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Application of a genetic algorithm for the optimal pipe diameter calculation in a potable water distribution network: A case study in Tarapoto, Peru

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Abstract

The genetic algorithm is a search and optimization technique inspired by natural evolution, effectively solving problems with multiple possible solutions. This article presents its application in the optimal calculation of pipe diameters in potable water distribution networks—a complex problem due to its combinatorial nature and the hydraulic constraints involved. A computational solution was developed using a genetic algorithm to identify diameter configurations that minimize the total cost of the pipes while ensuring adequate pressure and velocity conditions. The results, obtained from a simulated network of 34 pipes and 31 nodes, show that the algorithm achieved optimal solutions in a reduced computation time, with a 99.5% improvement in calculation efficiency and an 81% reduction in costs. It is concluded that the genetic algorithm is a powerful tool for the efficient design of hydraulic infrastructure.

Keywords: genetic algorithm, optimization, pipe diameter, water networks, computational engineering

Introduction

The efficient design of potable water distribution networks is a fundamental challenge for cities, especially in contexts of urban growth and sustained demand for water resources. One of the most critical aspects of this design is the selection of pipe diameters, as it directly affects hydraulic variables such as pressure and velocity and economic factors like system installation and operating costs (Pereyra et al., 2017). Inadequate diameters can lead to excessive friction losses or insufficient pressures, compromising service quality.

In the case of the district of Tarapoto, Peru, the issue of water leakage has been particularly evident. According to Flores-García (2019), 612 leaks were reported in 2015, a value that rose to 1,611 in 2016, highlighting a deficient hydraulic analysis of existing networks. These types of failures—classified as physical in origin—are linked to poor pipe sizing, inappropriate pressures, or out-of-range velocities (Albarrán Ulsen et al., 1997). Beyond the technical impact, this problem results in high maintenance costs and significant water loss, which is critical in regions with limited access to potable water.

Despite the availability of calculation methods such as the gradient method, their manual application—using spreadsheets, for example—can take up to 45 hours for a medium-sized network, as reported in a study applied to a network with 34 pipes and 31 nodes (Flores-García, 2019). This operational burden, combined with the complexity of the analysis, limits the use of advanced techniques by professionals in charge of the design and maintenance of hydraulic networks.

In this context, genetic algorithms (GAs) emerge as an alternative for solving combinatorial and multi-objective optimization problems. Inspired by natural evolution, these algorithms generate efficient solutions through selection, crossover, and mutation processes applied to a population of possible solutions (Goldberg, 1989; Moujahid et al., 2008). Their application to hydraulic networks has significantly improved costs, reliability, and compliance with hydraulic constraints (Palacios-Andrade & Benavides-Muñoz, 2009;Quevedo-Porras, 2017).

In response to this problem, the main objective of the present study is to develop and implement a model based on a genetic algorithm to optimize pipe diameter calculations in a potable water distribution network, integrating the gradient method for hydraulic analysis. This proposal aims to enhance the technical performance of water networks and reduce calculation time and operational costs, thereby contributing to the sustainability of potable water services in urban Peruvian contexts.

Literature Review

The design of potable water distribution networks requires a precise combination of technical and hydraulic criteria, such as flow velocity, available pressure at nodes, and required flow rate. Additionally, economic considerations must be incorporated to minimize the total installation cost, making this a combinatorial and multivariable problem by nature (Pereyra et al., 2017). In this type of design, calculating the optimal pipe diameter is one of the most critical decisions, as it directly influences the hydraulic performance of the network and the overall system cost (Ministerio de Vivienda, 2009).

Traditionally, this process has been carried out using iterative methods such as Hardy Cross, Newton-Raphson, or the gradient method, which ensure compliance with the laws of conservation of mass and energy. However, these methods present operational disadvantages when applied manually. For instance, using spreadsheets to apply the gradient method can require over 45 work hours for a medium-sized network (Flores-García, 2019). Furthermore, these methods are inefficient at exploring the complete set of possible combinations of commercially available diameters, which limits the optimization of the design.

To overcome this limitation, various studies have proposed using evolutionary algorithms, particularly genetic algorithms (GAs), as an effective solution to optimization problems in hydraulic networks. GAs are techniques inspired by natural evolution, operating on a population of possible solutions that evolve through selection, crossover, and mutation operators until they converge on optimal or near-optimal solutions (Goldberg, 1989; Abdelmalik & Larrañaga, 2008). Their strength lies in their ability to explore large search spaces with multiple constraints, making them suitable for nonlinear, discrete, or multi-decision problems.

