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Economic Performance of DMAs in Water Distribution Systems

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Abstract

An effective implementation of District Metered Areas (DMAs) in water distribution systems requires the analysis and cost comparison of various feasible solutions, which differ both in the number and the boundaries of the districts and provide different levels of benefits. The evaluation of the benefits provided by alternative DMA layouts (in terms of reduction of leakage, burst frequency, water and energy consumption) allows practitioners to make sensible decisions and create functional and efficient DMAs. This paper shows an analysis of the costs and benefits following the introduction of DMAs to water distribution systems, providing a framework for assessing the economic performance of DMAs, comparing different possible DMA layouts, and identifying the best solution among different options. A real water distribution network is considered as a case study, various DMA layouts are identified and ranked on the basis of the total benefit provided.

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Keywords: DMAs; alternative solutions; benefit analysis; multiple criteria; ranking.

1. Introduction

Various experiences have proved that District Metered Areas can provide many advantages to clean water distribution networks management. Metering the flow entering and leaving the DMAs allows for a simplified evaluation of the water balance, significant reduction in leakage, as it is easier and quicker to identify leaks, and improvements in water security, since the potential movement of contaminants throughout the system is minimized

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([2]). However, dividing a water distribution network into DMAs means also reducing the number of possible flow paths to demand nodes, which can cause stagnation, hence water quality issues, non-uniform water pressure over the network, and reduction of reliability, as highlighted in [8]. Therefore, it is important that the design of DMAs is undertaken with care, meeting a series of criteria and guidelines developed in literature (see e.g. Farley 1985, Morrison et al. 2007, and Baker 2009). The performance of the network divided into DMAs needs then to be evaluated, to ensure that the DMAs provide the expected advantages, without affecting the water quality or the reliability of supply. Evaluating the network performance implies identifying and calculating appropriate indicators which measure the network characteristics to be assessed. There are many examples/studies in literature in which DMAs design is followed by the evaluation of the performance of the resulting network ([1], [4], and [8]). Furthermore, performance assessment can be used as a mean to identifying the best DMAs layout among a certain number of possible solutions ([14]). As multiple objectives need to be considered in any DMAs design problem, it is important to assess, along with the effects on water quality and network reliability, also the economic benefits provided by the introduction of DMAs. This allows to quantify the savings that water companies can obtain by implementing DMAs, due to the reduction of leakage, burst frequency, and pressure-sensitive demand.

As such, this study represents a further development of [14], where a number of feasible DMAs layouts, that differ in the number and the size of the districts, were compared based on the Todini's resilience index, as a measure of reliability, and water age, as a surrogate measure of water quality. Various DMAs layouts are here compared based on three indicators related to the benefits obtained in terms of leakage reduction, burst frequency reduction and pressure sensitive demand reduction. These indicators are defined based on a mathematical model used in literature to evaluate the net benefit of implementing pressure management scheme [1].

The comparison of different solutions (i.e. feasible divisions of the network into a certain number of DMAs) allows to understand how the number of DMAs and the number of closures necessary to create the districts, i.e. the cost of implementing DMAs affect the benefits considered (leakage reduction, burst frequency reduction and pressure sensitive demand reduction).

As a result of the analysis undertaken, the best solutions with respect to the benefits provided are identified.

Nomenclature

DMA	District Metered Area
P_0	actual pressure at a generic node at generic time step before introducing DMAs
P_1	actual pressure at a generic node at a generic time step after introducing DMAs
N_1	empirical leakage exponent
N_3	empirical pressure-sensitive demand exponent
WLR	Water Leakage Reduction benefit
BFR	Burst Frequency Reduction benefit
WDR	Pressure-sensitive Water Demand Reduction benefit

2. Methodology

Initially, a number of feasible solutions, i.e. possible divisions of the water distribution network into DMAs, need to be identified. An automated methodology, based on graph theory and engineering principles developed by [7], is used to create a number of feasible solutions, varying in the number and boundaries of the DMAs. Then, three performance indicators are calculated, related to three different economic benefits provided by the implementation of DMAs: water leakage reduction, burst frequency reduction, and water sensitive demand reduction.

