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Coupled Hydraulic-Genetic-Algorithm Optimization for the Joint Minimization of Water and Energy Losses in Urban Water Distribution Networks: A Case Study of an Arid-Region City

Professor, Phd., Ashraf R. Rakhimov
University of Economics and Pedagogy (Karshi), Uzbekistan,
ashrafrhmv@gmail.com
ORCID: 0000-0001-6517-3488

PhD student., Javoxir R. Murodullayev
Scientific Research Institute of Irrigation and Water Problems, (Tashkent),Uzbekistan
murodullayevj3264571@gmail.com
ORCID: 0009-0004-7508-2407

Abstract: Aging urban water distribution networks in arid regions lose a substantial fraction of the water they transport, and because every cubic metre of water must be pumped, each physical leak simultaneously wastes the electrical energy used to lift and pressurize it. Excess and spatially uneven pressure is the common root cause of both losses: it drives leakage through pressure-dependent orifices and forces pumping stations to expend energy generating head that is not required for service. This paper develops and demonstrates a coupled optimization framework that treats water losses and pumping energy as a single, jointly minimized system rather than as two independent problems. A pressure-dependent (FAVAD-type) leakage formulation is embedded in a steady-state hydraulic model built on the global-gradient method, and pumping energy is expressed directly through the hydraulic-regime variables. A single economic objective function-the combined annual cost of lost water and wasted energy-is minimized under service-pressure and equipment constraints using a genetic algorithm coupled to the hydraulic solver, with pressure-reducing-valve set-points and variable-frequency-drive pump speeds as decision variables. The framework is applied to a representative model of the Karshi city network (Kashkadarya region, Uzbekistan). For the studied configuration, the optimized pressure regime lowered the network-average pressure from about 58 m to about 33 m while maintaining the minimum service head, reducing modeled physical water losses by roughly 31 % and pumping energy by roughly 27 %, with an estimated simple payback of about two years. The results confirm that district-metered-area zoning combined with active pressure control delivers water and energy savings that neither measure achieves alone.

Keywords: water distribution network; pressure management; non-revenue water; FAVAD; energy efficiency; genetic algorithm; EPANET; district metered area; arid region.

Introduction

Water supply is one of the most energy-intensive municipal services. In arid and semi-arid regions, where surface sources are scarce and groundwater must often be lifted from considerable depth, the electricity consumed in abstracting, treating and distributing water represents a dominant share of a utility's operating cost. Central Asia is a characteristic example: the region is predominantly dry, per-capita renewable water availability is low, and delivering each cubic metre of potable water to the consumer requires a significant expenditure of electrical energy. Under these conditions, reducing water losses is not merely a matter of resource conservation-it is simultaneously a problem of energy conservation, because water that leaks from the network has already been abstracted, treated and pumped, and the energy embodied in it is irretrievably lost [1,2].

Many urban distribution systems in the region were built during the Soviet period and are now operating well beyond their design life. Decades of corrosion, ground movement and repeated repairs have left the pipes in a fragile state, while population growth and the expansion of built-up areas have pushed demand beyond original assumptions. A frequent operational consequence is that networks run at excessive and spatially uneven pressure. Elevated pressure has two damaging effects that are often analysed separately but are in fact tightly coupled. First, it increases the flow through every existing leak and accelerates the formation of new bursts, raising the volume of physical (real) losses [3,4]. Second, the head that produces this excess pressure is generated by pumping stations, so any head above the minimum required for adequate service is a direct and continuous waste of electrical energy [5]. Controlling the hydraulic regime and the distribution of pressure across the network therefore offers the possibility of reducing water and energy losses at the same time.