In the specific context of water network design, Sanchez-Cruz (2017) developed a rehabilitation model using a simple genetic algorithm to improve pressure at low-head nodes. The author demonstrated that the GA can identify the pipes requiring replacement and define an optimal order for executing the associated tasks, reducing the system's total cost. Similarly, Palacios-Andrade & Benavides-Muñoz (2009) compared three methods—binary search, I-Pai Wu's method, and GA—having as the main objective cost of the designed network, concluding that GA was able to provide the most robust solutions, albeit with higher computational time. Zhang et al. (2023) compared a parallel genetic algorithm and a parallel particle swarm algorithm for parameter calibration in hydrological simulations. The results showed that, although the PSO converged faster, the GA achieved greater accuracy, obtaining a coefficient of determination (R^2) of 0.83, compared to 0.64 achieved by the PSO, demonstrating the superiority of the genetic algorithm in terms of accuracy and stability. Senavirathna & Walgampaya (2023) applied a genetic algorithm for the optimal design of a water distribution network in the service area of Gurudeniya, Sri Lanka, comparing it with the bee mating algorithm (HBMO). In their conclusions, they highlighted that the GA achieved more competitive solutions in terms of total cost and compliance with hydraulic constraints, consistently outperforming the HBMO in overall efficiency, albeit with a higher iteration requirement. Muranaka et al. (2024) conducted a comparative review of various evolutionary algorithms applied to the optimal design of water distribution networks, including NSGA-II, PSO, and genetic algorithm variants such as MOPS-GA. Their analysis demonstrated that MOPS-GA offered higher-quality solutions with better convergence compared to the other evaluated methods, standing out for its balance between hydraulic performance and economic efficiency.

At the national level, Quevedo-Porras (2017) applied the Strength Pareto Evolutionary Algorithm (SPEA), a multi-objective variant of GA, to design potable water networks in the Viñani-Tacna sector. The author validated that this technique could simultaneously satisfy hydraulic constraints (velocities and pressures) and commercial constraints (availability of pipe diameters) while minimizing costs and increasing system reliability. The study also highlighted that the gradient method was more efficient for solving hydraulic systems due to its matrix-based approach, which reduces computational time compared to traditional methods.

Using information systems to implement genetic algorithms has gained increasing relevance from a computational perspective. According to Laudon & Laudon (2012), an information system integrates technical and human components to collect, process, and distribute data to support strategic decision-making. In line with this, the present study integrates a custom-developed information system—built with Python and PHP—that automates the genetic algorithm alongside the gradient method, enabling users to comprehensively configure, calculate, and evaluate the hydraulic design of a simulated network.

In summary, the literature supports the claim that GA is a robust alternative to traditional methods for optimizing pipe diameters. Their ability to handle multiple variables, constraints, and evaluation criteria makes them powerful tools for the computational design of efficient hydraulic infrastructure, particularly in contexts where cost and computation time are critical.

Theoretical Framework

A potable water distribution network is a system of pressurized pipes designed to transport water from a reservoir to consumption points (Ministerio de Vivienda, 2009). There are two main topologies: open and looped (closed) networks. Looped networks, by forming mesh structures, offer greater reliability and operational redundancy, although they require more complex hydraulic analysis (Pereyra, 2016). Designing such networks poses significant challenges. Among the most critical are the proper selection of pipe diameters, which directly affects pressure and velocity conditions; the need to comply with technical regulations such as OS.050 (Ministerio de Vivienda, 2009), which sets strict limits for pressure (10–50 mca) and velocity (0.3–5 m/s); and the minimization of costs, which demands a balance between hydraulic efficiency and economic feasibility.

Furthermore, poorly dimensioned designs can lead to leaks due to overpressure, sedimentation due to low velocity, or excessive friction losses. This was reported in Tarapoto (Flores-García, 2019), where leakages increased due to hydraulic design issues. However, a real network from that city was not used for computational model validation. Figure 1 shows the Hanio Network, the distribution network used as the validation case. It is a synthetic network developed by Fujiwara and Khang (1990), consisting of 34 pipes, 31 nodes, and one reservoir.

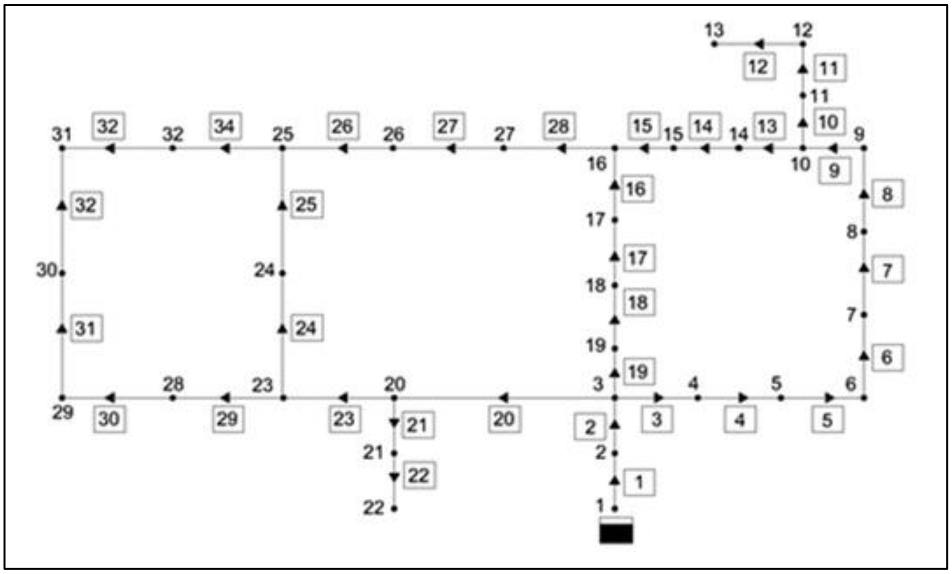

Figure 1. Schematic diagram of the Hanio Network

This network has been widely adopted as a benchmark in international research on the optimal design of water distribution systems.

