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Optimizing the Performance of Water Distribution Networks: Sectorization and Pressure Management for Leakage Reduction †

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Abstract: Sectorization and pressure management are techniques that simplify leak detection and its control in water networks. This article proposes a novel three-stage methodology. First, using complex network theory, it identifies conceptual cuts to form communities. Second, it optimizes District Measurement Areas (DMAs) by reconnecting these cuts, balancing resilience loss and open connections. Third, it reduces network pressure during off-peak hours by installing pressure-reducing valves to create Pressure Management Zones (PMZs). Applied to an academic network and a real network, this approach establishes both DMAs and PMZs, enhancing the supply quality and reducing leakages.

Keywords: leakage reduction; pressure control zones; pressure management

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1. Introduction

Improving the efficient utilization of water resources poses a significant challenge, especially in addressing water losses within Water Distribution Networks (WDNs). Of particular concern are background leakages, which involve continuous, low-volume water losses occurring in pipelines, connections, and other network components. Sectorization and pressure management have emerged as promising techniques for addressing these challenges. Sectorization involves dividing networks into smaller, more manageable areas known as District Metered Areas (DMAs), facilitating the identification and isolation of areas with anomalous water losses [1,2]. Meanwhile, pressure management controls the nodal pressure within hydraulic systems through devices like pressure-reducing valves (PRVs) strategically installed within the network [3,4]. While numerous studies have explored network sectorization and leak management through pressure control, a comprehensive strategy that integrates both techniques remains elusive. This study proposes a three-stage methodology for network sectorization and background leakage reduction. The first stage involves detecting community structures using the modularity index [5] to establish conceptual cuts delineating these structures. Subsequently, the design of optimal autonomous DMAs is pursued through multi-objective optimization using a simulated annealing algorithm. Finally, pressure management during off-peak hours is implemented by installing PRVs to minimize excess pressure in the network, thereby effectively reducing leak volumes. By applying this methodology to both an academic (25N) network and a real (HG) network, this study aims to demonstrate its efficacy in addressing the identified challenges and paving the way for a more sustainable water distribution system.

2. Materials and Methods

This work proposes to simulate leakages in all demand nodes using the emitter model. Emitters are devices where flow through an orifice discharging to the atmosphere is expressed as $L_i = C\ P_i^{\beta}$, where L_i and P_i are the leakage flow and the pressure at node i, respectively; C is the discharge coefficient equal to 0.25 and 0.003 for 25N and HG, respectively; and β is the pressure exponent, set equal to 0.5 for both.

2.1. First Stage: Community Detection

A community is a set of nodes that are highly connected to each other and weakly connected to nodes not belonging to the community. The Louvain algorithm [6] is an algorithm for optimal community detection based on the maximization of the modularity index Q (Figure 1), where A_{ij} are the elements of the adjacency matrix of size $n \times n$, with n being the number of nodes; γ is the resolution parameter; k_i is the degree of node i, i.e., the number of pipes connected to node i; M_i identifies the module i of the network; δ is the Kronecker delta function (equal to one only if M_i = M_j); and the sum runs over all possible pairs of nodes (i,j), with $i \neq j$. This index can take values between 0 and 1. A value of Q close to 1 indicates that the connection of intra-community nodes is greater than the connection between communities.

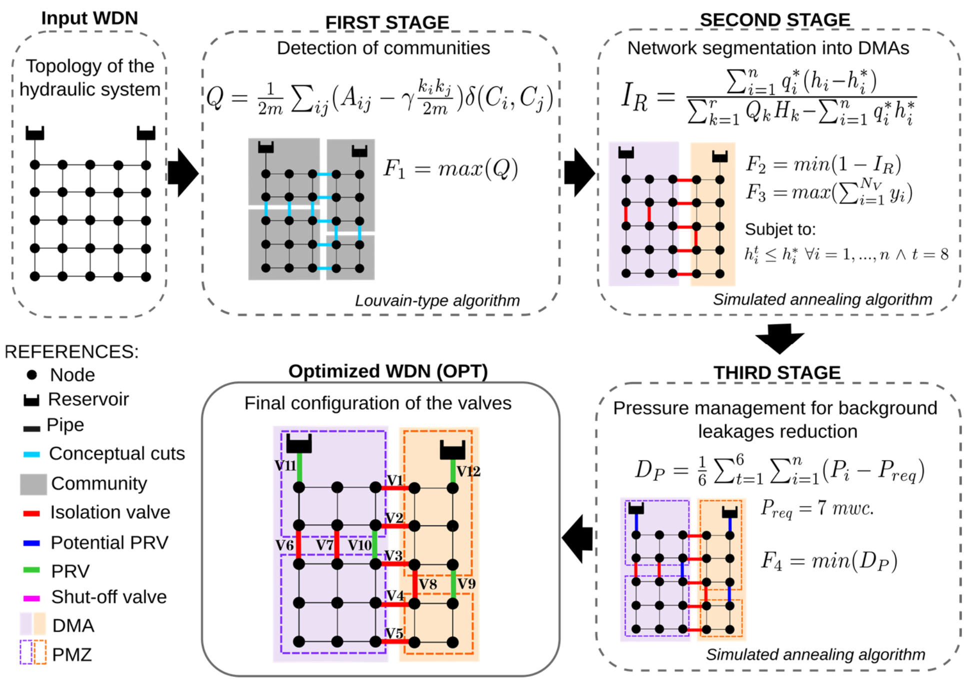

Figure 1. Schematic process depicting the methodology and results of the 25N network.