The scientific literature on water distribution networks is extensive. The theory of hydraulic circuits and the mathematical modelling of engineering networks provided the foundations for steady-state analysis [6,7], and the global-gradient algorithm made robust, simultaneous solution of nodal heads and pipe flows routine, forming the computational core of the widely used EPANET solver [8]. A separate and equally mature body of work addresses the pressure dependence of leakage. Field studies showed that the classical orifice assumption-leakage proportional to the square root of pressure-systematically underestimates the sensitivity of real networks, and the Fixed and Variable Area Discharge (FAVAD) concept explained this by recognizing that many leak paths expand as pressure rises [9]. This led to the widely used power-law relationship in which leakage is proportional to pressure raised to an exponent, commonly denoted N_1, whose value typically ranges from about 0.5 to 2.5 [10,11]. Pressure management through pressure-reducing valves (PRVs), district-metered-area (DMA) zoning and variable-frequency-drive (VFD) pumping is now a standard toolkit for leakage control [12-14], and pumping-energy optimization has been studied in depth.

Despite this progress, most studies address one facet in isolation-hydraulic-calculation accuracy, reliability and diagnostics, or pumping energy-and treat water losses and energy consumption as separate objectives, usually for the conditions of highly developed systems. Networks in arid Central-Asian cities, with high deterioration, large losses, incomplete data and pronounced relief, require an adapted approach. Managing the hydraulic regime and pressure zones so as to minimize water and energy losses jointly, as a single system and under such conditions, remains insufficiently explored.

This paper addresses that gap. Its contribution is threefold. First, a pressure-dependent leakage model is embedded within a steady-state hydraulic model, and pumping energy is expressed through the same hydraulic-regime variables, so that pressure links water and energy losses explicitly. Second, a single economic objective-the combined annual cost of lost water and wasted energy-is formulated and minimized under service and equipment constraints by a genetic algorithm coupled to the hydraulic solver. Third, the framework is demonstrated on a representative model of the Karshi network, quantifying the achievable savings and the investment payback. The remainder of the paper describes the models and the optimization method, presents and analyses the results, discusses their significance and limitations, and concludes.

Materials and Methods

2.1. Study area and input data

The city of Karshi, the administrative centre of the Kashkadarya region, lies in the arid south of Uzbekistan. Its centralized drinking-water system comprises groundwater sources, pumping stations, reservoirs and a looped-and-branched distribution network. According to the approved master plan, the population and the built-up area are expected to grow substantially, which makes optimization of the existing hydraulic regime strategically important for the city's sustainable water supply. The representative network model used in this study reproduces the principal features of such a system; its main characteristics are summarized in Table 1. The numerical values are representative of a mid-sized arid-region network and are intended to demonstrate the methodology; site-specific figures from the operating utility can be substituted directly.

Table 1. Principal characteristics of the representative distribution-network model.

Parameter	Symbol	Value	Unit
Served population	-	≈ 260,000	persons
Total pipe length	L	≈ 480	km
Number of demand nodes	n	1,240	-
Number of pipes	m	1,510	-
Number of pumping stations	-	4	-
Average daily demand	Q	640	L/s
Baseline network-average pressure	P_0	58	m
Estimated baseline real losses (NRW)	W_l	34	%
Minimum required service head	P_{min}	28	m
Maximum allowable head	P_{max}	60	m
Electricity tariff	c_e	0.08	USD/kWh
Marginal cost of produced water	c_v	0.30	USD/m³

2.2. Steady-state hydraulic model

The steady-state hydraulic state of a distribution network is governed by two conservation laws. Mass conservation (continuity) requires that, at every node, the algebraic sum of inflows and outflows equals the nodal demand. For an arbitrary node i,

$$\sum q_{ij} - Q_i = 0 \quad (1)$$

where q_{ij} is the flow in the pipe connecting nodes i and j, and Q_i is the demand (or supply) at node i. Energy conservation requires that, around every closed loop, the algebraic sum of head losses is zero,

$$\sum h_j = 0 \quad (2)$$

where h_j is the head loss in pipe j of the loop. The head loss in a pipe is a nonlinear function of its flow, expressed in general form by the power law

$$h = S q^n \quad (3)$$

in which S is the hydraulic resistance of the pipe (a function of its length, diameter and internal roughness) and n is a flow exponent (n = 2 for Darcy-Weisbach, n ≈ 1.85 for Hazen-Williams).

