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Research Article

Optimization of Drinking Water Distribution Networks through Hydrodynamic Simulations and Genetic Algorithms: An Approach to Agroecological Management

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ABSTRACT

Efficiency in the distribution of drinking water is crucial to ensure the sustainability of agroecological systems, especially in rural areas. In this study, a methodology that combines hydrodynamic simulations with genetic algorithms to optimize drinking water distribution networks is proposed. EPANET software is used to model the hydraulic behavior of the system, and a genetic algorithm implemented in Python to minimize costs and losses, considering agroecological criteria such as the rational use of the resource, energy sustainability and community integration. The results show significant improvements in pressure, flow and energy efficiency, promoting a more resilient and sustainable management of water resources.

Keywords: hydrodynamic simulations, genetic algorithms, drinking water networks, agroecology, EPANET, hydraulic optimization.

Introduction

The increasing pressure on water resources, derived from climate change, population growth and the intensification of agricultural activities, has generated an urgent need to optimize drinking water distribution systems. In rural areas and farming communities, efficiency in water management is a determining factor not only to guarantee human supply, but also to sustain agroecological production models that promote resilience, equity, and sustainability (Altieri & Nicholls, 2022; FAO, 2021).

Agroecology proposes a holistic paradigm in which ecological, technical and social principles are integrated into the management of agroecosystems. Under this approach, water is understood as a common good, whose use must be efficient, equitable and adapted to local dynamics. However, many rural water distribution networks lack optimized design, leading to inefficiencies such as inadequate pressures, leakage losses, and high energy consumption (Valdés-Pineda et al., 2023). These gaps directly affect the ability of rural communities to sustain viable agroecological practices.

In this context, computational simulation tools, such as EPANET, have gained relevance by allowing the detailed analysis of hydraulic conditions in distribution networks (Rossman et al., 2020). At the same time, advances in computational intelligence have facilitated the use of evolutionary algorithms such as genetic algorithms (GA), which have proven to be effective in solving multiobjective optimization problems in hydraulic engineering (Soleimani et al., 2022). These algorithms allow a wide space of solutions to be explored, evaluating multiple design and operation configurations that improve parameters such as pressure, flow rate and energy consumption.

Recent studies have highlighted the effectiveness of combining hydraulic simulations with genetic algorithms to improve the performance of water distribution networks. For example, research by Karami and Moghaddam (2023) and Zhang et al. (2021) showed that this methodology not only reduces costs and losses, but also increases the resilience of the system to variations in demand and operating conditions.

This work proposes a methodological strategy that integrates hydrodynamic simulations using EPANET with genetic algorithms implemented in Python, to optimize drinking water distribution networks from an agroecological perspective. The objective is to achieve a technical configuration that maximizes hydraulic and energy efficiency, while adapting to the specific needs of rural communities, thus contributing to strengthening water sovereignty and the sustainability of the agroecosystem.

Theoretical Framework

1. Hydrodynamic Simulations in Water Distribution Networks

Hydrodynamic simulations are a fundamental tool for the analysis and design of drinking water distribution systems. These simulations allow modeling the behavior of the flow within a network considering aspects such as pressure, velocity, flow and water quality, under various operating conditions. The EPANET 2.2 tool, developed by the EPA, is widely used for its ability to represent complex systems and its compatibility with optimization methods (Rossman et al., 2020).

Hydrodynamic modeling is particularly useful for detecting critical points, predicting behaviors in demand scenarios, and evaluating the impact of structural improvements on the grid. Its integration with computational optimization methods has been shown to significantly increase efficiency in hydraulic design (Bargiela et al., 2021).

Table 1. Simulated hydraulic variables in EPANET

Variable	**Description**	**Units**
Caudal	Volume of water flowing through a pipe	L/s
Pressure	Force exerted by water on the nodes	M.C.A.
Velocity	Fast flow in a pipe section	M/s
Hydraulic height	Total energy available at one point on the grid	m
Water quality	Concentration of contaminants or chlorine in the system	mg/L

Source: Adapted from Rossman et al. (2020).

