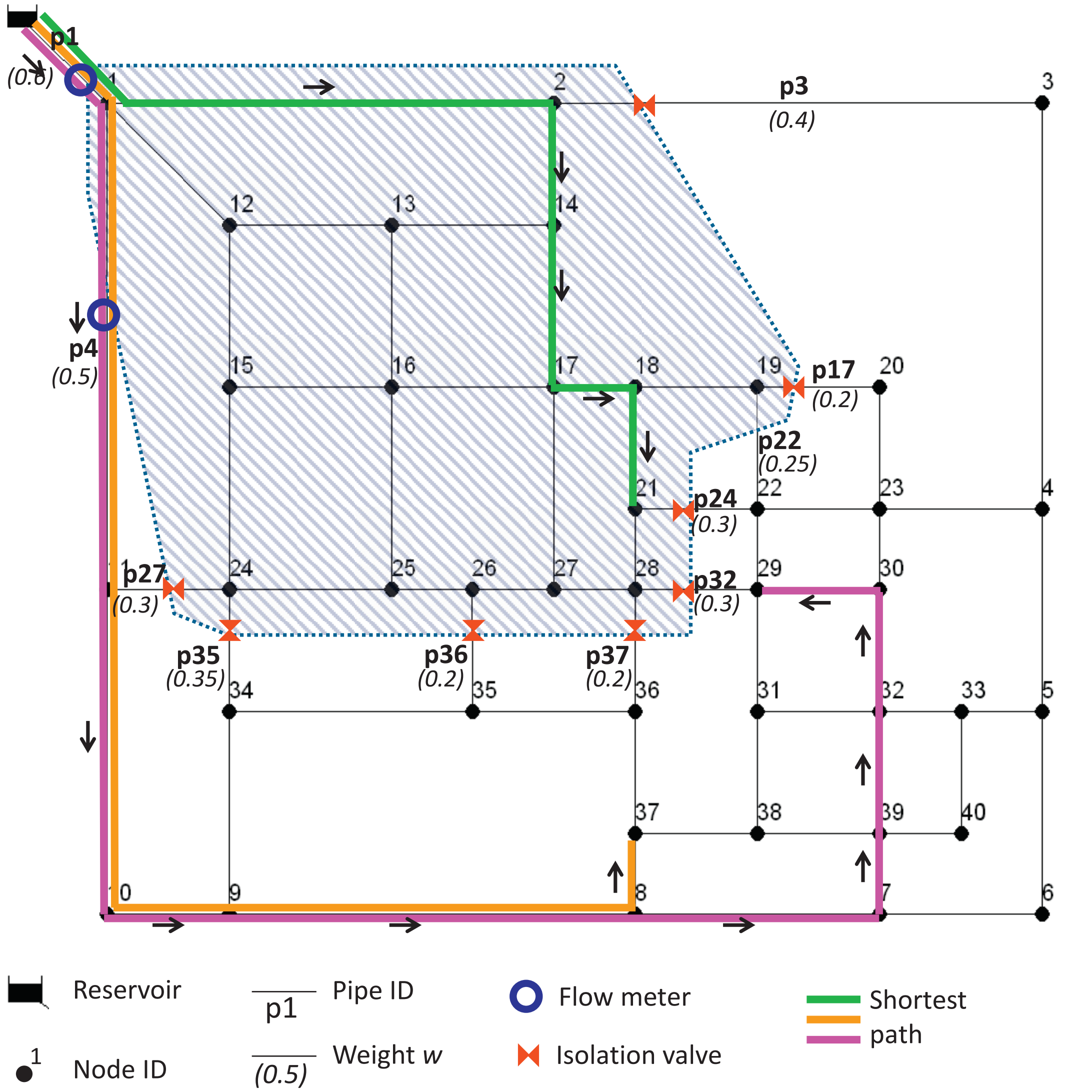

Fig. 2. Examples of shortest paths from the supply point to nodes 21, 29 and 37 for a given flow meters and isolation valves placements to form 2 DMAs.