The selection of this network is based on three key aspects:

- Its closed-loop and intricate mesh structure creates a challenging scenario from a hydraulic analysis perspective.
- The availability of well-documented technical data allows for precise reproduction and comparison of results.
- Its frequent mention in scientific literature facilitates the validation and benchmarking of optimization algorithms under standardized conditions.

To these characteristics, the Hanio network offers a rigorous framework for evaluating the genetic algorithm's ability to identify optimal diameter configurations, ensuring the results are replicable, comparable, and technically meaningful.

Genetic Algorithms and Network Optimization
Given the aforementioned challenges, genetic algorithms (GAs) emerge as an effective alternative for the optimal design of water distribution networks. These algorithms, inspired by the principles of natural evolution (Goldberg, 1989), enable the exploration of solutions that simultaneously satisfy hydraulic and commercial constraints. Applying a GA allows for reduced design times, process automation, and cost minimization while ensuring compliance with technical parameters. In this study, each potential solution is represented by an individual encoded as a binary sequence, where each segment corresponds to the diameter of a pipe. Parents are solutions selected based on their performance to undergo crossover and generate offspring—new and improved solutions.

Figure 2 presents the general schematic of how a genetic algorithm operates. The following describes its main stages:

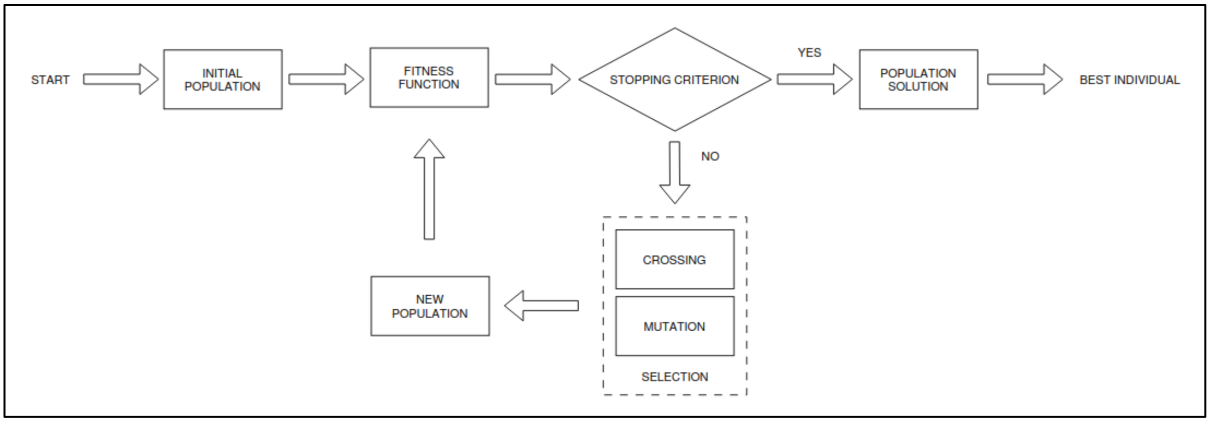

Figure 2. General operating scheme of a genetic algorithm

- **Population initialization.** An initial population of random solutions (individuals) is generated. Each individual represents a possible combination of pipe diameters, usually encoded in a binary or a discrete vector.
- **Fitness function evaluation.** Each individual is evaluated using a fitness function that measures the quality of the solution. In this case, the function considers pipe cost, pressure compliance (10–50 mca), and velocity compliance (0.3–5 m/s).

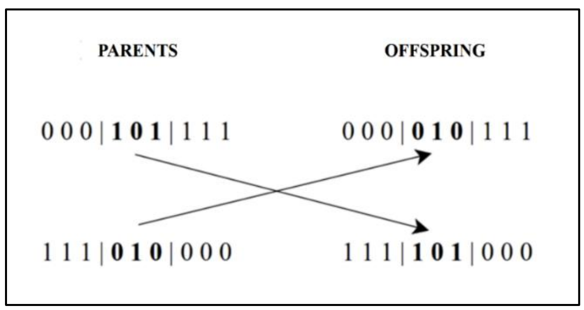

Figure 3. Crossover

- **Crossover.** Segments of the parents' chromosomes are exchanged to generate new individuals (offspring), promoting the combination of beneficial traits. Figure 3 presents how to work the crossover in GA.

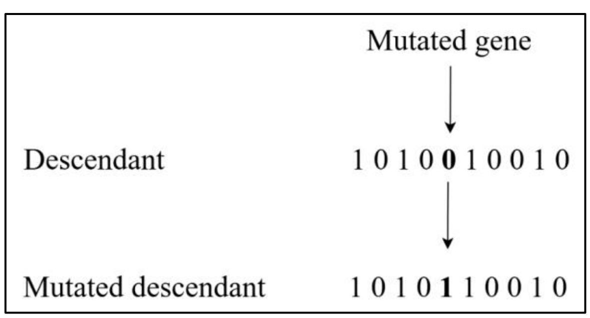

Figure 4. Mutation

- **Mutation.** Some genes (pipe diameters) are randomly altered with a low probability to maintain genetic diversity and prevent stagnation in local optima. Figure 4 presents how to work the crossover in GA.
- **Selection.** The fittest individuals are selected for reproduction, typically using roulette wheel selection, tournament selection, or elitist selection. This ensures that the best solutions have a higher probability of producing offspring.
- **Stopping criterion.** The process ends when the maximum number of generations is reached or when no significant improvements in the solution are observed.

