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Different design criteria for district metered areas in water distribution networks

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Abstract

In this paper the influence of several factors to establish a suitable DMA design is considered using an adaptation of the methodology previously developed by Gomes [1]. This methodology is based on graph theory concepts (Floyd-Warshall algorithm) and some user-defined criteria to establish the number and size of DMAs and uses a Simulated Annealing algorithm to identify the most appropriate number and location of metering stations, boundary valves and network reinforcement/replacement needs along the project plan. Different design criteria are applied to a case study and the results obtained by the methodology are used to draw some conclusions.

Keywords: District Metered Areas design; Floyd-Warshall algorithm; Simulated Annealing

1. Introduction

In the last decades water loss has been one of the major causes of inefficiency in water distribution networks (WDNs) [2, 3]. Water losses are influenced by several factors, including: system operating pressure, pipe burst frequency, speed and quality of repairs, age of pipes and fittings, quality of construction, soil characteristics, traffic and earth movements. The well-known best practices to reduce water losses include [3]: i) pressure management, ii)

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active leakage control, iii) speed and quality of repairs and iv) asset management. But water loss control can become quite complex in large WDNs, and in those cases the implementation of District Metered Areas (DMAs) is imperative to obtain good results. DMA design normally depends on the number of service connections (usually between 500 and 3000 properties), or the length of the network. DMA design based on length is more appropriate in rural systems and the number of service connections should be used in urban areas [4]. However, other factors may influence the size of DMA such as ground elevation, pipe diameter, infrastructural performance indicators, cost of active leakage control, and others.

To help the planners to establish the DMAs boundaries, and the optimum DMAs entry points, in the last years several news methodologies have been proposed [5, 6, 7, 8, 9]. In this paper a previously methodology developed by Gomes [1] was adapted to study different design criteria for DMAs design using a WDN described in [1, 5]. This methodology is based on graph theory concepts (Floyd-Warshall algorithm) and in some user-defined criteria to establish the number and size of DMAs and uses a Simulated Annealing algorithm to identify the most appropriate number and location of metering stations, boundary valves and network reinforcement/replacement needs along the project plan.

2. Methodology to DMAs design

Here a summary of the methodology previously developed by Gomes [1] is presented (see Fig. 1). More information about this methodology is available from [1, 5]. The methodology is based on graph theory concepts (Floyd-Warshall algorithm) and in some user-defined criteria to establish the number and size of DMAs and uses a Simulated Annealing algorithm to identify the most appropriate number and location of metering stations, boundary valves and network reinforcement/replacement needs along the project plan.

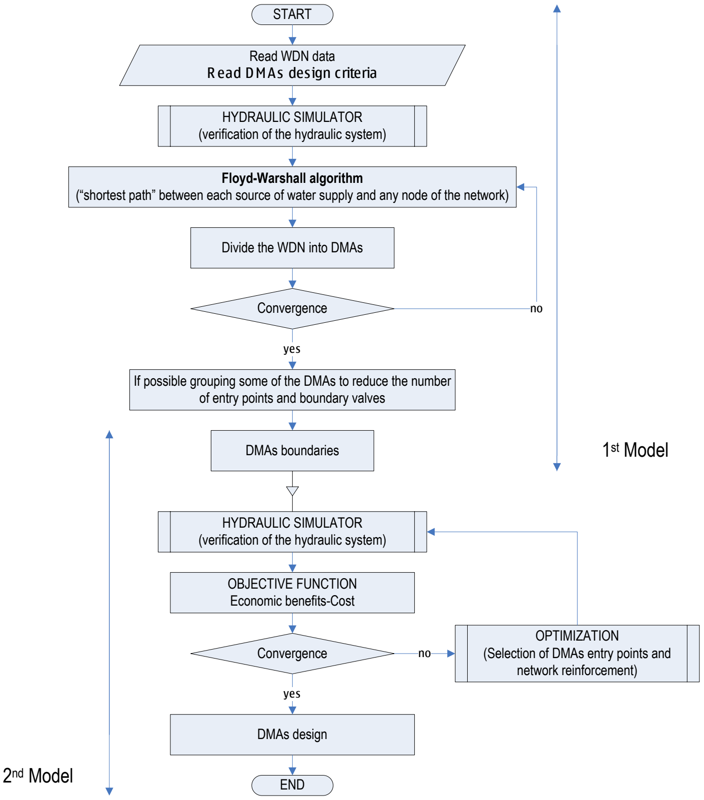

Fig. 1 – Methodology flowchart [1, 5].

