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Optimal District Metered Area design by Simulated Annealing

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Abstract. Water losses reduction in Water Distribution Systems (WDS) is nowadays an issue of growing importance for water companies to ensure the sustainability of these public services. In this context, the implementation of District Metered Areas (DMAs) and/or pressure management are considered the most effective tools for leakage control, particularly in large networks and in systems with deteriorated infrastructures and with high pressure.

Based in previous studies performed by the authors [1,2,3], the methodology described in this paper follows the ‘water losses management international best practices’ and makes it possible to evaluate the Net Present Value (NPV) of DMAs project, as well as the benefits that can be achieved by pressure management in WDS, particularly in terms of water production reduction. It is based on the analysis of the minimum night flow and the FAVAD concept, and it uses a pressure driven simulation model to predict the network hydraulic behaviour under different pressure conditions. Leakage assessment is performed using pressure driven analysis and the optimal location of pipes reinforcement/replacement and settings of the Pressure Reduction Valves (PRVs) are identified by a Simulated Annealing algorithm. The potential of this methodology is illustrated through an hypothetical case study.

Keywords: District Metered Areas, Pressure management, Simulated Annealing, Water losses

1 Introduction

Nowadays, WDS consists of a complex network of pipes with pumps, valves, and storage tanks, subjected to different loads (water demand and demand pattern) and operating rules, ensuring good levels of service over a given planning period. Some studies have shown that residential water demand makes up the majority of water use in urban WDS but the flow varies over time (day, month or year) depending on the number of customers, the water uses, level of water losses, season of the year, the level of economic development and the efficiency in the use of water. In this context, to guarantee high service levels, the appropriate water infrastructure planning and management requires reasonable water demand forecasts for the future years, as well the knowledge of hydraulic behaviour, degradation of infrastructures and the need of network expansion. However, water loss control is an issue of growing importance to ensure the sustainability of these public services and, for that reason, greater efforts are being made in this direction in several water companies worldwide.

The implementation of DMAs and/or pressure management are considered the most effective tools for leakage control, particularly in large networks and in systems with deteriorated infrastructures and with high pressure. The size of each DMA and the optimal DMA entry points vary from system

to system, and depend on the network configuration, the infrastructure condition, the water quality and the financial resources of the water companies. The experience demonstrates that in urban areas the adequate size for a DMA should be between 500 and 3,000 service connections, but it can be reduced to 500 to 1,000 in deteriorated infrastructures. By no means should be advisable to have a DMA containing more than 5,000 service connections, because it gets too difficult to control water losses (location of new bursts can become extremely demanding). Alternatively, in areas with low density of service connections, the size of a DMA should be fixed in terms of pipe length, because the difficulty to find bursts is more related to the pipe length than to the number of service connections. Each DMA should be supplied by a limited number of pipes in which flow meters are installed (entry points), to measure water imports (if a DMA supplies other DMAs, they also measure water exports), and these are not to be necessarily definitive because changes in the operating conditions may imply modifying the boundaries. There are many examples of success worldwide on implementation of DMAs [4]. Furthermore, several models have been developed to illustrate the cost and economic benefit of DMAs management in practice [5,6].

The methodology described in this paper follows the ‘water losses management international best practices’ and makes it possible to evaluate the Net Present Value (NPV) of DMAs project, as well the benefits that can be achieved by pressure management in WDS, particularly in terms of water production reduction. It is based on the analysis of the minimum night flow and the FAVAD concept, and it uses a pressure driven simulation model to predict the network hydraulic behaviour under different pressure conditions. Leakage assessment is performed using pressure driven analysis and the optimal location of pipes reinforcement/replacement and settings of the Pressure Reduction Valves (PRVs) are identified by a Simulated Annealing algorithm [7].