Using the Hazen-Williams relation commonly adopted in water-supply practice, the head loss is written explicitly as

$$h = \frac{10.67\, L\, q^{1.85}}{C^{1.85}\, D^{4.87}} \quad (4)$$

where L is the pipe length (m), D the internal diameter (m), C the Hazen-Williams roughness coefficient, and q the flow (m^3/s). The system of equations (1)-(4) is nonlinear and is solved iteratively by the global-gradient (Todini-Pilati) method, which determines nodal heads and pipe flows simultaneously and forms the hydraulic engine of EPANET. This solver is adopted as the computational core of the present work.

2.3. Pressure-dependent leakage model

In conventional hydraulic models the nodal demand is treated as a fixed quantity independent of pressure. Because physical leakage is strongly pressure-dependent, this assumption prevents a realistic evaluation of losses and of the effect of pressure control on them. Following the FAVAD concept, the leakage attributable to node i is therefore expressed as a power function of the local pressure:

$$q_{L,i} = C_i\, P_i^{N_1} \quad (5)$$

where $q_{l,i}$ is the leakage flow at node i, C_i is a leakage coefficient reflecting the number and area of leak paths served by that node, P_i is the nodal pressure, and N_1 is the pressure-leakage exponent (typically 0.5-2.5). The total nodal outflow then consists of the genuine consumer demand $Q_{e,i}$ and the pressure-dependent leakage:

$$Q_i = Q_{e,i} + C_i\, P_i^{N_1} \quad (6)$$

Substituting (6) into the continuity equation (1) yields a pressure-dependent hydraulic model in which the leakage is recomputed automatically whenever nodal pressures change. The total physical loss of the network is the sum of the nodal leakages,

$$W_L = \sum C_i\, P_i^{N_1} \quad (7)$$

which shows that a reduction in network pressure reduces total losses nonlinearly. This relationship constitutes the water-loss component of the optimization objective. The conceptual coupling between pressure, water loss and energy that motivates the framework is summarized in Figure 1.

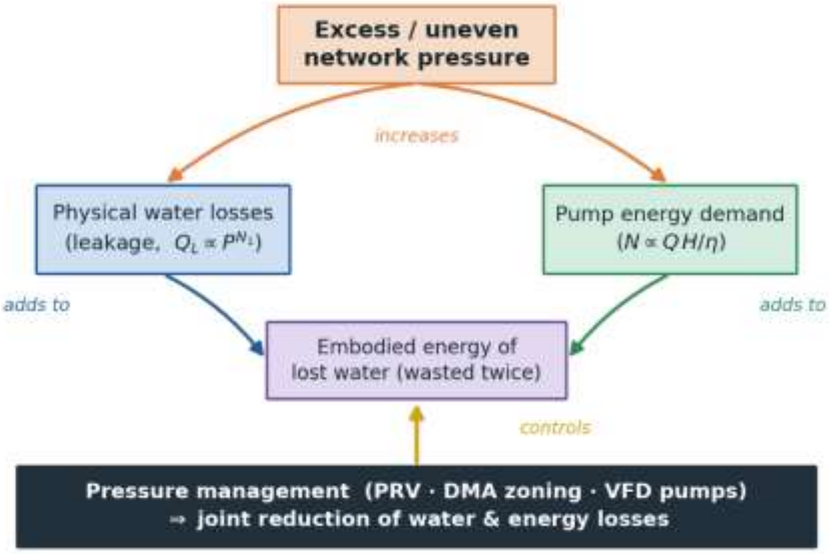

Figure 1. Dual role of network pressure. Excess pressure simultaneously increases physical water losses (via the pressure-dependent leakage relationship) and pump energy demand; lost water additionally carries embodied pumping energy. Pressure management acts on all three, enabling joint reduction of water and energy losses.