2.1 DMAs boundary (1st Model)

The 1st Model is used to divide the WDN in DMAs, based on the flow direction during the daily peak flow and using graph theory concepts - Floyd-Warshall algorithm (see Fig. 2). At the beginning the reference node to extend each DMA is identified and corresponds to the greatest accumulated value of the “shortest path” between each source of water supply and any node of the network (if there are several sources of water supply, for each one select the greatest accumulated value of the “shortest path”, and, from these, choose the downstream node with the lower value of the “shortest path”). Based on the reference node and considering all its adjacent pipes, the increase of each DMA occurs from downstream to upstream, in all possible directions (guided by the peak flow direction and the design criteria for the DMA). The criteria to DMAs design corresponds to the maximum number of service connections (urban systems) or maximum network length (rural systems) in each DMA. However, others project constraints may be used in the process such as the maximum ground elevation difference within the DMA and implicit/explicit constraints. In this context, the implicit and explicit constraints are user-defined conditions that stop the expansion of a DMA in a given direction (for example, some pipes can be explicitly defined as DMAs boundaries).

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i) Initialize array of shorter distance or adjacency matrix (NN = total number of nodes):
        $A[NN,NN] \leftarrow dist[i,j] = \begin{cases} 0 & \text{IF } i = j \\ dist_{i,j} & \text{IF } i \text{ connected to } j \\ \infty & \text{IF } i \text{ no connected to } j \end{cases} \quad \forall \{i,j\} \in NN$
ii) Initialize array of routes:
        $R[NN,NN] \leftarrow rot[i,j] = 0 \quad \forall \{i,j\} \in NN$

