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Hydraulic Design of Irrigation Networks with Optimization Methods

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Abstract – Agricultural sustainability is an issue of great concern worldwide, for the period between 2005 and 2050 will require a significant increase of 60% to 110% in food production. There is an urgent demand for efficient irrigation systems that meet design specifications. The network must guarantee adequate delivery of demand to users and sufficient pressure for the correct operation of the network's emitters. On the other hand, the implementation of an irrigation system requires a large economic investment, in this study optimization algorithms are implemented that will allow mitigating the design costs. This research is developed in a community of irrigators in a local area. The research begins with the agronomic design, then using the Clément model, the circulating flows of the irrigation network operating on demand are determined. The methods for the hydraulic design of the irrigation network were the conventional method, the Granados method, and the genetic algorithms. The results indicate that it is possible to obtain a significant investment cost reduction in piping, which varies considering one or the other method.

***Keywords*:** irrigation systems, demand, optimal algorithms, hydraulic design.

1. Introduction

Global population growth has led to increased demand for food and water resources, resulting in a significant increase in food production between 2005 and 2050 [1]. Latin America is no exception; the distribution, availability and seasonality of water resources are expected to be affected. In addition, the population is demanding a greater quantity and quality of products for consumption [2]. It is a priority to have efficient irrigation systems that allow the optimization of natural resources and improve the economy of families that depend on the agricultural sector [3].

One of the operating modes is "on demand" irrigation, which consists of withdrawing water from the network according to the needs of each hydrant during the actual irrigation day. This operation of the network is adapted to the specific needs of each moment, allowing the flow rates to vary throughout the day and the season [4],[5]. In Ecuador, about two-thirds of the economically active population works in agriculture [6] and their production is directly linked to the availability of irrigation systems. However, to achieve uniform water distribution and meet farmers' needs, these systems require high capital investment [7].

It is important to look for alternatives to obtain economic designs, in this context, irrigation systems have undergone a remarkable evolution, using different optimization models (algorithms, indicators, variables). Optimization algorithms focus on maximizing crop yield, minimizing water consumption, or optimizing hydraulic design costs [8].

Exact optimization methods are characterized by guaranteeing that the optimal solution is obtained in an exact manner, without approximations, while heuristic methods try to find acceptable, though not necessarily optimal, solutions in a reasonable time [9]. One of the most accurate methods for performing optimal hydraulic design, characterized by its ability to solve multi-stage optimization problems [10]. This type of programming provides a suitable optimization language to address the specific challenges that arise in irrigation networks, considering various interactions between variables such as: irrigation demand and operational constraints [11].

On the other hand, advances in technology make it easier to implement new techniques and designs, such as the use of intelligent algorithms [5]. These algorithms base their methodology on evolutionary processes, focusing on elements such as population and iteration with their biological operators [12]. However, despite these technological advances in agriculture, the optimization of resources continues to be a complex challenge [4].

In this context, the objective of this research is to perform the hydraulic design of an irrigation network operating on demand that integrates conventional and optimization methodologies. Its main purpose is to evaluate the cost of hydraulic design of the study network using the Hydraulic Gradient Methodology (HGM), the optimization methods of Granados (GM) and Genetic Algorithm Methodology (GAM).

2. Materials and methods

This research was conducted in the irrigation community of San José de Ceibopamba, Figure 1. The geographical coordinates of this area are South latitude: 4°11'34" to 4°12' 09" and western longitude: 79° 17'57.6" to 79° 17'34.8" [13].