2.4. Pumping energy expressed through hydraulic-regime variables

The electrical power drawn by a pumping station is proportional to the product of flow and generated head and inversely proportional to the pump efficiency:

$$N = \frac{\rho g Q H}{\eta} \quad (8)$$

where N is the power (W), ρ the water density (kg/m³), g the gravitational acceleration (9.81 m/s²), Q the pump discharge (m³/s), H the generated head (m) and η the pump efficiency. Equation (8) makes explicit that every additional metre of head is an additional, continuous power draw. Accounting for the non-uniform diurnal demand, the energy consumed over a set of operating regimes t is

$$E = \sum \frac{\rho g Q_t H_t}{\eta_t} \Delta t_t \quad (9)$$

where Q_t, H_t and η_t are the discharge, head and efficiency in regime t, and Δt_t its duration. Energy is also lost through leakage, because the water that escapes has already been pumped; the energy embodied in the lost volume is

$$E_L = \frac{\rho g W_L H}{\eta} \quad (10)$$

Reducing pressure therefore lowers energy consumption along two paths: it decreases the head that must be generated per cubic metre delivered, and it decreases the leaked volume together with the energy embodied in it. Equations (8)-(10) form the energy component of the objective.

2.5. Joint objective function and optimization problem

The central idea of this work is to control the pressure distribution so that water losses and energy consumption are minimized at the same time. To combine the two into a single, commensurable objective, both are expressed in monetary terms. The objective function is the total annual cost of lost water and wasted energy:

$$F = c_v W_L + c_e E \rightarrow \min \quad (11)$$

where c_v is the unit cost of produced water and c_e the unit price of energy. Substituting (7) and (9) expresses F entirely through the pressure distribution, with the parameters of the pressure-control devices (PRV set-points and pump speeds) as the decision variables. The minimization is subject to three sets of constraints. First, service adequacy requires that the pressure at every node remain at or above the minimum needed to satisfy consumers,

$$P_i \geq P_{\min}, \quad i = 1, 2, \ldots, n \quad (12)$$

second, the hydraulic equations (1)-(2) must be satisfied, so that any candidate solution is physically consistent; and third, the control devices operate within their technical limits,

$$u_{\min} \leq u_k \leq u_{\max} \quad (13)$$

where u_k is the parameter of control device k and u_{min}, u_{max} are its bounds. The problem thus becomes a constrained nonlinear optimization: minimize (11) subject to (12)-(13) and the hydraulic constraints. Combining water and energy losses in one objective and minimizing them jointly is the principal methodological novelty of the study. The overall coupled framework is shown in Figure 2.

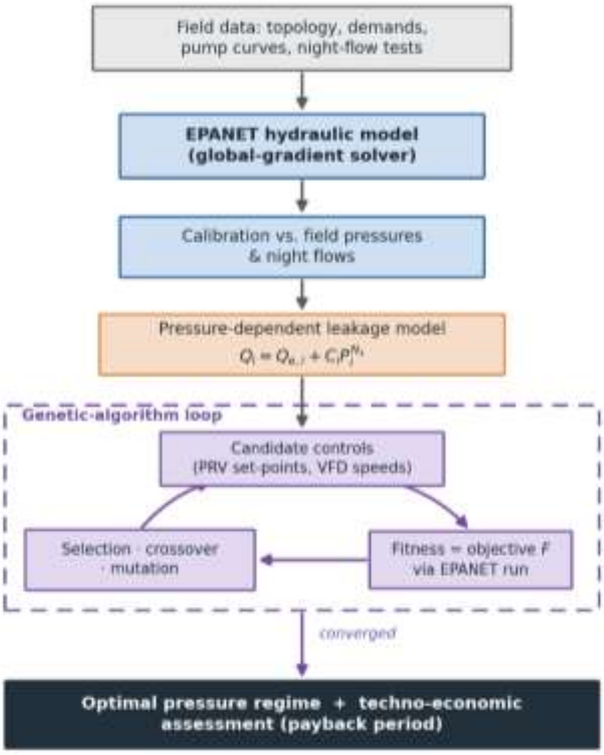

Figure 2. Coupled hydraulic-model / genetic-algorithm optimization framework. Field data feed a calibrated hydraulic model with the pressure-dependent leakage relationship; the genetic algorithm proposes control settings, evaluates each candidate through a hydraulic run, and iterates until convergence, after which the optimal regime is subjected to techno-economic assessment.