iii) Distance between node i and node j through node k:
DO k = 1, NN
    DO i = 1, NN
        DO j = 1, NN
            IF $dist[i,k] + dist[k,j] < dist[i,j]$ THEN
                $dist[i,j] \leftarrow dist[i,k] + dist[k,j]$
                IF $rot[i,k] = 0$ THEN
                    $rot[i,j] \leftarrow k$
                ELSE
                    $rot[i,j] \leftarrow rot[i,k]$
                ENDIF
            ENDIF
        ENDDO
    ENDDO
ENDDO
DO i = 1, NN
    DO j = 1, NN
        IF $rot[i,j] = 0$ THEN
            $rot[i,j] \leftarrow j$
        ENDIF
    ENDDO
ENDDO
```

Fig. 2. Floyd-Warshall algorithm [10].

The design criteria for the Floyd-Warshall algorithm is related to the physical characteristics of the network and/or hydraulic behaviour of the system, used to identify the shortest path between each source of water supply and any node of the network. As design criteria for the Floyd-Warshall algorithm it is possible to use, for example:

- the hydraulic behaviour of the system

There are several resistance laws to study the network hydraulic behaviour, such as the Darcy-Weisbach, Hazen-Williams or Manning-Stricler equations. Equation (1) shows the head loss formula for pipe j:

$$\Delta H_j = J_j \times L_j = K_j \times \frac{Q_j^{\alpha}}{D_j^{\beta}} \tag{1}$$

Where: ΔH - head loss; J - unit head loss; L - pipe length; K - a coefficient of the resistance law; Q - pipe flow; D - pipe diameter; α and β - exponents of the resistance law for flow and diameter, respectively.

Based on equation (1), several criteria could be established to identify the zones to start each DMA. Equation (2) uses the relationship between flow and pipe diameter according to the resistance law.

$$C_j = \frac{Q_j^{\alpha}}{D_j^{\beta}} \tag{2}$$

- the physical characteristics of the network

The physical characteristics of the network are related to the network length, pipe material, ground elevation and infrastructure age. In equation (3) a coefficient is assigned to each pipe j, based on the relationship between its length (L_j) and the total length of the network (NP = total number of pipes), where the pipe diameter (Dj) is used to weigh the length of pipe j.

$$C_j = \frac{\left(D_j \times L_j\right)}{\sum_{j=1}^{NP}\left(D_j \times L_j\right)} \tag{3}$$

- the performance indicators