The water leakage reduction is defined as the ratio between the water leakage after and before the introduction of DMAs (WL_1 and WL_0 respectively) and it has been calculated using the IWA-WLTF method, as detailed in [5]. This method assumes that reduction of water leakage in water distribution networks is a function of pressure change as follows:

$$\frac{WL_1}{WL_0} = \left(\frac{P_1}{P_0}\right)^{N_1} \tag{1}$$

where P_0 = pressure before reduction (m); P_1 = pressure after reduction (m); and N_1 = leakage exponent, which in this study is considered to be a function of the pipe material only (Tynemarch 2007). The water leakage reduction is calculated for each demand node at each time step and the average value is then considered as an indicator of the network performance in terms of water leakage reduction.

$$WLR = Avg_{nodes,\ t-steps}\left[\frac{WL_1}{WL_0}\right] \tag{2}$$

The percentage burst frequency reduction (BFR) is calculated using the relationship developed by [9], which depends on the pressure reduction obtained and takes into account the proportion of bursts which are not pressure dependant.

$$BFR_i = \left(1 - \frac{BF_{npd}}{BF_0}\right)\left[1 - \left(\frac{P_1}{P_0}\right)^3\right] \tag{3}$$

where: BF_{npd} is the burst frequency which is non pressure-dependant, BF_0 is the burst frequency before DMAs, and P_0 and P_1 are the pressure (m) before and after DMAs respectively. As for the water leakage reduction, the average value across the network and over the simulation period is considered as an indicator of the overall burst frequency reduction (BFR):

$$BFR = Avg_{nodes,\ t-steps}[BFR_i] \tag{4}$$

The reduction of pressure-sensitive water demand is defined as the ratio between the pressure-sensitive water demand (m^3/year) before and after the implementation of DMAs (WD_1* and WD_0* respectively) and it is calculated as by [5]:

$$\frac{WD_1^*}{WD_0^*} = \left(\frac{P_1}{P_0}\right)^{N_3} \tag{5}$$

Where P_0 and P_1 are the actual pressure before and after the introduction of DMAs and N_3 is an empirical exponent. The pressure has been evaluated at a network node level and the average value has been considered as representative of the pressure-sensitive water demand reduction. According to [5] the value of N_3 varies between 0.1 for internal residential consumption to 0.5 for external consumption. If the customer has a roof tank then N_3 is equal to zero. In this analysis it is assumed that the exponent N_3 is equal to 0.3, as an average between internal residential consumption and external consumption. Again, the network performance in terms of water-sensitive demand reduction is calculated as the average value over the simulation period as follows:

$$WDR = Avg_{nodes,\ t-steps}\left[\frac{WD_1}{WD_0}\right] \tag{6}$$

3. Case Study

A modified real world system is used here as a case study ([11]). Its geographic representation and the names of the components are distorted in order to protect the identity of the system. The adjustments made are related only to the appearance and do not have any influence on the connectivity and the hydraulic behavior of the network.

This network, frequently used as a test bed for various modeling exercises including the Battle of the Water Sensor Networks competition, serves approximately 150,000 people and its topology is illustrated in Figure 1. It represents a typical example of a looped urban distribution system, and includes two reservoirs, two tanks, four pumps, and five valves. The basic characteristics of this network are summarized in Table 1. The pressures for this network, at each node and each time step, have been calculated by performing an hydraulic analysis with the simulation software EPANET ([15]), where the head losses are evaluated with the Hazen-Williams formula.