2 Methodology

The DMAs design can be formulated as an optimization problem. This NP-hard problem is related to the number of DMAs and the total number of DMAs entry points, the pipes to reinforce/replace and the most advantageous type, location and settings for the PRVs. The objective function NPV(X) maximizes the net present value of the differences between the economic benefits from pressure management (reduction of water production cost minus the reduction of revenue from billed water) and the total implementation costs (flow meters, PRVs, chambers and pipes reinforcement/replacement), along the duration of the project plan, equations (1) to (3):

$$\text{maximum } NPV(X) = \sum_{i=1}^n \frac{B(X)_i - C(X)_i}{(1 + \text{int} R)^{\pi_i}} \quad (1)$$

$$C(X) = \sum_{p=1}^{NP} [C_{pipe,p}(D_p) \times L_p] + \sum_{m=1}^{NM} [C_{inlet,m}(DF_m) + C_{inlet,m}(DPRV_m)] + \sum_{v=1}^{NV} (viol_v \times \beta_v) \quad (2)$$

$$B(X) = [C_p \times \Delta VL - (C_v - C_p) \times \Delta VR] \times \left[365 \times \frac{(1 + \text{int} R)^{ny} - 1}{\text{int} R \times (1 + \text{int} R)^{ny}} \right] \quad (3)$$

where: $NPV(X)$ is the objective function or net present value of the project (€); X is the solution of the Simulated Annealing algorithm; n is the number of investment periods along the duration of the project plan; $B(X)_i$ is the total economic benefits during the investment period i and updated to the beginning of this investment period (€); $C(X)_i$ is the total investment costs at the beginning of the investment period i (€); π_i is the time from the beginning of the project to the investment period i (years); $\text{int}R$ is the annual interest rate (%); NP is the number of pipes; $C_{pipe,p}(D_p)$ is the unit cost for the pipes reinforcement/replacement (€/m); D_p is the diameter of the new pipe (mm); L_p is the pipe

length (m); NM is the number of DMAs entry points; $C_{inlet,m}(DF_m)$ is the global cost of each DMA entry point with flow meter and chamber (€/unit); DF_m is the flow meter diameter (mm); $C_{inlet,m}(DPRV_m)$ is the global cost of the PRV at each DMA entry point (€/unit); $DPRV_m$ is the PRV diameter (mm); NV is the number of constraints violations; $viol_v$ is the maximum violation for the constraint v ; βv is the unit cost of penalty for violating constraint v ; n_y is the duration of each investment period (years); C_p is the cost of water production (€/m³); C_v is the water selling price (€/m³); ΔVL is the total reduction of water losses after pressure management (m³); and ΔVR is the total reduction of billed water after pressure management (m³).

3 Results

Figure 1 shows the layout of the WDS, which is characterized by low density of service connections. Using the methodology describe in section 2, three scenarios were studied in order to evaluate the NPV of the DMAs design, as well as the benefits from pressure management. In Scenario 1, the DMA entry point should be driven by network hydraulic behaviour (each DMA entry point includes a flow meter – FM). In Scenario 2, the DMA entry point should be driven to obtain the maximum benefits from pressure management (each DMA entry point includes a flow meter and, if necessary, a PRV). In Scenario 3, the DMA entry point should be driven to obtain the maximum benefits from pressure management, including the network hydraulic behaviour after network reinforcement/replacement (each DMA entry point includes a flow meter and, if necessary, a PRV). Table 1 shows the results obtained.

