

Effectiveness of a Scaled WDN Benchmark for Optimization Applications [†]

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[†] Presented at II International Conference on Challenges and Perspectives in Urban Water Management Systems (CSDU-CSSI DAYS 25), Trieste, Italy, 18–19 November 2025.

Abstract

In the past few decades, researchers have developed various pressure management techniques to control pressure, recover energy, and reduce leakage in water distribution networks. Most of these techniques have been developed and validated under numerical conditions. Only rarely has it been possible to receive feedback from the field after application, creating a gap between the numerical approach and field application. To address this gap, the Experimental Network for the Evaluation of the Digital Twin (E-NET) has been developing at Politecnico di Milano as a scaled laboratory model of a widespread numerical benchmark network to create a bridge between numerical simulations and laboratory practice. In this study, a well-known technique for Pressure Reducing Valves (PRVs) placement was applied to both the original benchmark and the scaled laboratory (E-NET) networks. It was confirmed that leakage reduction, as well as the optimal location and setting of PRVs, remain consistent across both systems. This demonstrates the feasibility of developing methodologies based on the scaled benchmark, thereby opening the way for experimental verification of the proposed methods.

Keywords: Pressure Reducing Valve; optimization; leakage; E-NET

1. Introduction

Pressure management is a key strategy to reduce leakage, with devices such as Pressure Reducing Valves, Pumps as Turbines, and Green Valves [1]. However, one of the main challenges remains the optimal location and adjustment of such devices, due to the nonlinear hydraulic behavior of networks and the large parameter space involved. To address this, heuristic optimization techniques such as Genetic Algorithms, Particle Swarm Optimization, and Ant Colony Optimization have been extensively applied [2]. Despite these advances, most optimization methodologies and leakage reduction approaches have been tested only under numerical conditions, typically using synthetic benchmarks such as the [3], Palermo [4], KL [4], Two-Loop [5], and Anytown [6]. Laboratory validation remains very limited, with existing works focusing mainly on the physical performance of devices rather than testing the consistency of optimization outcomes [7].

To bridge this gap, this study introduces E-NET [8], a scaled laboratory version of the network (hereafter referred to as the JX network), which has been widely applied in the literature [3]. E-NET reproduces the hydraulic characteristics of the original network under controlled experimental conditions, enabling the evaluation of optimization-based pressure management strategies in both numerical and laboratory environments. Genetic Algorithm



Academic Editors: Patrizia Piro,
Bruno Brunone, Federico Roman,
Umberto Sanfilippo and
Michele Turco

Published: 27 July 2026

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optimization was applied to assess whether the optimal location and opening of pressure-reducing valves remain consistent across the original and scaled numerical networks, thus providing a foundation for testing leakage reduction strategies under real conditions.

2. Materials and Methods

The JX network consists of 22 nodes, 37 links, and three reservoirs supplying water to the system. The total length of the network is more than 44 km, with varying pipe roughness, diameters, node elevations, and emitters. E-NET preserves the topology of the JX network but adapts it to laboratory constraints, using HDPE pipes, a total length of about 1 km, and constant nodal elevations. Reservoirs were replaced by pumps with frequency regulators, and the system is fully monitored through a SCADA platform. Each node is equipped with a pressure sensor and two flow meters to separately measure demand and leakage (Figure 1). For further details about the JX and E-NET networks, the reader is referred to [3] and [9], respectively.

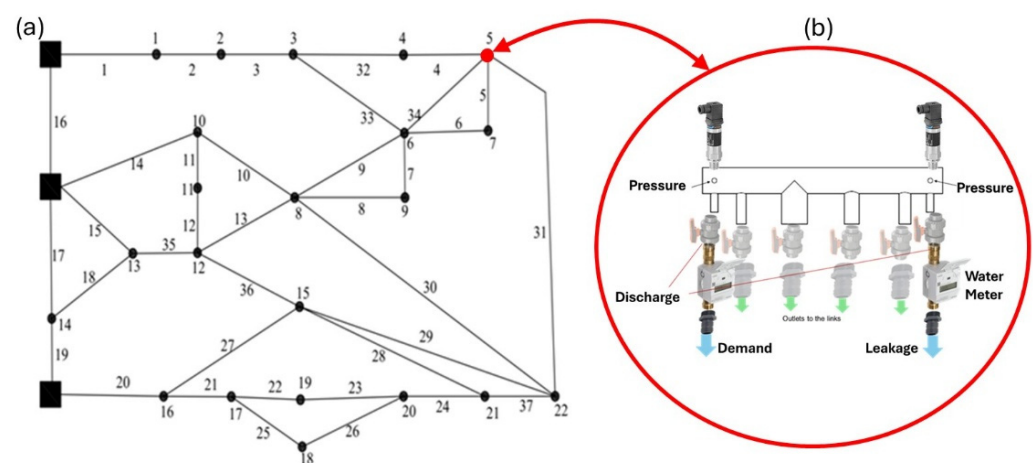


Figure 1. (a) Schematic layout of the JX benchmark network; (b) Experimental E-NET node configuration with pressure sensors, discharge outlets equipped with water meters.