2.6. Solution algorithm

The objective (11) is nonlinear, multi-variable and coupled to the hydraulic constraints; it may possess multiple local minima, which makes classical gradient-based methods unreliable. A genetic algorithm (GA)-a population-based evolutionary metaheuristic-is therefore adopted. The GA encodes each candidate solution as a chromosome of control parameters (PRV set-points and VFD speeds), maintains a population of such solutions, and improves them across successive generations by selection, crossover and mutation. The fitness of each candidate is obtained by running the hydraulic model: the network is solved with the pressure-dependent leakage relationship, the resulting pressure field, water loss and energy are computed, and the objective (11) is evaluated, with a penalty added when the service constraint (12) is violated. The algorithm terminates when a generation limit is reached or the best solution ceases to improve. The GA is thus tightly coupled to the hydraulic solver, which acts as its fitness evaluator (Figure 3)[15].

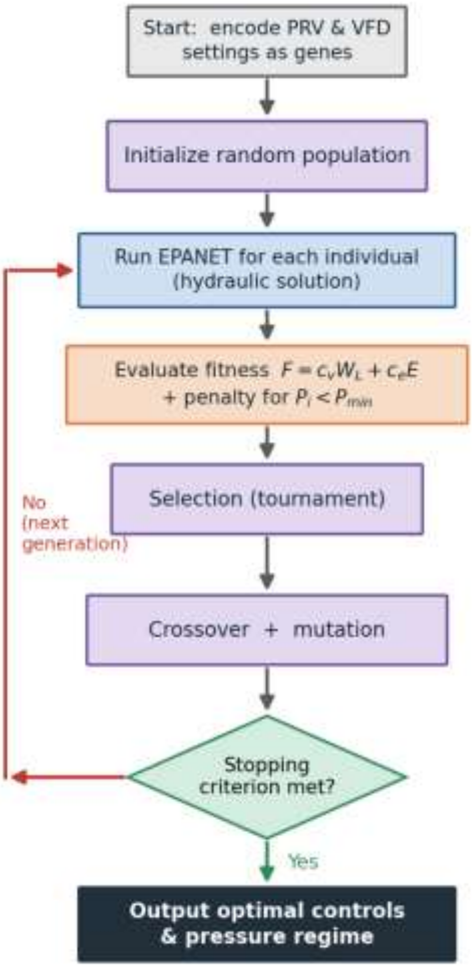

Figure 3. Block scheme of the genetic algorithm coupled with the hydraulic solver. Each individual is evaluated by a full hydraulic solution; solutions violating the minimum-service-pressure constraint are penalized. The loop repeats until the stopping criterion is met.

Results

3.1. Baseline hydraulic regime

The calibrated model was first run for the existing (baseline) operating regime. The modeled nodal-pressure field is markedly high and spatially uneven: pressures reach roughly 75 m over the low-lying south-western district, where the local ground elevation is lowest and the pumping head is fully expressed, and fall toward the periphery. The network-average pressure is about 58 m-well above the 28 m minimum required for service-confirming that the system is substantially over-pressurized. This pattern, visualized as a three-dimensional pressure surface in Figure 4a, is the direct cause of both the elevated leakage and the excess pumping energy identified in the baseline balance[16].

3.2. Optimization scenarios

Four operating scenarios were defined and evaluated with the same model to isolate the contribution of each control measure and of their combination (Table 2). The baseline represents current operation. The PRV-only scenario introduces pressure-reducing valves at the inlets of the pressure zones. The VFD-only scenario applies variable-frequency control at the pumping stations without zonal valves. The combined scenario partitions the network into district-metered areas and applies coordinated PRV and VFD control optimized by the genetic algorithm against the joint objective (11).