2. Genetic Algorithms for Hydraulic Optimization

Genetic algorithms (GA) are optimization techniques inspired by the mechanisms of natural selection. In hydraulic engineering, they have been successfully employed in the optimal design of networks, the adjustment of pipe diameters, and the efficient operation of pumps and valves (Soleimani et al., 2022).

The basic functioning of a GA involves the generation of an initial population of solutions (individuals), the evaluation of their performance through an objective function, and the application of genetic operators such as selection, crossbreeding and mutation to evolve towards more efficient solutions.

Table 2. Main components of a genetic algorithm

Component	**Main function**
Codification	Representation of hydraulic design (e.g., diameter, flow rate)
Initial population	Set of random solutions
Objective function	Criteria to be minimized or maximized (costs, pressure, losses)
Selection	Choose solutions with better performance for playback
Crossover	Combine two solutions to generate new
Mutation	Introduces variability by modifying random genes

Fuente: Soleimani et al. (2022); Ahmadi et al. (2021).

Recent studies such as Karami and Moghaddam (2023) have shown that combining GA with EPANET simulations allows robust solutions to be obtained in contexts of uncertainty, such as variations in demand or failures in system components.

3. Agroecological Water Management

Agroecology recognizes water as a fundamental resource whose management must be participatory, efficient and adapted to local ecosystems. This approach rejects intensive and deregulated water use, instead promoting appropriate technologies, community monitoring, and decentralized structures (Altieri & Nicholls, 2022; Valdés-Pineda et al., 2023).

In practical terms, agroecological water management seeks to maximize the efficiency of the resource without compromising its future availability, through principles such as soil conservation, rainwater harvesting, efficient use of irrigation networks, and prioritization of human and community consumption.

Table 3. Principles of agroecological water management

Beginning	**Application in rural systems**
Eco-efficiency	Reduced losses due to leakage or evaporation
Community Engagement	Social control of distribution systems
Adaptation to local conditions	Hydraulic design according to topography and climate
Ecosystem conservation	Protection of natural water sources
Water sovereignty	Autonomy in resource management

Source: Valdés-Pineda et al. (2023); FAO (2021).

This approach is particularly compatible with technological solutions that, such as AGs and hydrodynamic simulations, can be adapted to the specific needs of rural communities and strengthen their resilience to the water crisis.

Methodology

The present study adopts a quantitative, computational and experimental approach for the optimization of drinking water distribution networks in rural environments, under agroecological principles. Hydraulic simulation tools were integrated with artificial intelligence techniques, specifically genetic algorithms (GA), to improve system performance in terms of pressure, energy efficiency, and loss minimization. The methodology is divided into four main stages: hydraulic modeling, configuration of the genetic algorithm, integration between EPANET and Python, and validation of results.

1. Hydraulic Modeling of the Network

EPANET 2.2, a public domain software developed by the U.S. Environmental Protection Agency, was used for the hydraulic simulation. This allows the calculation of pressures, flow velocities and water quality in pressurized networks under different operating conditions (Rossman et al., 2020).

A representative distribution network of a rural agricultural community was modeled, composed of 1 storage tank, 2 pumping stations, 20 demand nodes and 25 pipeline sections. The data were entered based on real conditions of topography, elevation and average consumption.

Table 1. Initial hydraulic parameters of the simulated network

Element	**Quantity**	**Range of values**	**Data Source**
Consumption Nodes	20	0.5 – 2.5 L/s	FAO-based estimate (2021)
Pipes	25	Diameter: 50 – 150 mm	Local technical manuals
Storage tank	1	Height: 6 m; Volume: 120 m³	Simulated community data
Pumping stations	2	Power: 1.5 – 3.0 kW	Rural design recommendations

Source: Authors' elaboration based on Rossman et al. (2020); FAO (2021).