In specialized literature there are several performance indicators related to water infrastructure management. One of the most useful performance indicators is Infrastructural Leakage Index (ILI), which represents the ratio between Current Annual Real Losses (CARL) and Unavoidable Annual Real Losses (UARL) [3]. Here UARL for a pipe j is proposed as design criteria for the Floyd-Warshall algorithm, equation (4).

$$C_j = UARL_j = \left(\alpha_n \times L_n + \beta_c \times N_c + \lambda_c \times L_c\right)_j \times \left(\frac{P_j}{P_{ref}}\right)^{N1} \tag{4}$$

where: α_n - water losses per network unit length; L_n - pipe length; β_c - water losses per service connection until the property boundary; N_c - number of services connections; λ_c - water losses per service connection between property boundary and the flow meter; L_c - average service connection length between the property boundary and the flow meter; P_j - average service pressure in pipe j; P_{ref} - a reference service pressure taken as 50 m; N1 - exponent of the water losses/pressure relationship (generally varies between 0.50 and 1.50).

2.2 DMAs design (2nd Model)

Using the DMAs boundaries obtained in the 1st Model, the 2nd Model uses a simulated algorithm to identify the best DMAs entry points and if necessary the network reinforcement to ensure the minimum service pressure after

DMAs implementation. The objective function NPV(X), equation (5), maximizes the net present value of the differences between the economic benefits (water loss reduction arising from the average pressure reduction) and the total costs of the DMA implementation (chambers and flow meters, and pipes reinforcement/replacement), during the course of the project plan:

$$\text{maximum}: \quad NPV(X) = \sum_{i=1}^{n} \frac{B(X)_i - C(X)_i}{(1 + intR)^{t_i}} \tag{5}$$

where: NPV(X) - net present value of the project (€); n - number of investment periods for the duration of the project plan; $B(X)_i$ - total economic benefits during the investment period i updated to the beginning of that investment period; $C(X)_i$ - total investment costs at the beginning of the investment period i (€); t_i - time between the start of the project and the beginning of the investment period i (years); intR - annual interest rate (%).

3. Case study