Research Hypothesis

Given that traditional hydraulic design methods, such as spreadsheets, are slow and limited in their ability to explore multiple diameter combinations, a computational approach based on evolutionary algorithms is proposed to improve the process significantly. Specifically, a GA is expected to reduce computation time, lower investment costs in piping, and ensure compliance with technical parameters.

- **H_a (Alternative Hypothesis):** *The genetic algorithm significantly improves the calculation of pipe diameters in a potable water distribution network compared to the manual method.*
- **H_0 (Null Hypothesis):** *The application of the genetic algorithm does not improve the calculation of pipe diameters in a potable water distribution network.*

Gradient Method

The gradient method is an efficient numerical technique for solving hydraulic systems in pressurized networks. It allows for the simultaneous calculation of piezometric heads at nodes and pipe flow rates. Unlike classical iterative methods such as Hardy Cross or Newton-Raphson, this approach employs a matrix formulation based on linear algebra, significantly reducing computation time, especially when working with sparse matrices (Saldarriaga, 1998).

The present study implemented the gradient method in Python and directly integrated it into the custom-developed information system. Its primary function is not optimization but rather the hydraulic evaluation of the solutions proposed by the genetic algorithm. Once a chromosome with a specific diameter configuration is generated, the gradient method calculates the pressures and velocities in each pipe of the network to verify compliance with the technical standards established by OS.050 (Ministerio de Vivienda, 2009).

A candidate solution is considered valid only if the pressures remain between 10 and 50 mca and the velocities between 0.3 and 5 m/s. In noncompliance, a penalty proportional to the deviation is applied, negatively impacting the solution's fitness function. This hybrid approach ensures that the optimal solutions proposed by the algorithm are both cost-efficient and hydraulically feasible. The gradient method is chosen because of its mathematical robustness and compatibility with evolutionary computational processes. It allows for repeated and automated use in each iteration of the genetic algorithm without compromising system performance.

General Formulation

The optimization problem addressed in this study consists of determining the optimal configuration of pipe diameters in a potable water distribution network to minimize the total installation cost while satisfying hydraulic constraints related to pressure and velocity.

Let:

- D_i: diameter selected for pipe i where $i = 1, 2, \ldots, n$
- $C(D_i)$: cost associated with selecting diameter (D_i)
- H_j: pressure at node j, subject to $H_{min} \leq H_j \leq H_{max}$
- V_i: velocity in pipe i, subject to $V_{min} \leq V_i \leq V_{max}$

Objective function:

$$\min \sum_{i=1}^{n} C(D_i)$$

Subject to:

$$H_{min} \leq H_j \leq H_{max}, \quad \forall \text{j} \in \text{nodes}$$

$$V_{min} \leq V_i \leq V_{max}, \quad \forall \text{i} \in \text{pipes}$$

This formulation is implemented within the genetic algorithm, where each individual represents a candidate solution encoded as a vector of diameters. The hydraulic evaluation of each solution is carried out using the gradient method, ensuring that only technically feasible configurations contribute positively to the fitness function.

Problem Encoding

In hydraulic engineering practice, the pipes used in potable water distribution networks are commercially available in a limited set of standardized sizes. Manufacturers predefine these commercial diameters, and their availability constrains the possible configurations of the system. In this study, six standard sizes were considered: 50.8 mm, 76.2 mm, 101.6 mm, 152.4 mm, 203.2 mm, and 254 mm, which represent the only valid options for assigning to each pipe segment in the network.

The effectiveness of a genetic algorithm largely depends on how the problem to be solved is computationally represented. This research aims to find the optimal combination of commercial diameters for each pipe in a potable water distribution network. To achieve this, it was necessary to transform this discrete decision problem into a format manageable through genetic encoding. Each individual in the population represents a candidate solution: a complete configuration of diameters for all the pipes in the network. Given that a discrete set of six commercial diameters is used, a binary encoding of three bits per pipe was employed. Table 1 presents the equivalence between the diameters and their respective binary encoding:

Table 1. Binary coding of available commercial diameters

Diameter (mm)	Inches	Unit Cost (PEN)	Binary code
50.8	2	50.4	000
76.2	3	109.5	001
101.2	4	182	010
152.4	5	392.3	011
203.2	6	668.5	100
254.0	7	1035.1	101

Figure 5 provides an example of a chromosome. In the case study, each individual or solution consists of 34 groups of 3 bits.

001 010 011 101 100 ...

Figure 5. Example of a chromosome

This representation allows the direct application of the genetic algorithm's selection, crossover, and mutation operators, preserving the structural integrity of the solutions and facilitating the exploration of the search space. Moreover, by limiting the encoding to valid values corresponding to available commercial diameters, the generation of physically infeasible solutions is avoided. In conjunction with the gradient method, this encoding facilitates the automated evaluation of each configuration's hydraulic behavior, integrating technical feasibility into the model's fitness function.