Part II – Selection of the narrow set of solutions to be hydraulically analyzed

5. Among the n_{sol} solutions we select a set of n_{hyd} solutions to be hydraulically analyzed by carrying out the following operations for each solution *s* (with s=1: n_{sol}):

5.1. If there is only one supply point ($N0$ = 1), for each network node, we will calculate the shortest (possible) weighted distance from the supply point using the Dijkstra algorithm (1959) (see Fig. 2) when reference to the districtualization associated to the solution considered is made. For this purpose each pipe in the network will be associated with a corresponding weight *w* defined in eq.(1). If the network has a number of supply points ($N0$>1), for each node we will calculate the shortest weighted distances from each supply point and take the shortest one.

5.2. We will add all these distances together so as to associate *each solution s* with a correspondent and unique "global distance" *Dglob*(*s*).

5.3. Among the n_{sol} solutions we select the n_{hyd} having the smallest global distance *Dglob*.

It is worth observing that, generally speaking, the number of solutions n_{hyd} to be hydraulically analyzed could be made equal to the total number of solutions n_{sol}; in such a case we would hydraulically analyze all of the solutions identified. However, in the case of medium-sized or large real distribution systems, this could result in long computation times. We shall note in any case that the solutions which show the best performance in terms of resilience while meeting the minimum network pressure requirements are those which are characterized by the lowest weighted global distances *Dglob* (see Alvisi and Franchini, 2013). Although it cannot be said that the solution with the shortest weighted global distance is also the one with the maximum resilience, it is logical to observe that, given how the weights are defined (see eq.(1)), the solutions corresponding to short weighted global distances give rise to lower head losses and consequently better resilience values. Based on these considerations, the choice of hydraulically analyzing only a narrow number of solutions characterized by low weighted global distances *Dcum* enables us to obtain a good compromise between quality of the results and computation times.

Part III – Choice of the optimal solution within the narrow set

6 For each of the n_{hyd} solutions we carry out a hydraulic pressure-driven simulation with reference to selected operative conditions, calculate the corresponding resilience index *Ir* (Todini, 2000) and select the solution that furnishes the highest value.

To conclude, it is worth pointing out that steps 1 to 5 enable us to identify and analyse a large number of possible solutions for allocating network nodes so as to form an assigned number of DMAs of predefined dimensions and flow meters placement. It is important to note that no hydraulic simulation is performed in any of these steps, as they are based solely on simple graph operations. On the other hand, analysing the graphs obtained as a result of the procedure for the creation of DMAs, and taking account, in this analysis, of weights reflecting the conductance of the pipes, makes it possible to acquire information that is useful for identifying solutions which can potentially ensure a good system performance also from a hydraulic standpoint, and are thus candidates for a more in-depth analysis conducted via hydraulic simulation with the aim of identifying a "near optimal" solution for the creation of DMAs.

3. Application

3.1. Case study

The proposed procedure for the creations of district metered areas was applied to the real case study of the water distribution system serving the municipality of Castelfranco Emilia (MO) (Fig. 3). The distribution system, which extends for an overall distance of about 160 km, draws its water from a well field that feeds a tank situated in proximity to the town center and ensures an average head of about 40 m relative to the ground level. A flow meter is presently already installed at the tank outlet. The system serves about 21000 inhabitants, corresponding to *Utot*=5946 users, with an average daily water demand of around 60 l/s.