A WDN described by Gomes et al [1, 5, 6] was used to compare the different criteria for DMAs design. The system can be described as follows: 1) the average flow at the network entry point is 383.40 m^3/h; 2) the network is approximately 26.5 km long and is gravity-fed from one reservoir (source); 3) the minimum and maximum service pressures are 26.23 m and 52.69 m, respectively; and 4) the minimum and maximum service pressures required are 25.74 m and 60.00 m, respectively. This study considered a 10-year project plan (n=1), in which consumption can be considered constant and the infrastructure decay rate was 1.0% per year (reduction of the Hazen-Williams coefficients). To estimate the net present value of the project for different criteria for DMAs design, an annual interest rate of 5% was used. The production cost and selling price of water were taken as 0.50 €/m^3 and 0.75 €/m^3, respectively). The unit cost of pipes to reinforce/replace, and flow meter and chamber costs were the same presented in [6].

3.1. DMAs boundary – using different design criteria for Floyd-Warshall algorithm

Based on different design criteria for the Floyd-Warshall algorithm (see section 2.1), and the maximum number of service connections in each DMA (3000 services connections), Fig. 3 (a), (b) and (c) shows the results for the DMAs boundaries. The difference in the DMAs boundaries is related to the design criteria used in the Floyd-Warshall algorithm: Fig. 3 (a) - hydraulic behaviour (equation (2)); Fig. 3 (b) - physical characteristics of the network (equation (3)) and Fig. 3 (c) - the performance indicator (equation (4)).

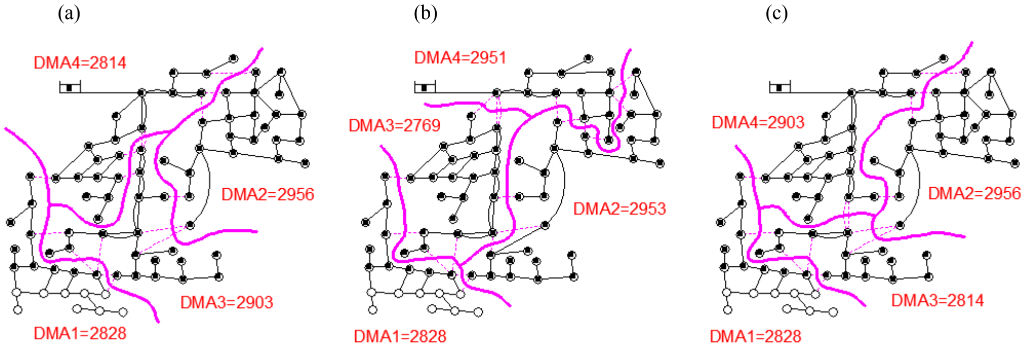


Fig. 3. DMAs boundaries based on hydraulic behaviour (a), physical characteristic of the network (b) and performance indicators (c).

3.2. DMAs boundaries – using the same design criteria for the Floyd-Warshall algorithm

The best practices suggest that the maximum number of service connections or the maximum network length are the most appropriate criteria to establish the size of DMAs, respectively in urban and rural areas. However, other project constraints may be used in this process such as the minimum ground elevation difference within the DMA and implicit/explicit constraints, which stop the expansion of a DMA in a given direction. To study the influence of these design criteria, in Fig. 4 to 7 the results for a case study are presented using the maximum network length in each DMA (from left to right): 5000 m (5.0 km); 7500 m (7.5 km) and 10000 m (10.0 km). The design criteria for the Floyd-Warshall algorithm was based on equation (2).