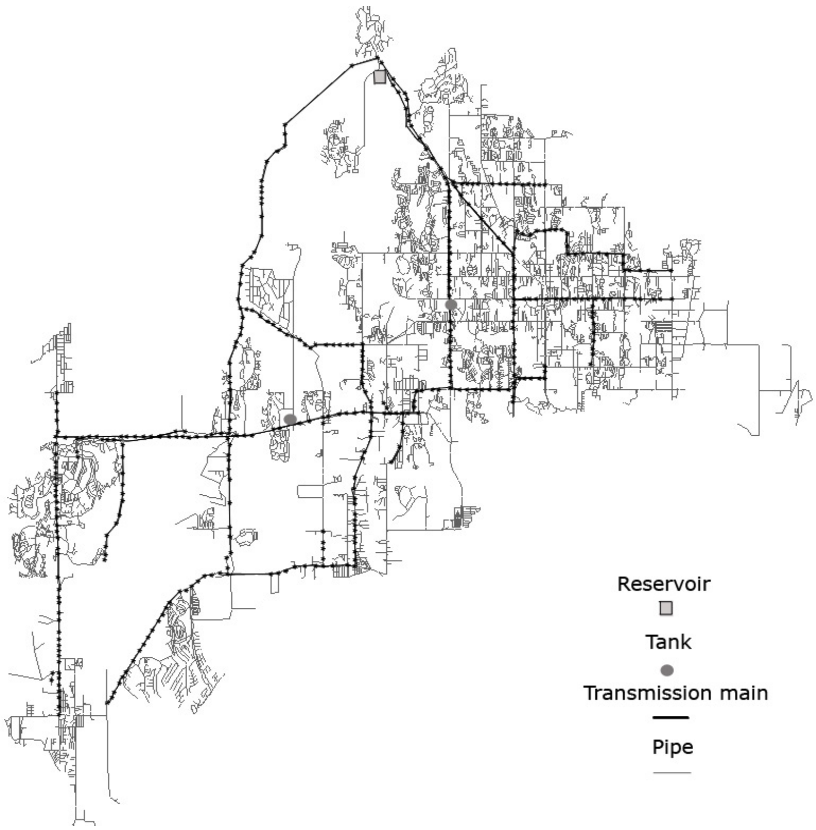

Figure 1 - The water distribution network used as a case study

A total number of 73 possible solutions (N = 73), characterized by having between 32 and 45 DMAs, have then been developed using the graph-theory based methodology detailed in [7]. These solutions have finally been analysed to calculate the benefits provided by the implementation of DMAs in terms of leakage reduction, burst frequency reduction and pressure-sensitive demand reduction. The results are detailed in the following paragraphs.

Table 1 - Characteristics of the network used as a case study

Property	Value
Number of nodes	12523
Number of links	14822
Number of reservoirs	2
Number of tanks	2
Number of pumps	4
Duration	192 hours
Total pipe length	1844.04 km
Total water demand	1.279 m^3/s
Average water demand	0.121 l/s
Transmission mains number	870
Transmission mains length	162.86 km
% of transmission mains	9.2 %
Number of trunk main nodes	828

4. Results

An EPANET simulation has been run for each solution to calculate the pressures across the network with the DMAs and the benefits for the N =73 possible solutions have been evaluated. Table 2 summarizes the benefits that can be achieved by implementing DMAs: the calculated leakage reduction benefit range approximately between 26% and 59%, the burst frequency reduction benefit between 53% and 60%, and the pressure sensitive reduction benefit between 67% and 85%..

Table 2 - Summary of the achievable benefits

Benefit	Value Range
Waater Leakage Reduction	26.6% - 59.7%
Pressure-sensitive Demand Reduction	67.2% - 85.6%
Burst Frequency Reduction	53.1% - 60.2%

Figures 2 shows the relationship between the number of DMAs and the leakage reduction benefit, the burst frequency reduction benefit, and the water-sensitive demand reduction benefit respectively. It appears that the higher number of DMAs or the number of boundary valves to be closed, the less is the reduction in leakage.

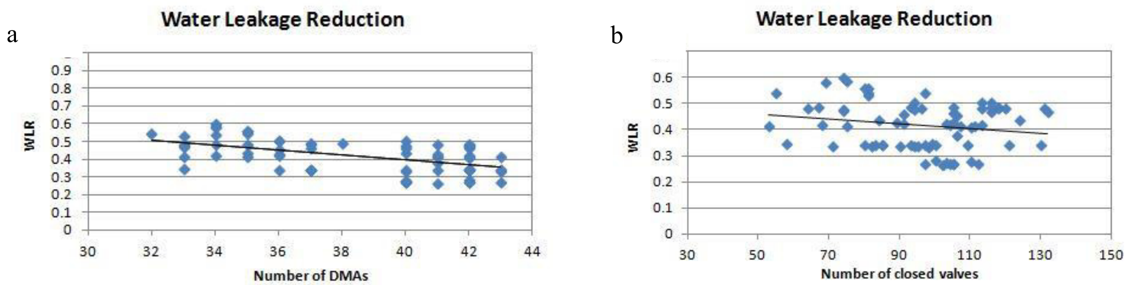

Figure 2 - Relationship between number of DMAs (a) or number of boundary valves (b) and water leakage reduction