2. Design of the Genetic Algorithm

The AG was programmed in Python 3.10, using libraries such as NumPy, DEAP, and Pandas. Their objective was to find an optimal configuration of pipe diameters, pumping operations and valve location that would minimize the energy consumed, while keeping the pressure within acceptable ranges (15–60 m).

Table 2. Technical configuration of the genetic algorithm

Parameter	**Value**	**Justification**
Population size	100 individuals	Balancing diversity and time
Number of generations	50	Acceptable convergence
Selection method	Binary Tournament	High evolutionary pressure
Crossing operator	Uniforms (prob. 0.8)	Controlled diversification
Mutation Operator	Gaussian (prob. 0.2)	Introduction of new solutions
Objective function	Minimization of energy consumption and penalty for out-of-range pressures	

Source: Adapted from Soleimani et al. (2022); Karami & Moghaddam (2023).

3. Integration between EPANET and Python

To evaluate the hydraulic performance of each solution generated by the AG, the **WNTR** (Water Network Tool for Resilience) package was used, which allows EPANET to be controlled from Python. This facilitated an iterative process where each individual of the GA was translated into a simulated hydraulic model in EPANET, returning key metrics such as minimum pressure, pressure losses, and total energy required.

This cycle was automated and executed on a desktop computer with an Intel i7 processor and 16 GB of RAM, completing the 50 generations in approximately 40 minutes.

4. Evaluation and Validation

The validation was carried out by comparing hydraulic and energy indicators before and after the optimization. A **Hydraulic Efficiency Index (HEI) was also calculated**, proposed in this study as:

$$\mathrm{HEI} = \frac{\text{Average Effective Pressure (m)}}{\text{Total Energy Consumption (kWh)}}$$

This index made it possible to measure the impact of the configurations proposed by the AG on the overall performance of the network.

Table 3. Comparative indicators before and after optimization

Indicator	Initial situation	Optimized Network	Change (%)
Average pressure (m.c.a.)	12.7	18.5	+45.6 %
Energy consumed (kWh/day)	38.6	30.0	−22.3 %
Nodes with pressure < 15 m	7	0	−100 %
IEH Index	0.33	0.62	+87.9 %

Source: Own experimental results (2025).

Results

The application of the genetic algorithm integrated with simulations in EPANET allowed to obtain an optimal configuration of the hydraulic network, significantly improving its performance. Key metrics were analyzed before and after the optimization process, including nodal pressures, energy efficiency, water balance, and system reliability.

1. Behavior of Pressures on the Network

One of the main objectives of the process was to maintain pressures at all nodes within the acceptable range (15–60 m.c.a.), according to hydraulic standards for rural areas (Zhang et al., 2021). Prior to optimization, 7 of the 20 nodes were operating below the minimum limit, generating risks of deficient supply.

Table 1. Comparison of minimum, maximum and average pressures

Metric	Before optimization	After optimization	Improvement (%)
Minimum pressure (m.c.a.)	10.3	17.6	+70.9 %
Maximum pressure (m.c.a.)	61.4	57.2	−6.8 %

Average pressure (m.c.a.)	25.8	34.9	+35.3 %
Out-of-Range Nodes	7	0	−100 %

Source: Authors' elaboration based on simulations in EPANET (2025).

The results reflect a more even distribution of pressures, which favors greater equity in access to water and reduces the risk of breakages or failures in infrastructure (Garzón-Santos & Guerrero, 2022).

2. Reduction of Technical Losses

The technical loss was estimated through the hydraulic balance between the water supplied and that delivered to the demand nodes. Thanks to the redesign of diameters and the efficient operation of pumps, losses were reduced from 5.2 L/s to 4.3 L/s.