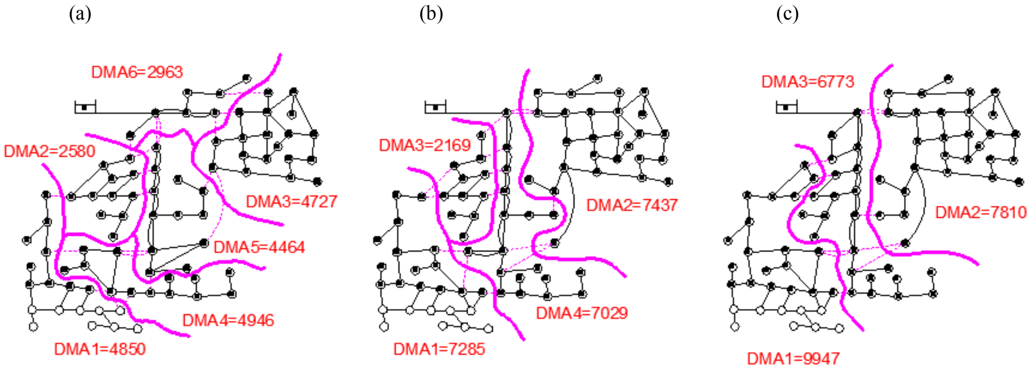

(a) (b) (c)

Fig. 4. DMAs boundaries driven by network length.

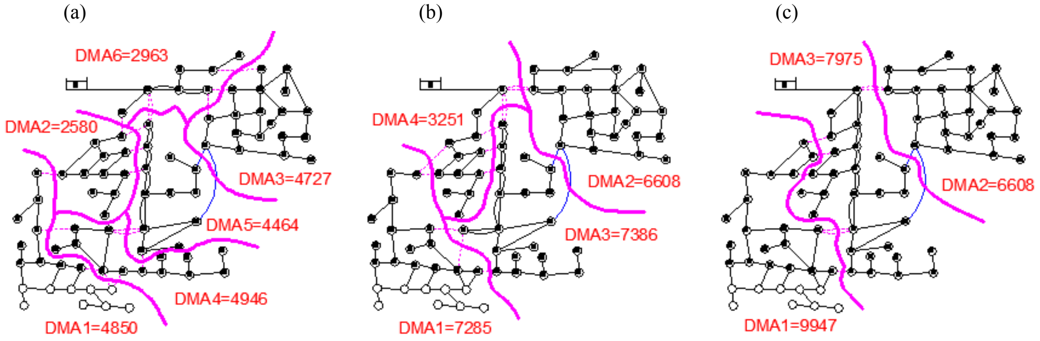

(a) (b) (c)

Fig. 5. DMAs boundaries driven by network length and pipes constraint (pipes blue).

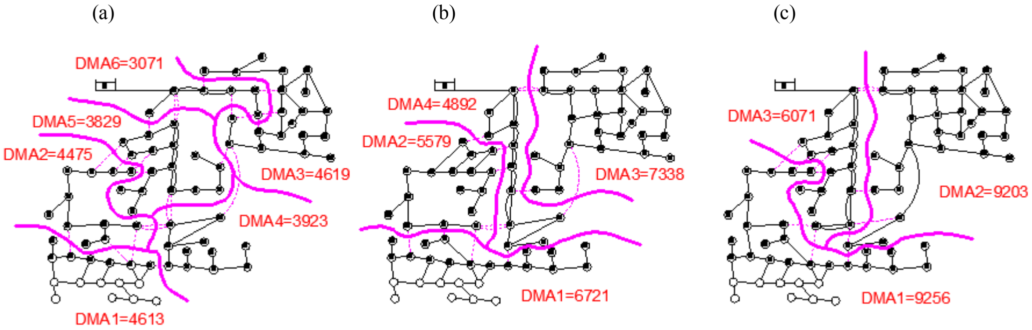

(a) (b) (c)

Fig. 6. DMAs boundaries driven by network length and ground elevation.

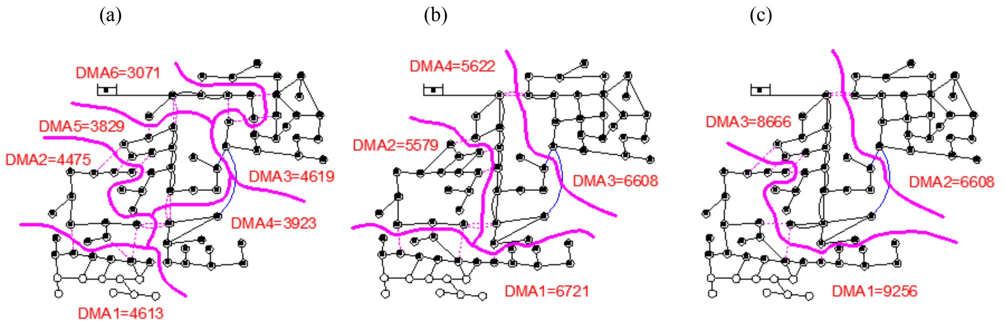


Fig. 7. DMAs boundaries driven by network length, ground elevation and pipes constraint (pipes blue).

Similarly, in Fig. 8 to 11 the results for a case study using the maximum number of service connections in each DMA are presented (from left to right): 3000, 3500, 4000 and 4500 service connections.

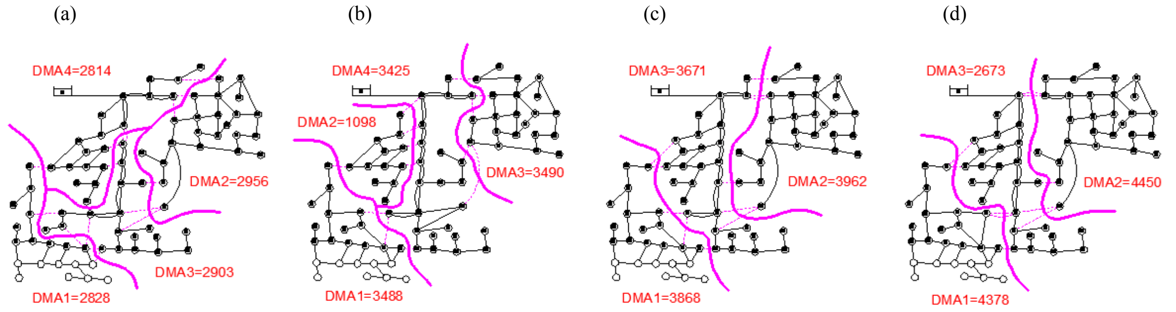


Fig. 8. DMAs boundaries driven by number of service connections.

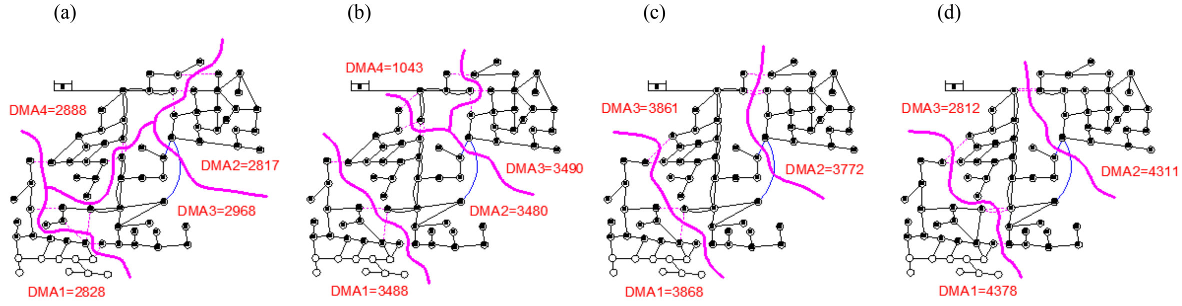


Fig. 9. DMAs boundaries driven by number of service connections and pipes constraint (pipes blue).

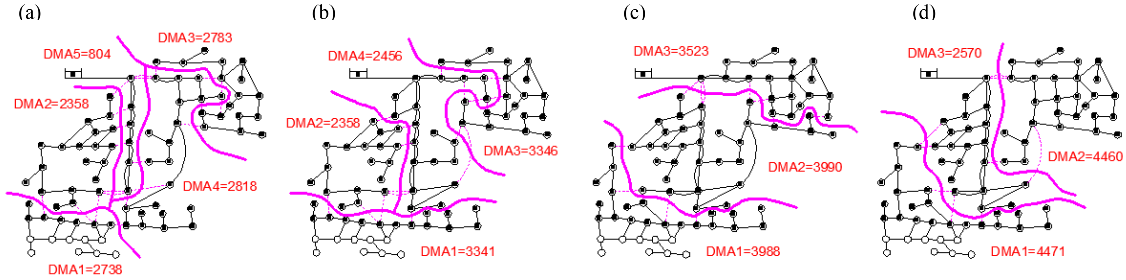


Fig. 10. DMAs boundaries driven by number of service connections and ground elevations.

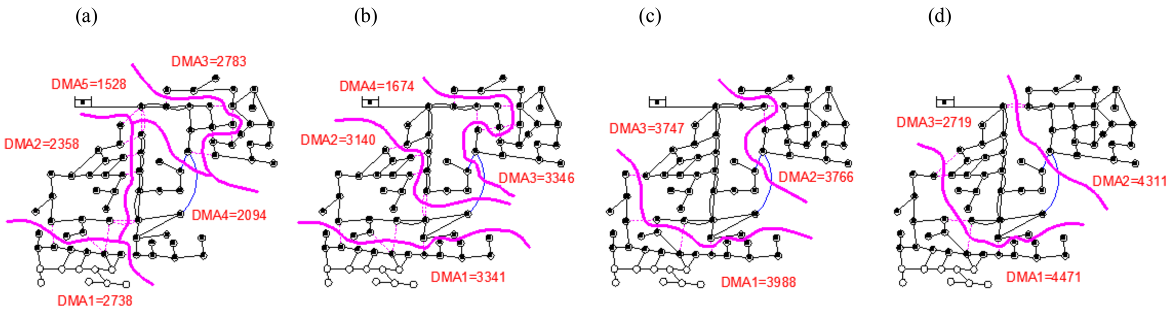


Fig. 11. DMAs boundaries driven by number of service connections, ground elevation and pipes constraint (pipes blue).

3.3. DMAs design

In this section, the total investment cost for the DMAs design was analysed for some different design criteria presented in section 3.2. The problem of the DMAs design is complex because its implementation (closure of boundary valves) changes the hydraulic behaviour and sometimes network reinforcements are required. To study the DMAs boundaries, the use of optimization models is preferred and the present study used the methodology described in section 2.2. As example, Tables 1 to 4 show the results for the DMAs design presented in Fig. 8 (d), 9 (d), 10 (d) and 11 (d), considering different numbers of DMAs entry points. In Fig. 8 (d) and 9 (d), the maximum number of DMAs entry points is equal to 6, while in Fig. 10 (d) and 11 (d) is 4, because 2 connections are permanently closed. Fig. 12 show the relationship between NPV and the DMAs entry points. Fig. 13 shows DMAs design, including the location of the Metering Station (MS) and boundary valves (Closed Valves - CV) – the network reinforcements are represented by green lines.