Model Variables

The following variables were considered in this study:

- Independent variable (X): Application of the genetic algorithm. This represents using the computational model based on GA as an optimization technique.
- Dependent variable (Y): Pipe diameter calculation in a potable water distribution network. This is measured through four indicators:
    - Y1: Adequate water velocity (m/s)
    - Y2: Adequate water pressure (mca)
    - Y3: Design computation time (minutes)
    - Y4: Total pipe cost (PEN)

Methodology

This study adopts a quantitative, applied, and experimental approach to demonstrating the effectiveness of a genetic algorithm (GA) as an optimization tool for calculating pipe diameters in a potable water distribution network. A computational system was implemented that integrates the algorithm with the hydraulic gradient method, and the results were evaluated using both technical and economic (Flores-García, 2019). The research follows a one-group pretest-posttest experimental design, comparing the performance of the traditional (manual) method with the GA-based computational method. This comparison enables the identification of improvements across four dimensions: hydraulic compliance (pressure and velocity), computation time, and investment cost.

The methodological development was structured in the following stages:

1. **Network modeling:** The Hanio network consisted of 34 pipes, 31 nodes, and a reservoir, with technical data from the study (Fujiwara & Khang, 1990).

2. **Solution encoding**: Each possible solution represents a combination of commercial diameters for each pipe. The genetic algorithm encoded these solutions as chromosomes.

3. **Development of the computational system:** A computational environment that integrates the GA with the gradient method was created. The platform was developed in Python and PHP, using NumPy, Pandas, and PostgreSQL libraries for data storage and analysis.

4. **Fitness function definition:** The function evaluates each individual based on the following criteria:
    a. Pressure between 10 and 50 mca
    b. Velocity between 0.3 and 5 m/s
    c. Total pipe cost

5. **Execution of the genetic algorithm**: Execution parameters were set as follows: initial population (50), number of generations (300), crossover probability (0.7), and mutation probability (0.1).

6. **Results comparison:** The GA results were compared to the design obtained using spreadsheets with the gradient method applied manually.

Table 2. Genetic algorithm configuration parameters

Parameter	Value
Population size	30 individuals
Number of generations	300 generations
Probability of crossing over	0.7
Probability of mutation	0.1
Type of selection	Roulette
Type of crossing	Crossing a point
Type of mutation	Uniform mutation
Fitness function	Cost + Penalty for pressure/speed out of range
Stopping criterion	Maximum number of generations

Data analysis techniques and model validation

Descriptive and comparative techniques were applied. To assess improvements in the dependent variables (calculation time, cost, pressure, and velocity), a mean difference analysis and percentage comparison were performed against the manual method. Additionally, compliance with hydraulic standards was verified according to the Technical Standard OS.050 (Ministerio de Vivienda, 2009).The system was validated through controlled testing on the Hanio network. To ensure the reliability of the results, multiple executions of the algorithm were conducted, observing the stability of the solutions. Furthermore, the outcomes were compared with values reported in previous studies using the same network (Fujiwara & Khang, 1990; Quevedo-Porras, 2017).

Results

Reduction in Calculation Time

The genetic algorithm significantly reduced processing time. While the manual method based on Excel required approximately 45 hours to complete the hydraulic design, the automated model completed the process in just 13.5 minutes, representing a 99.5% improvement in time efficiency (Flores-García, 2019).

Compliance with Hydraulic Conditions

The designs generated by the genetic algorithm fully met the regulatory ranges for pressure (10 to 50 mca) and velocity (0.3 to 5 m/s) in 100% of the evaluated pipes, as established by the OS.050 technical standard (Ministerio de Vivienda, 2009). In contrast, the manual design showed noncompliance in 4 of the 34 pipes, requiring redesign and subsequent adjustments. The Appendix shows the summary of results, comparing the results of the manual method with the GA method. Manual | GA

Cost Optimization

The computational model achieved a diameter configuration that reduced the total investment cost in piping by 81% compared to the initial design. This reduction resulted from the automatic selection of optimal combinations of commercial pipe diameters that balanced cost and hydraulic efficiency.

Table 4: Performance comparison between methods

Indicator	Manual method	Genetic algorithm	Improvement (%)
Calculation time (minutes)	2,700 (≈45 hours)	13.5	99.5%
Hydraulic compliance	88.2%	100%	+11.8%
Total cost (S/.)	16,453.42	3,180.70	81% less

The above results validate the hypothesis proposed in this study by demonstrating that using genetic algorithms enables the identification of hydraulically feasible configurations and significantly optimizes design time and associated costs. These findings are consistent with previous research highlighting the capacity of evolutionary algorithms to solve complex infrastructure problems, as Quevedo-Porras (2017) and *Palacios-Andrade & Benavides-Muñoz (2009)* noted. Furthermore, they reinforce that integrating information systems into engineering design processes can enhance operational efficiency and decision-making *(Laudon & Laudon, 2012)*.