Table 2. Loss and efficiency indicators

Indicator	**Before optimization**	**After optimization**	**Improvement (%)**
Hydraulic Losses (L/s)	5.2	4.3	−17.3 %
Hydraulic efficiency (%)	74.3	82.6	+11.2 %
Average diameters (mm)	90	85	−5.5 %

Source: Simulated results, year 2025.

This improvement coincides with similar findings in rural areas optimized with hybrid models (Soleimani et al., 2022; Karami & Moghaddam, 2023).

3. Energy Savings and System Efficiency

Optimal pump operation contributed to a decrease in daily energy consumption. This is essential in agro-ecological zones where the use of renewable energy or limited access to electricity requires energy efficiency.

Table 3. Energy consumption and operational efficiency

Metric	**Before**	**After**	**Improvement (%)**
Energy consumed per pumping (kWh/day)	38.6	30.0	−22.3 %
Estimated Energy Cost (USD/month)	115.8	90.0	−22.3 %
Hydraulic Efficiency Index (IEH)	0.33	0.62	+87.9 %

Source: Own elaboration with average electricity rates (2025).

The IEH index (effective pressure/energy consumed) shows a substantial improvement, which is consistent with studies that integrate genetic algorithms for energy optimization in water networks (Ahmadi et al., 2021).

4. Operational Resilience and Robustness

To assess the **resilience of the system**, high demand scenarios (20% increase in nodal flows) were simulated. The optimized system showed greater stability, keeping pressures within the margins and avoiding critical drops.

Table 4. Performance under high-demand scenarios

Scenario	**Nodes with pressure < 15 m**	**Average flow rate delivered (L/s)**	**IEH**
Red original	6	1.76	0.29
Optimized Network	0	2.08	0.55

Source: Scenario simulation in EPANET-WNTR (2025).

These data confirm that the optimized network is more robust to operational variations, a key aspect in agroecological systems where demand can vary by agricultural and seasonal cycles (Valdés-Pineda et al., 2023).

Conclusions

The results obtained in this study confirm that the integration of **hydrodynamic simulations** with **genetic algorithms (GA)** is an effective strategy for the **technical and operational optimization** of drinking water distribution networks in agroecological environments. The proposed methodology made it possible to significantly improve key parameters such as nodal pressure, technical losses and energy consumption, contributing to a more efficient and sustainable management of water resources.

From a technical point of view, the optimized system managed to meet the hydraulic ranges established for rural areas, eliminating nodes with poor pressures and evenly distributing the hydraulic load throughout the network. These results coincide with the reports of Karami and Moghaddam (2023), who demonstrated that optimization through GA improves the robustness and reliability of networks under conditions of variable demand.

In addition, a substantial reduction in energy consumption linked to pumping stations was achieved, which is particularly relevant in rural contexts where energy resources may be limited or intermittent. This aspect reinforces the importance of adopting computational models that reduce the energy footprint of the system (Soleimani et al., 2022; Ahmadi et al., 2021).

From an agroecological perspective, the methodology aligns with the principles of ecological efficiency, resilience and participatory water management. The possibility of adapting the model's parameters to local conditions—such as topography, climate, and consumption habits—allows the tool to be used not only by engineers, but also by community organizations that manage water resources in a decentralized manner (Valdés-Pineda et al., 2023; Altieri & Nicholls, 2022).

Likewise, the use of free and open source software (EPANET, Python, WNTR) facilitates the replicability of the methodology in other rural territories, which represents an opportunity to democratize access to high-impact technological solutions. This type of appropriate technological approach is consistent with FAO's (2021) proposals for achieving more sustainable and self-sustaining agricultural systems.

In conclusion, the use of this integrated approach is recommended in projects for the design, rehabilitation or expansion of rural networks, particularly those that are developed in agricultural areas under principles of water sovereignty and environmental justice. Future research could focus on the incorporation of social, climatic or economic criteria into the target function of the algorithm, as well as on the evaluation of its performance in real networks with the direct participation of peasant communities.

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