Table 1. DMAs design driven by number of service connections (SC).

DMAs entry points	**Network reinforcement cost (€)**	**Metering stations cost (€)**	**Economic benefits (€)**	**NPV (€)**
2 Metering stations	-98690	-94174	38554	-154310
3 Metering stations	-18566	-92156	12616	-98106
4 Metering stations	-3348	-96713	13212	-86849
5 Metering stations	0	-100931	9490	-91442
6 Metering stations	0	-105150	0	-105150

Table 2. DMAs design driven by number of service connections and ground elevations (SC + GE).

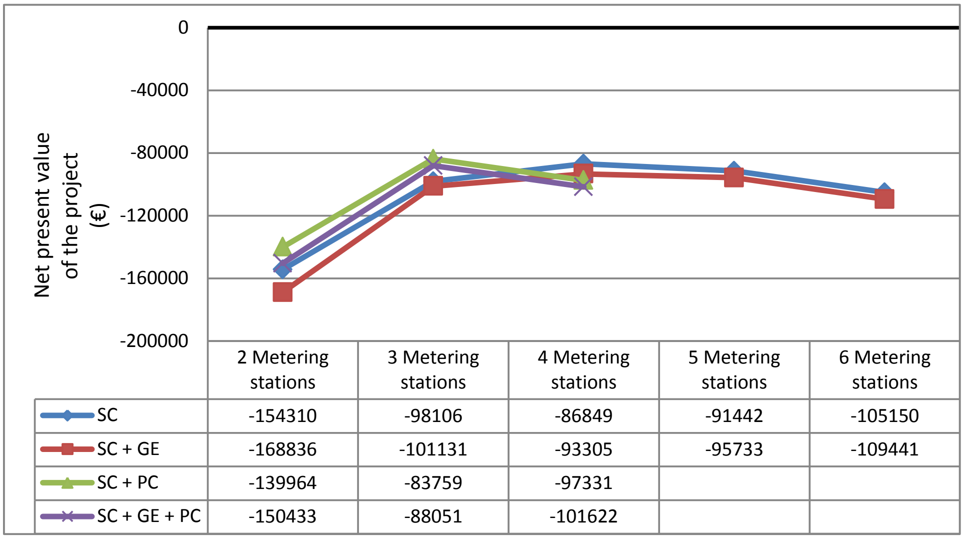
DMAs entry points	**Network reinforcement cost (€)**	**Metering stations cost (€)**	**Economic benefits (€)**	**NPV (€)**
2 Metering stations	-145154	-101482	77800	-168836
3 Metering stations	-18566	-96447	13882	-101131
4 Metering stations	-5677	-101004	13376	-93305
5 Metering stations	0	-105223	9490	-95733
6 Metering stations	0	-109441	0	-109441

Table 3. DMAs design driven by number of service connections and pipes constraint (SC + PC).

DMAs entry points	**Network reinforcement cost (€)**	**Metering stations cost (€)**	**Economic benefits (€)**	**NPV (€)**
2 Metering stations	-89075	-94174	43285	-139964
3 Metering stations	-8951	-92156	17347	-83759
4 Metering stations	-8951	-96374	7994	-97331

Table 4. DMAs design driven by number of service connections, ground elevation and pipes constraint (SC + GE + PC).

DMAs entry points	**Network reinforcement cost (€)**	**Metering stations cost (€)**	**Economic benefits (€)**	**NPV (€)**
2 Metering stations	-129628	-101482	80677	-150433
3 Metering stations	-8951	-96447	17347	-88051
4 Metering stations	-8951	-100665	7994	-101622



	2 Metering stations	3 Metering stations	4 Metering stations	5 Metering stations	6 Metering stations
SC	-154310	-98106	-86849	-91442	-105150
SC + GE	-168836	-101131	-93305	-95733	-109441
SC + PC	-139964	-83759	-97331		
SC + GE + PC	-150433	-88051	-101622		

Fig. 12. Relationship between NPV and DMAs entry points (Metering Stations).

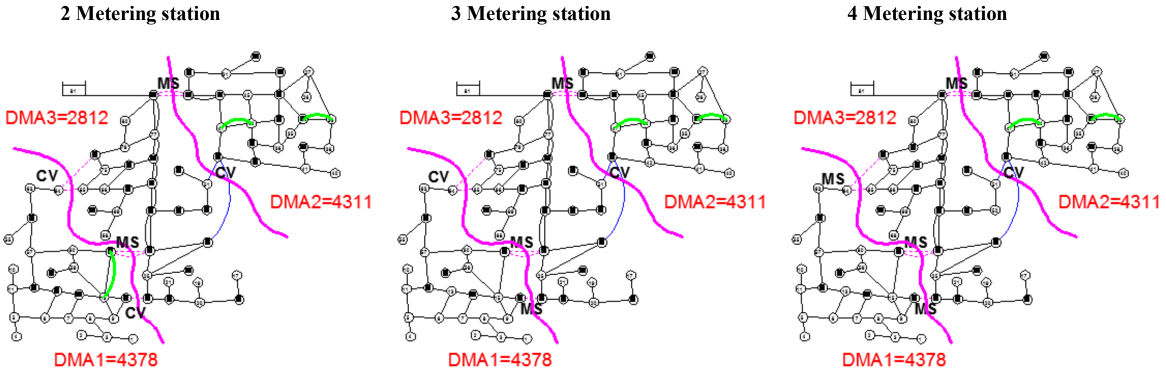

2 Metering station **3 Metering station** **4 Metering station**

Fig. 13. DMAs design for number of service connections and pipes constraint (SC+PC) criterion.

4. Results analysis and conclusions