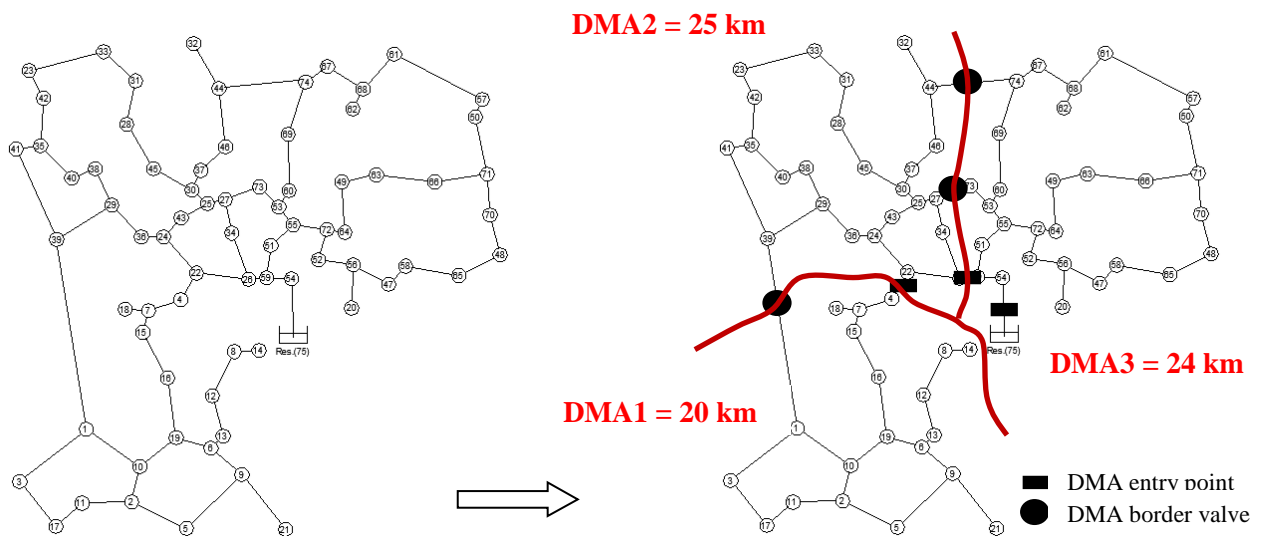


Figure 1 Water Distribution System layout, before (left) and after (right) the DMAs design.

Figure 1 (right) shows the most appropriate locations for the flow meters at DMAs entry points and the DMAs boundary valves for Scenario 1. The network hydraulic behavior show that the service pressure is still high - above the minimum service pressure required to satisfy the demand. The benefits from pressure management were estimated in Scenario 2. Taking as reference the NPV of the DMAs design resulting from Scenarios 1 and 2, it is possible to demonstrate that, in this case, the economic viability of the project is dependent on the pressure management. Two types of PRV are proposed during the project plan: Fixed-outlet PRV and Pressure-modulated PRV. The operating conditions of the PRVs establish two pressure zones: the first includes DMA1 and DMA2, and the second includes DMA3. Regarding Scenario 3, results show that the pipe reinforcement (at the beginning of the project plan) allows a readjustment of the service pressures throughout the network and, consequently, increase the NPV of the project.

Table 1 NPV of the DMAs design for different scenarios.

Investment period (years)		Average daily reduction*		DMA entry point	Cost of network reinforcement or replacement (€)	Cost of flow meter and PRV (€)	Benefits (€)	NPV (€)
		VR	VL					
Scenario 1	0-10	0.00	0.02	DMA1 – pipe 78 (FM) DMA2 – pipe 79 (FM) DMA3 – pipe 82 (FM)	0	-31 391	3 238	-29 076
	10-20	0.00	0.03	DMA1 – pipe 78 (FM) DMA2 – pipe 79 (FM) DMA3 – pipe 82 (FM)	0	-7 154	5 650	
Scenario 2	0-10	1.32	12.87	DMA1 – pipe 78 (FM) DMA2 – pipe 79 (FM + PRV) DMA3 – pipe 82 (FM + PRV)	0	-39 582	1 308 645	2 041 446
	10-20	1.07	11.18	DMA1 – pipe 78 (FM) DMA2 – pipe 79 (FM + PRV) DMA3 – pipe 82 (FM + PRV)	0	-7 072	1 265 202	
Scenario 3	0-10	1.40	13.64	DMA1 – pipe 78 (FM) DMA2 – pipe 79 (FM + PRV) DMA3 – pipe 82 (FM + PRV)	-66 684	-39 582	1 371 470	2 051 658
	10-20	1.08	11.44	DMA1 – pipe 78 (FM) DMA2 – pipe 79 (FM + PRV) DMA3 – pipe 82 (FM + PRV)	0	-7 072	1 288 123	

* Values expected at the end of each investment period.

VL: volume of water losses upstream of the flow meter VR: billed volume (consumption and water losses downstream of the flow meter).

4 Conclusions

Water loss reduction in Water Distribution Systems (WDS) is nowadays an issue of growing importance for water companies to ensure the sustainability of these public services. On the other hand, reducing water losses to zero is practically impossible and would be extremely expensive. The methodology presented in this paper has shown that the DMA design and pressure management can be used to reduce the total water losses in WDS and, at the same time, spread the investment cost through the project plan.

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