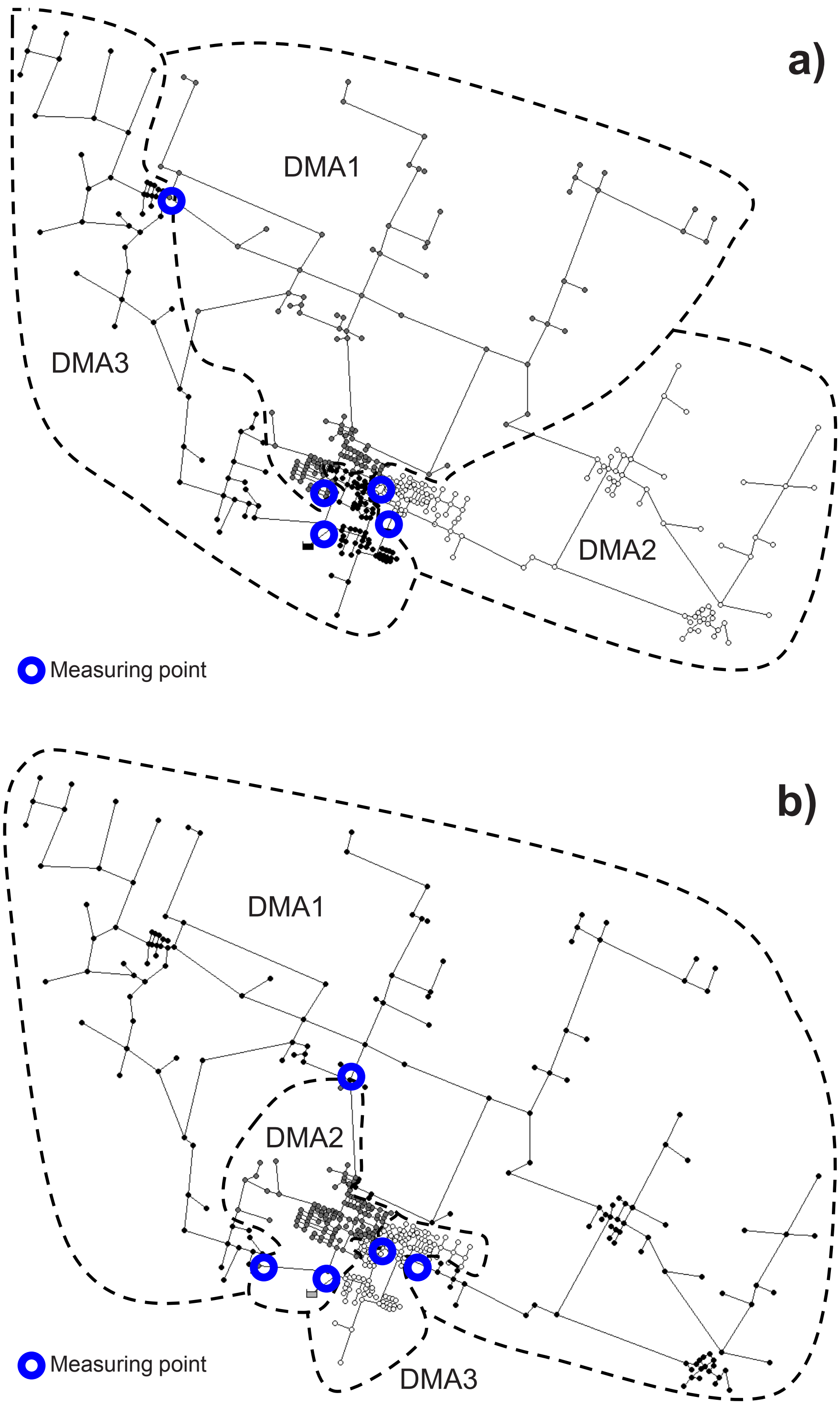

Fig. 3. Layout of the water distribution system of Castelfranco Emilia following the creation of 3 DMAs according to a) the proposed procedure the and b) the M-Sym procedure, assuming that 5 flow meters are placed in the network.

The procedure was applied in order to partition the water distribution system into n_{DMA}=3 DMAs assuming that other 4 flow meters are placed in the network, in addition to the one already placed in the feed pipe at the tank outlet, for a total of 5 measuring points. The number of solutions n_{hyd} to be hydraulically analyzed was assumed equal to 20.

Below we report and discuss the results obtained and we compare these results with those that would be obtained if we were to apply a similar procedure recently proposed by Di Nardo et al. (2011). This latter procedure is based on pairing Metis© graph partitioning software (Karypis, 2011) with a hydraulic simulator of the network, and, accordingly, it will hereinafter be briefly indicated with the acronym M-Sym. More details about this procedure can be found in Di Nardo et al. (2011). It is worth remembering here that according to this procedure, Metis© graph partitioning software is used to allocate the nodes among the DMAs whereas the flow meters and closed pipes are selected 1) by identifying all the connecting pipes between DMAs, 2) considering all of the possible combinations of open and closed connecting pipes for the assigned number of meters to be placed, 3) by performing for each combination a pressure-driven hydraulic simulation under peak hour demand conditions and finally 4) by selecting the combination which maximizes the resilience index *Ir*.