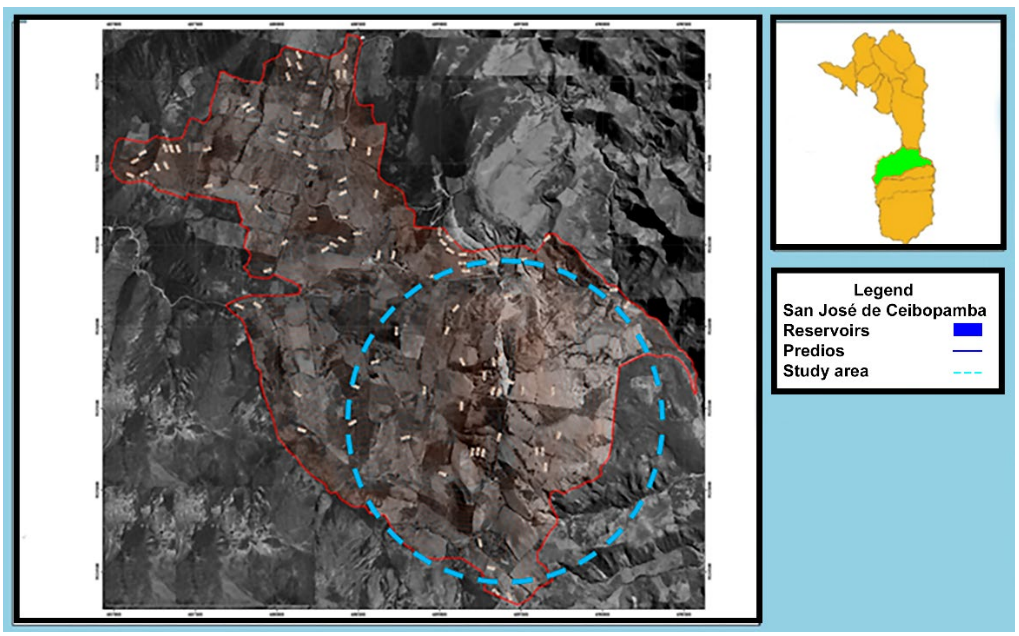

Fig. 1: Study area: San José de Ceibopamba irrigation system.

2.1. Irrigation network infrastructure

The San José de Ceibopamba Irrigation System currently consists of a dam-type reservoir in the La Chonta Stream and a PVC pipe system in all sections of the network. The entire irrigation system operates by gravity, with four branches that make up the irrigation system parcel, will operate 24 hours a day, in days of 12 hours of delivery and 12 hours for water accumulation [13], The irrigation system is on demand and uses the Senninger 2023 HD-3/4"M rotor sprinkler with diffuser. Its flow rate is 4.19 (GPM) with a working pressure of 25 (PSI). The network design specification for flow velocity is in the range of 0.5 m/s to 2.5 m/s, and the set point pressure of the known demand nodes is 20 mwc.

2.2. Network topology

For this study, the branch labeled R1 was selected (figure 2). This network supplies 186 hydrants distributed over an area of 100.93 hectares of irrigated land. With a flow of 327.013 l/s, it meets the water needs of a total of 125 users.

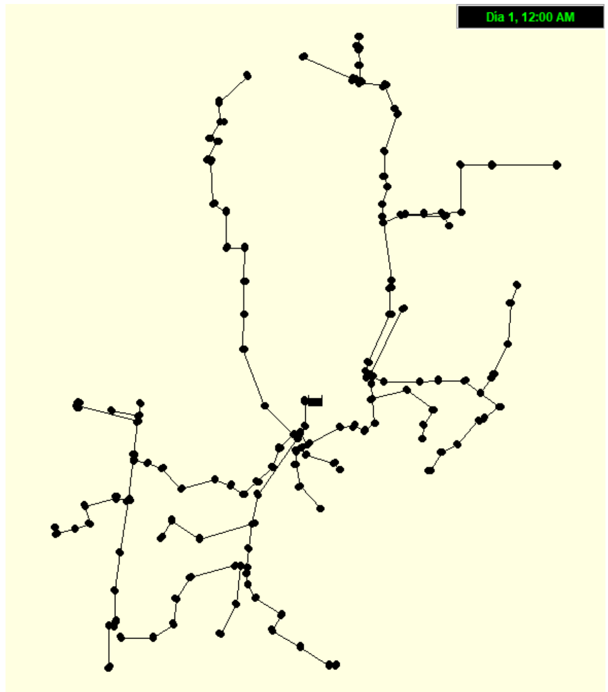

Fig. 2: Topology of branch R1 of the San José de Ceibopamba irrigation system.

Table 1 shows the initial data for the hydraulic design of the irrigation network.

Table 1: Initial data for hydraulic design of network R1.

Data	Value	Units
Number of hours per day (t)	24	hours
Freedom Degrees (FD)	4	
Network performance (NP)	0.67	
Total length of network (Lacum)	9529.35	m
Total area of branch irrigation (S)	100.93	ha
Number of branch hydrants	186	
Guarantee of supply (GS)	90	%
Quality of operation (U)	1.285	
Number of sections in the network	144	
Reservoir elevation	1798.50	m
Minimum pressure (Pmin)	20	mwc
Effective irrigation day (ERD)	16	hours

The following nomenclature was adopted to identify the hydraulic design methods for the network under study:

- ✓ Method 1: Hydraulic Gradient Method (HGM)
- ✓ Method 2: Granados Method (GM)
- ✓ Method 3: Genetic Algorithm Method (GAM)

Figure 3 shows in detail the methodology used in the research.