Discussion

This research developed a computational system based on a genetic algorithm to optimize the calculation of pipe diameters in potable water distribution networks. The proposed approach was validated using the Hanio network—a classical closed-loop topology model—and effectively generated hydraulically viable configurations that fully complied with regulatory pressure and velocity ranges (Ministerio de Vivienda, 2009). Compared to the traditional manual method, the model reduced calculation time by 99.5% and total pipe costs by 81%, thereby demonstrating substantial improvements in both technical and economic efficiency (Flores-García, 2019). Beyond contributing to the development of automated solutions in hydraulic engineering, this work provides theoretical support for using evolutionary algorithms as robust tools for solving optimization problems in urban infrastructure (Palacios-Andrade & Benavides-Muñoz, 2009; Quevedo-Porras, 2017). The proposed system offers an accessible alternative for professionals in the field by integrating computation, analysis, and design capabilities into a single platform.

Comparative Perspective with Other Computational Optimization Methods

Although the proposed genetic algorithm model demonstrated substantial improvements over the traditional manual approach, it is important to situate these results within the broader context of contemporary computational optimization techniques. In recent years, alternative metaheuristic methods such as Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), and hybrid algorithms have gained relevance in the domain of water distribution system design due to their ability to handle multi-objective functions and adapt to complex hydraulic constraints (Gheitasi et al., 2021; Bilal et al., 2021).

These methods, particularly PSO and its variants, have shown comparable performance in minimizing pipe costs while enhancing pressure uniformity and resilience. However, several studies emphasize that the effectiveness of each algorithm depends on the specific problem structure, encoding scheme, and the balance between exploration and exploitation in the search process (Sarbu & Popa-Albu, 2023). Furthermore, hybrid models—combining the strengths of evolutionary algorithms and local search heuristics—have been proposed to improve convergence speed and solution quality in highly constrained environments (Taiwo et al., 2025).

Despite these advances, the use of genetic algorithms remains prevalent in engineering applications due to their flexibility, ease of implementation, and robustness across a wide range of optimization scenarios. The present study contributes to this stream by operationalizing a domain-specific implementation of GA integrated with the hydraulic gradient method, yielding significant reductions in computational time and investment costs.

Nevertheless, future studies may enrich comparative analysis by implementing and benchmarking multiple algorithms under standardized network configurations. Such an approach would not only validate the efficiency of GA in relative terms but also provide insights into the algorithmic suitability for specific problem conditions, thereby advancing the methodological rigor in water infrastructure design. Future research is recommended to apply this approach to real-world networks, explore multi-objective variants of the genetic algorithm, and deepen the analysis by incorporating additional criteria such as sustainability, reliability, and maintenance.

Theoretical Implications

From an information systems perspective, the implemented model can be classified as a decision support system (DSS), as it integrates computational algorithms, data processing, and user interaction to support structured decision-making in engineering contexts. In line with the conceptual framework proposed by Laudon & Laudon (2012), the system incorporates technical components (algorithms and hydraulic simulations) and human components (engineer input and decision interpretation), fulfilling the role of a DSS for optimizing infrastructure design. This conceptual positioning strengthens the interdisciplinary nature of the study, bridging the domains of information systems and civil engineering.

This study contributes to advancing knowledge in hydraulic engineering and computational optimization by empirically validating the effectiveness of a hybrid approach that combines genetic algorithms (GAs) with the gradient method. This methodological integration is a robust alternative to traditional methods, particularly for problems characterized by high combinatorial complexity and multiple technical constraints. From a theoretical perspective, the study demonstrates that GAs, by operating on populations of solutions and applying evolutionary operators, can efficiently explore large and discrete search spaces. The gradient method, in turn, ensures that the proposed configurations meet regulatory hydraulic requirements, acting as a technical evaluator within the evolutionary cycle.

It is worth noting that although some theses and research studies in Peru had previously applied genetic algorithms to the hydraulic domain, no similar studies had been reported at the regional level. Therefore, this study represents one of the first formal applications of this approach in the San Martín region, contributing local evidence of its utility and relevance. This contextual contribution expands the possibilities for scientific and technical application in regions with operational and budgetary conditions that differ from those of the capital. The proposed methodological framework can also be extended to other multivariable problems in urban infrastructure, such as the design of sewer systems, stormwater drainage, or electrical networks—thereby strengthening the role of evolutionary algorithms in civil engineering.

Practical Implications

The combined use of the genetic algorithm and the gradient method enables an efficient response to one of the most common challenges in hydraulic engineering: the optimal selection of pipe diameters in potable water distribution networks. This approach optimizes the design from a technical perspective and delivers significant operational benefits. One of the main strengths of this study lies in its experimental nature, as it directly compares the performance of the traditional manual method—based on spreadsheets—with the results obtained using the automated genetic algorithm. This comparison revealed quantifiable improvements: a reduction of over 99% in computation time and an 81% decrease in total pipe costs while maintaining compliance with regulatory standards for pressure and velocity.

By integrating the gradient method into each iteration of the evolutionary process, the model ensures a rapid and accurate evaluation of the hydraulic behavior of the generated solutions. This interaction between technical assessment and evolutionary optimization makes analyzing thousands of configurations in significantly less time feasible, representing a tangible improvement over conventional procedures. Additionally, the model can be adapted to various network topologies and operational conditions, making it a replicable alternative in other regions of the country. This is especially relevant in areas such as San Martín, where low-cost, high-impact technical solutions directly applicable to the local context are in high demand.