The results from section 3.1 show that different design criteria for the Floyd-Warshall algorithm give rise to different boundaries for the DMAs design, because the initial point to increase each DMA is different. For a specific WDN, the most appropriated design criteria should be selected according to the hydraulic behaviour, physical characteristics or performance indicators.

In section 3.2 the DMAs boundaries were driven by the maximum number of service connections and by the maximum network length in each DMA. To study the influence of WDN characteristics, the minimum ground elevation difference within the DMAs and implicit/explicit constraints were also used. The results from Fig. 4 to 11 show that a different design criterion for the DMAs determines the number and the location of the DMAs boundaries. The design criterion based on the minimum ground elevation difference within the DMAs seems to be the most appropriate to implement pressure management at the DMAs entry points and the implicit/explicit constraints to stop the expansion of a DMA in a given direction (for example to avoid crossing rivers, municipalities boundaries, highways, and others).

Using an optimization model, and taking as reference the DMAs design based on the number of service connections presented in section 3.3, the results for the DMAs design were presented. In Tables 1 to 4, the cost of the network reinforcements, metering stations and economic benefits are presented. The cost of the network reinforcements decreases with the increase of the number of DMAs entry points. The cost of flow metering stations changes according to the number of DMAs entry points and diameter of the flow meter. The economic benefits are related to the adjustment of the service pressure at the DMAs entry points and the network reinforcements, and are a consequence of the water loss reduction arising from the average pressure reduction. In the case study, the economic benefits increase with the reduction of the number of DMAs entry points. For the case study, the maximum number of DMAs entry points is 6. However, if the pipes used as constraints for the DMAs design were considered as closed, for the design criteria SC+PC and SC+GE+PC, the maximum number of DMAs entry points would be 4. The DMAs design option SC and SC+GE, as well as SC+PC and SC+GE+PC, follow the same. The minimum cost for the DMAs design was 83 759 € (design criteria SC+PC) – 3 Metering Stations and 3 boundary valves (Closed Valves – CV), as shown in Fig. 13.

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