2.1. Scaling Process and Simulations

In the scaling process, the Reynolds number and the Hazen–Williams head loss equations were simultaneously applied to reproduce the pipe head loss conditions of the original JX network within E-NET. These relations were used to calculate the equivalent pipe diameters and velocities, ensuring that the head loss in each scaled pipe was representative of that in the original network.

$$Re = \frac{VD}{\nu} \quad (1)$$

$$S = \frac{10.67Q^{1.852}}{C^{1.852}D^{4.8704}} \quad (2)$$

where Q is flow rate (m^3/s), ν is kinematic viscosity (m^2/s), D is pipe diameter (m), V is flow velocity (m/s), and C is the Hazen–Williams roughness coefficient. For more details on the scaling process, readers are referred to [9].

2.2. Simulation and Optimization

In this study, EPANET 2.2 (U.S. Environmental Protection Agency, Cincinnati, OH, USA) was used to simulate the hydraulic behavior of both the original and scaled laboratory networks to assess head losses and flow direction in pipes, and pressure in nodes.

An optimization approach proposed in [10] was employed to determine the optimal location and settings of Pressure Reducing Valves for leakage minimization. In their work,

they applied diameter multipliers instead of directly modeling PRVs and subsequently converted these multipliers into valve settings. The same procedure was adopted in this study.

The optimization considered two demand multipliers, 0.6 and 1.4, representing the lowest and highest demand conditions within a 24 h cycle (see [9] for more details). Since Genetic Algorithms are stochastic in nature, optimization results may vary even under identical initial conditions. Therefore, ten independent runs were performed to ensure the robustness and consistency of the obtained solutions.

3. Results

Table 1 summarizes the optimization outcome for both the original and scaled networks under two demand multipliers (0.6 and 1.4), considering configurations with one PRV. For comparison, leakage values in E-NET were multiplied by the scale factor of 44, corresponding to the pipe length ratio, so that results could be evaluated on a consistent basis [9]. The leakage rate at each node was estimated using the pressure-based leakage equation proposed by [11] and reported in Equations 3 and 4. Maintaining hydraulic similarity is essential when scaling WDNs, since continuity and energy conservation principles imply that properly scaled lengths, diameters, and demands should preserve the same pressure distribution patterns [12].

$$l_{e,i} = \beta L_{T,i} P_i^\gamma \quad (3)$$

$$L_{T,i} = \sum_j 0.5 L_{ij} \quad (4)$$

where $l_{e,i}$ is the leakage (L/s) at node i , β is the leakage coefficient equal to 0.00001, P_i is the node's pressure (m), γ is the leakage exponent equal to 1.18 [11], and $L_{T,i}$ is the sum of the half-lengths pipes that connect node i to other node node j .

Table 1. GA-based optimization results for a single PRV under low (0.6) and high (1.4) demand conditions in the JX and E-NET networks.

Network	Load Condition	Valve Location	Adjustment	Frequency	Leakage (L/s)
JX	0.6	35	0.003	10	19.33
E-NET	0.6	35	0.008	10	21.34
JX	1.4	35	0.563	3	18.62
		13	0.228	7	19.34
E-NET	1.4	35	0.632	5	19.62
		13	0.453	5	19.32

Note: "Adjustment" indicates the diameter multiplier corresponding to the valve setting. "Frequency" represents the number of times each solution appeared across 10 independent GA runs. Leakage values are expressed as the mean leakage associated with the respective frequency.

Results for the single-valve configuration (Table 1) show that both the valve locations and adjustment values are largely consistent between the two networks across load conditions. Minor discrepancies in settings are mainly due to elevation differences, which slightly alter nodal pressures. Overall, the similarity in leakage levels and the coincidence of valve positions confirm that the scaled model reproduces the hydraulic behavior of the original JX network.

4. Conclusions

The findings demonstrate functional equivalence between the JX and E-NET networks, highlighting the robustness of the scaling approach in capturing key pressure and flow dynamics. Importantly, the fact that identical valve locations were identified in both networks suggests that the scaling procedure preserves not only global hydraulic patterns but also local pressure zones where PRVs are most effective. Their consistent placement across scaled and original systems validates that the scaled model can be reliably used to develop pressure management strategies, with the advantage of being able to potentially test them in laboratory conditions. This reinforces the role of E-NET as a practical benchmark for investigating leakage reduction techniques and for developing Digital Twin applications.

Author Contributions: Conceptualization, S.M. and G.F.; methodology, A.F.; validation, A.F. and G.F.; formal analysis, S.M.; investigation, A.F.; writing—original draft preparation, A.F. and G.F.; writing—review and editing, S.M.; visualization, G.F.; supervision, S.M. All authors have read and agreed to the published version of the manuscript.

Funding: The project was supported by MUSA—Multilayered Urban Sustainability Action—project, funded by the European Union—Next Generation EU, under the National Recovery and Resilience Plan (NRRP) Mission 4 Component 2 Investment Line 1.5: Strengthening of research structures and creation of R&D “innovation ecosystems”, set up of “territorial leaders in R&D” (project code ECS 00000037).

Data Availability Statement: Data are available from the corresponding author upon reasonable request.

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

Abbreviations

The following abbreviations are used in this manuscript:

E-NET	Experimental Network for the Evolution of the Digital Twin
JX	Jowitt and Xu

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