Finally, in line with the recommendations of the original study, the following suggestions are proposed for future implementations: (1) Evaluate the model on real networks of varying scale, including those with variable boundary conditions and local empirical data; (2) Explore multi-objective variants of the genetic algorithm that consider not only cost and regulatory compliance, but also criteria such as sustainability, reliability, or ease of maintenance (3) Integrate energy and operational parameters to expand the analysis toward comprehensive hydraulic design (including not just construction, but also operational phases), (4) Promote the training of professionals in computational optimization techniques applied to engineering, in order to facilitate the adoption of these approaches in both regional professional practice and academia.

Limitations and Future Research

This study acknowledges certain limitations to provide a more comprehensive interpretation of the findings. First, the optimization model was validated using the Hanio network—a synthetic benchmark widely used in the literature—rather than a real-world potable water distribution system. While this ensures the replicability and comparability of the results, it does not capture the full complexity of operational, structural, or environmental factors present in real urban networks.

Second, the model focused exclusively on single-objective optimization, minimizing pipe cost while ensuring compliance with regulatory standards. However, other relevant criteria—such as system resilience, energy consumption, maintenance costs, or environmental sustainability—were not included. Future studies may explore multi-objective extensions of the algorithm to address these additional dimensions.

Third, although the genetic algorithm demonstrated significant improvements compared to the manual method, no comparative analysis was conducted with other computational approaches such as Particle Swarm Optimization, Ant Colony Optimization, or hybrid metaheuristics. Comparative benchmarking with alternative algorithms would strengthen the assessment of the model's relative performance.

Finally, the model parameters (e.g., population size, mutation rate) were selected based on preliminary experimentation and heuristic tuning. While the results were stable across multiple runs, a more systematic parameter calibration using design of experiments or sensitivity analysis could further enhance the robustness and generalizability of the approach.

Accordingly, future research should aim to (1) test the proposed system on real-world networks with variable demand and topologies, (2) incorporate additional optimization criteria for a multi-objective framework, (3) compare the performance of the genetic algorithm against alternative heuristics, and (4) implement automated parameter tuning to optimize algorithm performance across different scenarios.

References

Bilal, Pant, M., & Snasel, V. (2021). Design Optimization of Water Distribution Networks through a Novel Differential Evolution. *IEEE Access*, *9*, 16133–16151. https://doi.org/10.1109/ACCESS.2021.3052032

Flores-García, I. (2019). *Aplicación del Algoritmo Genético para el Cálculo del Diámetro de las Tuberías de una Red de Distribución de Agua Potable en el Distrito de Tarapoto 2018* [Universidad Nacional de San Martín]. https://repositorio.unsm.edu.pe/backend/api/core/bitstreams/b564b222-d9af-4da9-b666-3c311158e8f5/content

Fujiwara, O., & Khang, D. B. (1990). A two-phase decomposition method for optimal design of looped water distribution networks. *Water Resources Research*, *26*(4), 539–549. https://doi.org/10.1029/WR026i004p00539

Gheitasi, M., Kaboli, H. S., & Keramat, A. (2021). Multi-objective optimization of water distribution system: a hybrid evolutionary algorithm. *Journal of Applied Water Engineering and Research*, *9*(3), 203–215. https://doi.org/10.1080/23249676.2021.1884613

Goldberg, D. E. (1989). *Genetic Algorithms in Search, Optimization, and Machine Learning*. Addison-Wesley.

Laudon, K. C., & Laudon, J. P. (2012). *Sistemas de Información Gerencial, 12va Edición* (12th ed.). Pearson Educación. https://juanantonioleonlopez.wordpress.com/wp-content/uploads/2017/08/sistemas-de-informacic3b3n-gerencial-12va-edicic3b3n-kenneth-c-laudon.pdf

Ministerio de Vivienda, C. y S. (2009). OS.050: Redes de distribución de agua para consumo humano. In *Reglamento Nacional de Edificaciones*. Ministerio de Vivienda, Construcción y Saneamiento del Perú. https://cdn.www.gob.pe/uploads/document/file/2686380/OS.050%20Redes%20de%20distribuci%C3%B3n%20de%20agua%20para%20consumo%20humano%20DS%20N%C2%B0%20010-2009.pdf

Moujahid, A., Inza, I., & Larrañaga, P. (2008). *Algoritmos Genéticos*. http://www.sc.ehu.es/ccwbayes/docencia/mmcc/docs/t2geneticos

Muranaka, R. S., Rangel, J. S., Marotta, M. A., & Soares, A. K. (2024). Comparison of evolutionary algorithms applied to optimal design of water distribution networks. *RBRH*, *29*. https://doi.org/10.1590/2318-0331.292420240055

Palacios-Andrade, L. O., & Benavides-Muñoz, H. (2009). *Diseño Económico de Redes de Distribución de Agua a Presión por el Método del Algoritmo Genético*.

Pereyra, G., Pandolfi, D., & Villagra, A. (2017). Diseño y optimización de redes de distribución de agua utilizando algoritmos genéticos. *Informes Científicos Técnicos - UNPA*, *9*(1), 37–63. https://doi.org/10.22305/ict-unpa.v9i1.236

Quevedo-Porras, V. Z. (2017). *Aplicación del Algoritmo genético Multiobjetivo Strength Pareto Evolutionary Algorithm y su Efectividad en el Diseño de Redes de Agua Potable. Caso: Sector Viñanitacna*. Universidad Privada de Tacna.