2.2. Second Stage: Network Sectorization into DMAs

In the second stage of the proposed method, the objective is to optimally position a number Nv of isolation devices to sectorize the network into autonomous DMAs. To achieve this, it is necessary to determine which of the conceptual cuts obtained in the first stage should be materialized. This stage is formulated as a two-objective optimization problem: (i) maximizing the number Nv of physical cuts or isolation valves yi, equivalent to minimizing the number of pipes that connect the DMAs; and (ii) minimizing the resilience loss $(1 - I_R)$ at the time of peak demand (i.e., hour 8:00). The resilience index I_R [7] is a metric used to quantify the hydraulic reliability of a network and depends on q_i^* and h_i^* which are constant values denoting the demand and minimum head of node i, respectively; h_i is the head of node i; Q_k and H_k are, respectively, the discharge and head of reservoir k; and r is the number of reservoirs. The optimization process is performed using the simulated annealing algorithm [8], allowing the user to define the locations of the potential

PRVs in order to manage the pressures in the next stage. This technique ensures that accepted solutions meet the total demand satisfaction (that is, $P_i \geq P_{req}$, where P_{req} is the required pressure) and that, moreover, each DMA is supplied by at least one reservoir.

2.3. Third Stage: Pressure Management for Background Leakage Reduction

The third stage of this method is framed as a single-objective optimization task aiming to create PMZs and enable pressure management along with the consequent reduction in background leakages. The objective is to reduce the cost function D_p given by the temporal average of the difference in nodal pressure of the network calculated between 0:00 and 5:00 h, i.e., during periods of lower demand (see Figure 1). The design variables are the elements S_{ij} of the matrix $\mathbf{S}$ of size $6 \times V_t$, where 6 is the number of hours, and V_t is the total number of PRVs installed in the network, equal to the number of open connections between the DMAs plus the valves located at the outlets of the reservoirs. Thus, the element S_{ij} is the operating parameter of valve j at hour i. Each parameter, or setting, corresponds to the maximum pressure value accepted by the downstream device. The optimization process for this stage is carried out using the SMOSA version of the simulated annealing algorithm.

Since the problem in this case study required the solution of the hydraulic system, EPANET 2.2 software was used to obtain the network pressures and demands with a Pressure Demand Approach (PDA) model.

3. Results

This comprehensive methodology was applied to both an academic network, denoted as 25N, and a real network, referred to as HG, as illustrated in Figures 1 and 2, respectively.

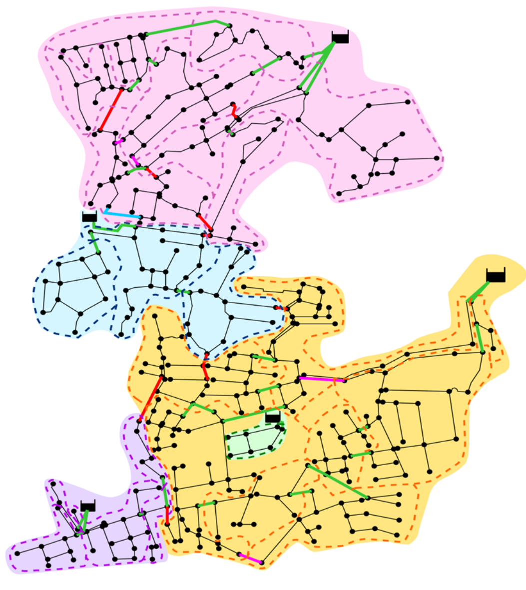

Figure 2. DMAs (colors) and PMZs (dotted lines) for the HG network.

In the case of network 25N, the results depicted in Figure 1 reveal that the initial phase detected 10 conceptual cuts (highlighted in cyan) and identified a structure comprising four communities, with $\gamma = 1$. The optimization in the second phase led to the segmentation of the hydraulic system into two autonomous DMAs through the installation of eight isolation valves (highlighted in red). Finally, the third stage achieved the optimal configuration of the potential PRVs (highlighted in blue) by activating all of the four valves (highlighted in green) installed within the WDN. This process delineated four PMZs. Overall, the optimization process reduced leakage volumes by approximately 14% between the unaltered network (289 m^3) and the optimized network (247 m^3).

Figure 2 also illustrates the final configuration of the HG network following the application of the three stages. The initial stage (with $\gamma = 1.6$) identified 27 modules.

Subsequent segmentation in the second stage divided the network into five autonomous DMAs by installing 10 isolation valves, aiming to minimize the number of flowmeters from the Pareto front. The third stage determined that out of the 38 potential PRVs, 33 should be activated. Additionally, it was identified that four potential PRVs should be replaced with shut-off valves, highlighted in magenta in Figure 2 (as they only switch between open and closed states), and one potential PRV should not be installed. This new configuration defined the network into 23 PMZs, beneficial for pressure management. The complete optimization resulted in an approximate 8% reduction in daily leakage volumes in the WDN when comparing the original network volume (613 m^3) to the optimized network volume (565 m^3).

4. Conclusions

This paper introduces a three-stage methodology aimed at reducing background leakages by controlling pressures during low-demand nighttime periods. The proposed strategy integrates sectorization and pressure management through the optimal placement of PRVs. Applied to both an academic and a real network, the results demonstrate a reduction in daily leakage volumes ranging from 8% to 14%.

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Data Availability Statement: The data, figures, tables and scripts presented/used in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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