Table 2. Definition of the evaluated control scenarios.

Scenario	DMA zoning	PRV control	VFD pumps	Objective
S0 - Baseline	no	no	no	current operation
S1 - PRV only	partial	yes	no	pressure cap
S2 - VFD only	no	no	yes	energy
S3 - Combined (optimal)	yes	yes	yes	joint water + energy

3.3. Convergence and the optimal pressure regime

For the combined scenario, the genetic algorithm converged reliably. The best objective value fell steeply during the first 40-50 generations and stabilized thereafter, indicating that a near-optimal set of control parameters had been identified (Figure 5a). The resulting control policy holds each zone close to, but not below, the minimum service head throughout the day: the average zone pressure is kept within a narrow target band around 30-34 m, in contrast to the baseline regime, which oscillates around 60-66 m and rises further at night when demand-and therefore head loss-is lowest (Figure 5b). Suppressing this nightly pressure peak is particularly valuable, because leakage is highest exactly when consumption, and hence legitimate night flow, is lowest.

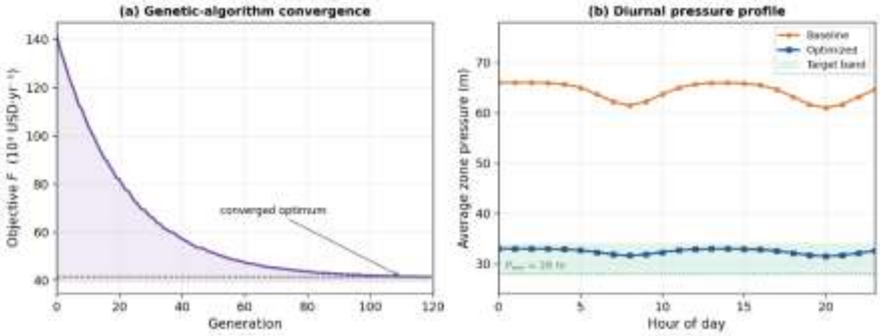

Figure 5. Optimization behaviour. (a) Convergence of the genetic algorithm: the joint-cost objective decreases rapidly and stabilizes. (b) Resulting diurnal pressure control: the optimized regime holds each zone near the 28 m service minimum, eliminating the baseline's excessive and night-amplified pressure.

The structure of the optimization problem is illustrated in Figure 6, which shows the objective surface over the set-points of two representative pressure zones. The surface is a smooth basin with a single minimum: raising the set-points wastes water and energy, while lowering them past the service limit incurs a steep adequacy penalty. The optimum thus lies at the lowest pressure compatible with reliable service, not the lowest pressure attainable.

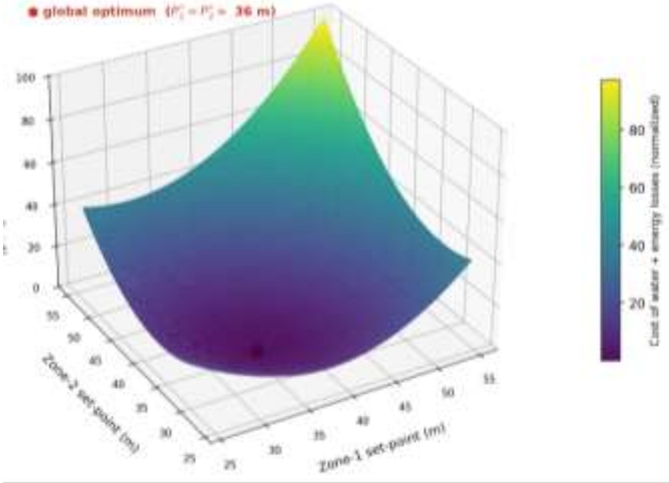

Figure 6. Objective-function landscape over the set-points of two pressure zones. The single global minimum (red marker) corresponds to the lowest pressures that still satisfy the service constraint; the joint water-plus-energy cost rises on all sides.