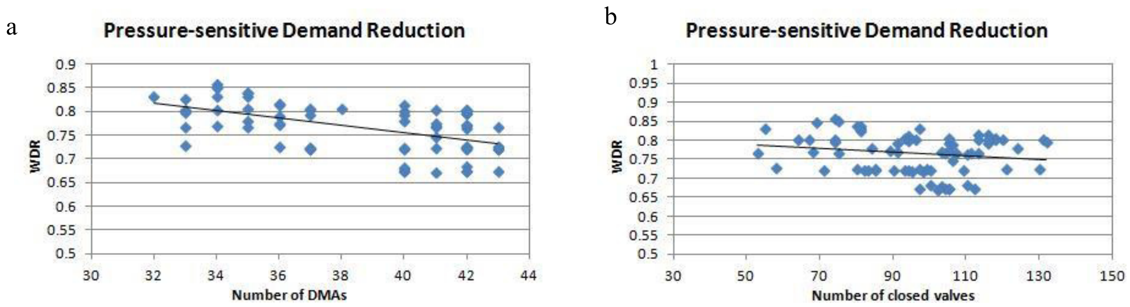

Figure 3 - Relationship between number of DMAs (a) or number of boundary valves (b) and pressure-sensitive demand reduction

The same applies for the benefit provided in terms of pressure-sensitive demand reduction: Figure 3 illustrates that the percentage reduction declines with the number of DMAs and the number of boundary valves to be closed to implement DMAs. These results indicate that, when divided the network into a higher number of DMAs, pressure management schemes should be implemented to reduce the pressure across the network and therefore reduce leakage.

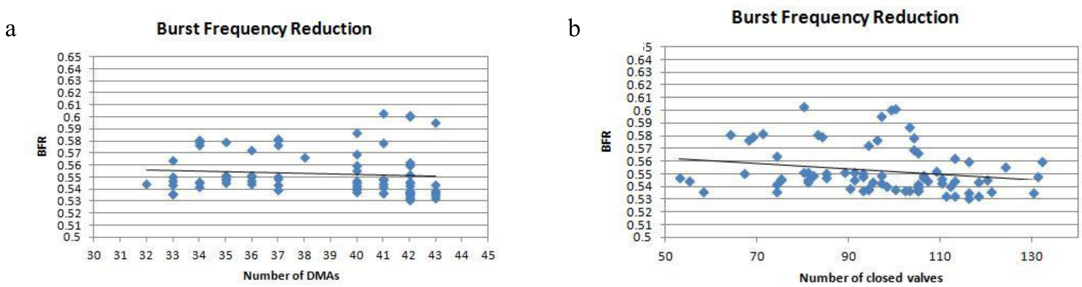

Figure 4 – Relationship between number of DMAs (a) or number of boundary valves (b) and burst frequency reduction

The burst frequency reduction benefit, shown in Figure 4, demonstrate an overall declining trend with both the number of DMAs and the number of closed valves. However, the results also point out that the highest reductions in the burst frequency can be obtained when a relatively number of DMAs are created (41, 42 and 43 – see Figure 4a), which correspond to a number of boundary valves to be closed of 99, 100 and 97 respectively. Therefore, it can be concluded that, although in general the burst frequency reduction benefit decreases with the number of DMAs and the number of valves to be closed, the best performing solutions present a great number of DMAs and a also relatively high number of closed valves.

5. Conclusion

The performance analysis carried out in this study has showed that introducing DMAs provides economic benefits in terms of leakage reduction, burst frequency reduction and pressure-sensitive demand reduction. From the analysis it also emerged that the benefits depend on the number of DMAs and on the number of boundary valves to be closed: the higher the number of DMAs or the number of boundary valves, the less is the leakage and pressure-sensitive demand reduction. Therefore, it is recommended that, when creating a elevated number of DMAs, an appropriate pressure management scheme is implemented to reduce the pressure across the network. The results showed the same trend for the burst frequency reduction benefit, although the best performing solutions are characterized by a high number of DMAs.

The benefits have been quantified for a number of possible alternative solutions, and the best performing solutions with regard to leakage reduction, burst frequency reduction and pressure sensitive demand reduction. As a result, the procedure presented in this paper provides a framework for assessing the economic performance of different DMAs options.

Finally, it should be mentioned that if the data about the current performance of the water distribution network was available (i.e. current level of leakage, current burst frequency, and current pressure-sensitive demand), along with the cost of water and of implementing and maintain DMAs, it would be possible to calculate the total net benefit (£) of each solution. However, in order to do such analysis, a real water distribution, for which all the required parameters are known, needs to be used as a case study.

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