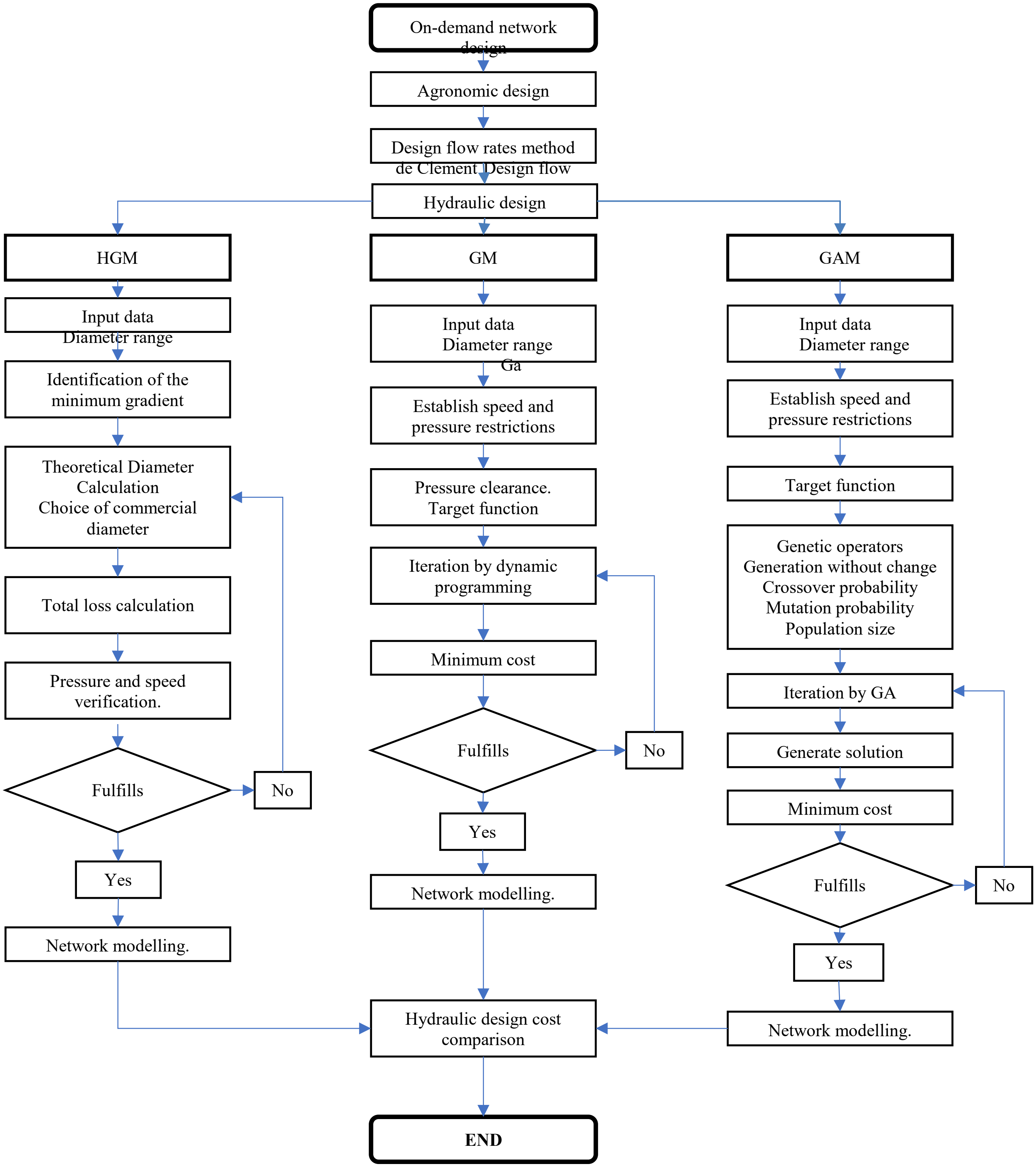

Fig. 3: Flowchart with research methodology

2.3. Problem Statement

The problem can be expressed as a standard minimization problem with restrictions. The function to be minimized (objective function) in this study is expressed in the equation (1):

$$C_T = \sum_{j=1}^{NL} C_j(D_j) \cdot L_j \tag{1}$$

Where C_T symbolizes the total pipe cost expressed in monetary units; $C_j(D_j)$ is the unit cost per linear meter for each diameter.; L_j is the length of pipe j expressed in meters, and NL is the number of pipes that make up the network.

The objective function must satisfy the following restrictions:

$$v_j \geq 0{,}5\ m/s \quad j = 1, \dots, NL \tag{2}$$
$$v_j \leq 2{,}5\ m/s \quad j = 1, \dots, NL \tag{3}$$
$$p_i \geq 20\ m \quad i = 1, \dots, NH \tag{4}$$

In equations (2) and (3), v_j is the velocity in pipe j. In equation (4), p_i is the pressure in node i representing a hydrant and NH is the total number of hydrants.