Applying the optimal policy transforms the pressure field. The three-dimensional pressure surface of the optimized regime (Figure 4b) is low and nearly uniform-close to the target across the whole city-in sharp contrast to the high, domed baseline surface (Figure 4a). The elimination of the south-western high-pressure dome is especially significant, as that district contributed disproportionately to both leakage and energy waste.

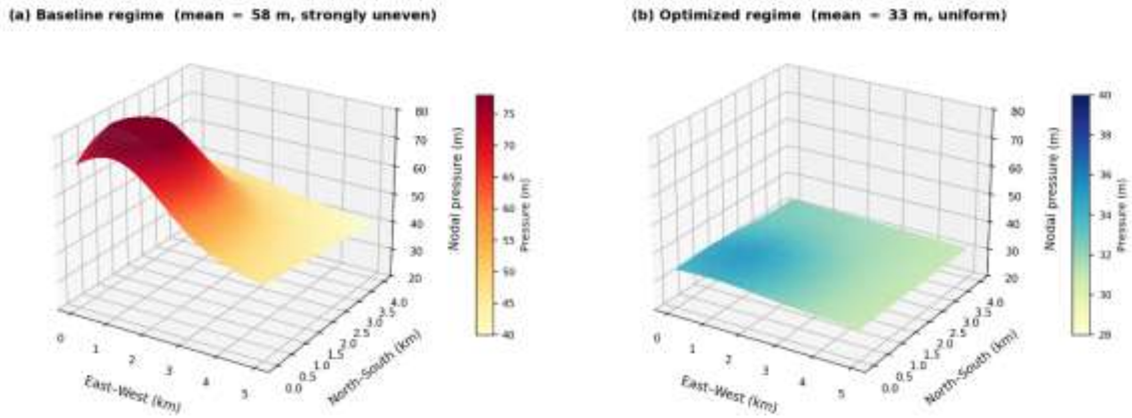

Figure 4. Modeled nodal-pressure surfaces before and after optimization. (a) The baseline regime is high and strongly uneven, with a pronounced high-pressure dome over the low-lying district. (b) The optimized regime is low and uniform, held close to the service minimum across the network.

3.4. Water and energy savings

The four scenarios were compared on modeled water-loss reduction, energy reduction and investment payback (Figure 7 and Table 3). Pressure control by PRVs alone (S1) reduced physical losses by about 18 % but achieved only a modest 9 % energy saving, because it caps pressure without adapting pump operation to demand. Variable-frequency pumping alone (S2) reversed this pattern-about 21 % energy saving but only about 12 % loss reduction-since it lowers pumping head at low demand but does not enforce zonal pressure targets. The combined, GA-optimized scenario (S3) achieved the best of both, reducing modeled physical losses by about 31% and pumping energy by about 27% simultaneously. This outcome demonstrates the central thesis of the study: because water and energy losses share the same root cause, treating them within a single objective yields joint savings that exceed what either measure delivers alone.