3.2. Application of the procedure and discussion of the results

Fig. 3 shows the solutions obtained with the proposed procedure and the M-Sym procedure for the creation of 3 DMAs in the water distribution system of Castelfranco Emilia. Table 2 summarizes the values of the system performance indicators under peak hour demand conditions both for the network before districtualization, and for the network districtualized according to the solutions provided by the proposed procedure and by the M-Sym procedure. In particular, Table 2 shows, together with the resilience index value *Ir*, the values of the minimum (*Hmin*) and mean (*Hmean*) network pressure heads and the value of the coefficient *Ird*, thus defined (Di Nardo et al., 2011) as:

$$Ird = \left(1 - Ir/Ir_0\right) \cdot 100 \tag{2}$$

where *Ir* is the resilience index of the district-metered system and Ir_0 the resilience index of the system in the absence of district metered areas. This coefficient highlights the resilience reduction due to the districtualization. All these values were computed through pressure driven hydraulic simulation (Alvisi and Franchini, 2009) by assuming a value of the nodal pressure head required to ensure that the water demand is fully meet equal to 27 m and a minimum nodal pressure head needed to ensure outflow equal to 5 m.

By looking at Table 2 it can be observed that the proposed procedure leads to a solution characterized by a resilience index equal to 0.79, that is very similar to the *Ir* of the network before districtualization (*Ir*=0.8). The solution provided by the procedure thus entails only a 1.8% reduction in the resilience index compared to the situation before the creation of DMAs; also the minimum and mean network pressure heads are very similar to those of the the network before districtualization. It is worth noting, on the other hand, that if we applied the M-Sym procedure we would arrive at a solution that is very different from the one furnished by the proposed procedure (see Fig. 3b vs. Fig. 3a) and the resulting system performance is worse being *Ir*=0.72, corresponding to a 10% reduction in the resilience index compared to the situation before the creation of DMAs; furthermore the minimum network pressure head is around 25 m, that is lower than the nodal pressure head required to ensure that the water demand is fully meet equal to 27 m and thus, according to this districtualization solution, not all the water demands would be satisfied during the peak hour.

Finally, the solutions provided by both procedures for the creation of 3 DMAs were also verified under fire-flow conditions. To this end, several network nodes uniformly distributed along the network were selected; the tests were carried out sequentially considering each of the selected nodes one by one and superimposing in each of them a fire flow demand of 10 l/s to the peak-hour water demand (Murray et al., 2009); the resilience index, mean and minimum pressure heads were then computed through a pressure-driven simulation for each test-case and the average values of the quantities of interest are summarized in and the corresponding results are reported in Table 3.

Table 2. Performance indicators under peak hour demand conditions associated with the solutions provided by the proposed procedure and the M-Sym procedure for the creation of 3 DMAs in the water distribution system of Castelfranco Emilia.

	Ir	*Ird (%)*	*Hmin (m)*	*Hmean (m)*
No DMAs	*0.80*	-	*30.79*	*36.82*
Prop. Proc.	0.79	1.78	29.81	36.54
M-Sym	0.72	10.01	25.32	35.73

As can be observed, also under fire-flow conditions the districtualization solution provided by the proposed procedure is characterized by performances quite similar to those of the non-district metered system, the resilience index and the average minimum pressure head being around 0.71 and 27.2 m respectively (vs. 0.74 and 28.7 m of the non-district metered system), whereas the solution provided by the M-sym procedure is characterized by slightly lower values, around 0.64 and 23.9 m respectively.

Table 3. (Average) Performance indicators under fire-flow conditions associated with the solutions provided by the proposed procedure and by the M-Sym procedure for the creation of 3 DMAs in the water distribution system of Castelfranco Emilia.

	Ir	*Ird (%)*	*Hmin (m)*	*Hmean (m)*
No DMAs	*0.74*	-	*28.71*	*36.02*
Prop. Proc.	0.71	3.57	27.15	35.66
M-Sym	0.64	12.92	23.89	34.78

4. Conclusions

A procedure for the automatic creation of district metered areas in a water distribution system has been presented. The procedure has a modular structure and is mainly based on techniques derived from graph theory for allocating the network nodes so as to form an assigned number of DMAs of a predefined size and for determining the location of the open pipes where flow meters will be placed.

The results obtained by the application of the procedure to create 3 DMAs in a real water distribution system, and the comparison of these results with those obtained using a procedure previously proposed in the scientific literature, showed the effectiveness and flexibility of the procedure proposed here. In fact, it was observed that the proposed procedure makes it possible to identify a solution for the creation of DMAs which is characterized by system performance indices (resilience index, minimum and mean pressure heads) that are distinctly superior to those of the solution provided by the procedure we compared our own with both under peak hour and fire flow demand conditions.

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