Saldarriaga, J. G. (1998). *Hidráulica de tuberías*. McGraw-Hill Interamericana.

Sanchez-Cruz, J. A. (2017). *Un Método para Rehabilitar Redes de Distribución de Agua Potable Basado en un Algoritmo Genético*. Universidad Nacional Autónoma de México.

Sarbu, I., & Popa-Albu, S. (2023). Optimization of urban water distribution networks using heuristic methods: an overview. *Water International*, *48*(1), 120–148. https://doi.org/10.1080/02508060.2022.2127611

Senavirathna, K. H. M. R. N., & Walgampaya, C. K. (2023). *Genetic Algorithm Based Combinatorial Optimization for the Optimal Design of Water Distribution Network of Gurudeniya Service Zone, Sri Lanka*.

Taiwo, R., Zayed, T., Bakhtawar, B., & Adey, B. T. (2025). Explainable deep learning models for predicting water pipe failures. *Journal of Environmental Management*, *379*, 124738. https://doi.org/10.1016/j.jenvman.2025.124738

Zhang, X., Li, Y., & Chu, G. (2023). Comparison of Parallel Genetic Algorithm and Particle Swarm Optimization for Parameter Calibration in Hydrological Simulation. *Data Intelligence*, *5*(4), 904–922. https://doi.org/10.1162/dint_a_00221

Appendix: Summary of the result (Manual | AG)

N° Pipe	Diameter(mm)	Speed	Pressure	Cost (S/)
T01	254 | 50.8	15.889 | 6.71	45.626 | 40.53	103510 | 5040
T02	203.2 | 76.2	3.439 | 8.93	51.611 | 19.88	902475 | 147825
T03	152.4 | 50.8	7 | 8.53	55.75 | 22.65	353070 | 45360
T04	203.2 | 50.8	6.674 | 7.29	53.217 | 24.36	768775 | 57960
T05	254 | 152.4	8.836 | 3.12	49.407 | 26.62	1500895 | 568835
T06	50.8 | 76.2	9.207 | 7.65	54.953 | 30.98	22680 | 49275
T07	76.2 | 50.8	3.966 | 7.85	33.386 | 27.69	93075 | 42840
T08	76.2 | 76.2	11.985 | 4.6	26.418 | 13.75	93075 | 93075
T09	152.4 | 50.8	7.397 | 4.8	31.66 | 26.34	313840 | 40320
T10	254 | 76.2	3.49 | 5.98	57.886 | 11.32	983345 | 104025
T11	203.2 | 76.2	2.561 | 8.86	17.538 | 46.6	802200 | 131400
T12	76.2 | 50.8	11.165 | 7.82	57.434 | 46.84	383250 | 176400
T13	152.4 | 76.2	6.953 | 3.29	9.229 | 40.22	313840 | 87600
T14	152.4 | 50.8	15.651 | 6.85	49.642 | 24.22	196150 | 25200
T15	50.8 | 50.8	14.435 | 4.59	58.937 | 39.25	27720 | 27720
T16	254 | 50.8	4.716 | 6.53	24.506 | 10.38	2825823 | 137592
T17	152.4 | 50.8	4.352 | 6.14	32.901 | 18.82	686525 | 88200
T18	254 | 50.8	2.348 | 6.6	39.614 | 45.2	828080 | 40320
T19	76.2 | 101.6	10.187 | 8.68	26.58 | 23.28	43800 | 72800
T20	76.2 | 76.2	9.73 | 4.72	24.744 | 21.3	240900 | 240900
T21	203.2 | 50.8	14.353 | 3.32	51.373 | 14.58	1002750 | 75600
T22	101.6 | 101.6	14.983 | 6.38	14.608 | 34.73	91000 | 91000
T23	76.2 | 50.8	12.66 | 5.25	43.544 | 22.92	290175 | 133560
T24	1035.1 | 76.2	4.822 | 6.3	11.875 | 32.59	1273173 | 134685
T25	392.3 | 50.8	1.53 | 6.26	35.282 | 46.21	509990 | 65520
T26	1035.1 | 101.6	1.3 | 5.35	10.817 | 39.69	879835 | 154700
T27	101.6 | 101.6	15.446 | 4.41	12.411 | 35.34	54600 | 54600
T28	254 | 101.6	9.928 | 6.25	39.772 | 15.6	776325 | 136500
T29	101.6 | 50.8	10.843 | 8.76	34.809 | 39.33	273000 | 75600
T30	101.6 | 50.8	13.397 | 4.75	14.127 | 33.33	364000 | 100800
T31	152.4 | 50.8	3.641 | 8.97	16.376 | 10.79	627680 | 80640
T32	152.4 | 152.4	12.12 | 6.14	5.487 | 38.35	58845 | 58845
T33	254 | 76.2	4.663 | 8.47	59.767 | 34.81	890186 | 94170
T34	76.2 | 76.2	14.781 | 6.97	19.817 | 42.2	104025 | 104025