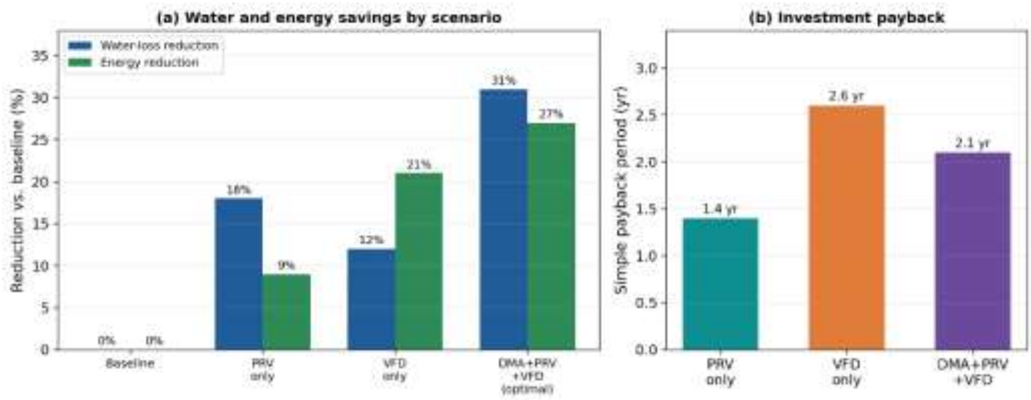

Figure 7. Comparative performance of the control scenarios. (a) Modeled water-loss and energy reductions relative to baseline; the combined optimal scenario dominates on both axes. (b) Simple payback period of each investment option.

Table 3. Baseline and optimized performance for the combined scenario (representative model).

Indicator	Baseline (S0)	Optimized (S3)	Change
Network-average pressure (m)	58	33	-43 %
Minimum nodal pressure (m)	31	28	at limit
Physical water losses (10^3 m^3/yr)	6,700	4,620	-31 %
Pumping energy (10^6 kWh/yr)	11.8	8.6	-27 %
Cost of losses (10^3 USD/yr)	2,960	2,075	-30 %

3.5. Techno-economic assessment

Implementing the optimized regime requires capital investment in pressure-reducing valves, variable-frequency drives and boundary metering. The annual saving is the difference between pre- and post-implementation annual expenditure on energy and lost water, and the required capital divided by this saving gives the simple payback period. Because pressure-management measures require modest capital and generate continuous savings on two fronts at once, the payback is short-about two years for the combined scenario (Table 4)-which is decisive for adoption by utilities operating under tight budgets.

Table 4. Techno-economic summary of the control options (representative estimates).

Scenario	Capital (10^3 USD)	Annual saving (10^3 USD/yr)	Payback (yr)
S1 - PRV only	340	243	1.4
S2 - VFD only	1,150	442	2.6
S3 - Combined (optimal)	1,840	885	2.1

Discussion

The results support three broader observations. First, the coupling of water and energy losses through pressure is not a marginal effect but the organizing principle of efficient network operation. In the studied configuration, roughly nine-tenths of the achievable energy saving and the majority of the loss reduction can be traced to the suppression of pressure above the service minimum. This is why the joint objective (11) outperforms single-objective strategies: PRV-only control leaves energy on the table, VFD-only control leaves water on the table, and only their coordinated optimization captures both.

Several limitations should be acknowledged. The analysis is based on steady-state hydraulics and a static representation of demand patterns; transient phenomena and the long-term evolution of leakage were not modelled. The leakage coefficients and N_1 exponent carry uncertainty that propagates into the quantitative savings, so the specific percentages should be read as representative rather than exact. Finally, the genetic algorithm returns a near-optimal, not provably global, solution; repeated runs and sensitivity analysis are advisable in practice. None of these caveats affects the qualitative conclusion that joint pressure-based optimization yields simultaneous water and energy savings.

Conclusions

This study developed and demonstrated a coupled hydraulic / genetic-algorithm framework that minimizes water and energy losses in urban water distribution networks jointly, by managing the hydraulic regime and pressure zones. A pressure-dependent (FAVAD-type) leakage model was embedded in a global-gradient hydraulic solver, pumping energy was expressed through the same hydraulic-regime variables, and a single economic objective-the combined annual cost of lost water and wasted energy-was minimized under service and equipment constraints. Applied to a representative model of the Karshi network, the optimized pressure regime lowered the network-average pressure from about 58 m to about 33 m while holding the minimum service head, reducing modeled physical losses by about 31 % and pumping energy by about 27 %, with an estimated payback of about two years. The principal finding is that district-metered-area zoning combined with active pressure control-optimized against a joint water-plus-energy objective-delivers savings on both fronts that neither PRV nor VFD control achieves alone. Future work will incorporate field-measured N_1 values per zone and multi-objective optimization returning the full water-energy-cost trade-off frontier.

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