2.4. Optimization methods

- ✓ Method 1: Hydraulic gradient method (HGM): Identifies the minimum hydraulic gradient of the lines of the network under study (R1), this methodology is conventional.
- ✓ Method 2: Granados Method (GM): Uses dynamic programming for the determination of the diameters in the mesh sections. The variables of pressure slack and gradient of change are considered in dynamic programming. This algorithm decomposes the initial solution into more manageable and specific subnetworks and establishes a relationship between them. The combination of the optimal solutions obtained from these smaller components leads to a more efficient global solution.[14].
- ✓ Method 3: Genetic Algorithm Method (GAM): The methodology starts with an initial population that is decoded into a set of chromosomes. Then, evolutionary processes are applied to this set, simulating the evolution of species that replace genes in the initial population, thus generating a new set of chromosomes as a solution. In this case, an integer coding approach was used as explained in [15].

3. Results and discussion

The results obtained by applying the above methodology are mentioned:

- ✓ The calculated continuous fictitious flow rate is 0.54 l/s/ha.
- ✓ Figure 4 shows the design results in graphs, where the variation in the distribution of the diameter sizes for each design method is observed, which is the origin of the disparity in the economic cost, especially in the results obtained by the HGM compared to the GM and GAM methods. The distribution of diameters obtained in each method is also reflected, so it is concluded that the HGM uses larger pipe sections compared to the MG and GAM.

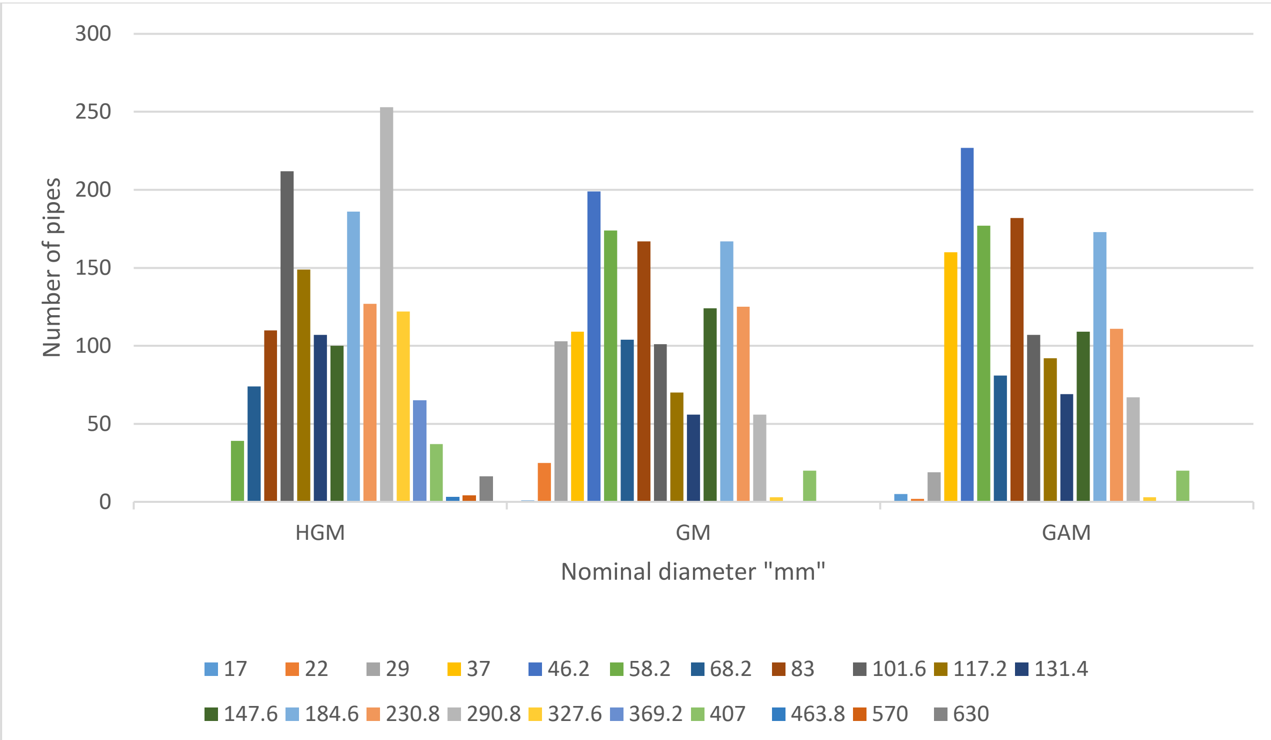

Fig. 4: Distribution of diameters for each hydraulic design method

Figure 5 shows the variation in cost resulting from the hydraulic design of network R1, highlighting that the percentage of savings is 24% and 26% with the use of GM and GAM respectively compared to HGM.
It can be concluded that the optimization methods achieved lower costs in their hydraulic design compared to the conventional design method used.

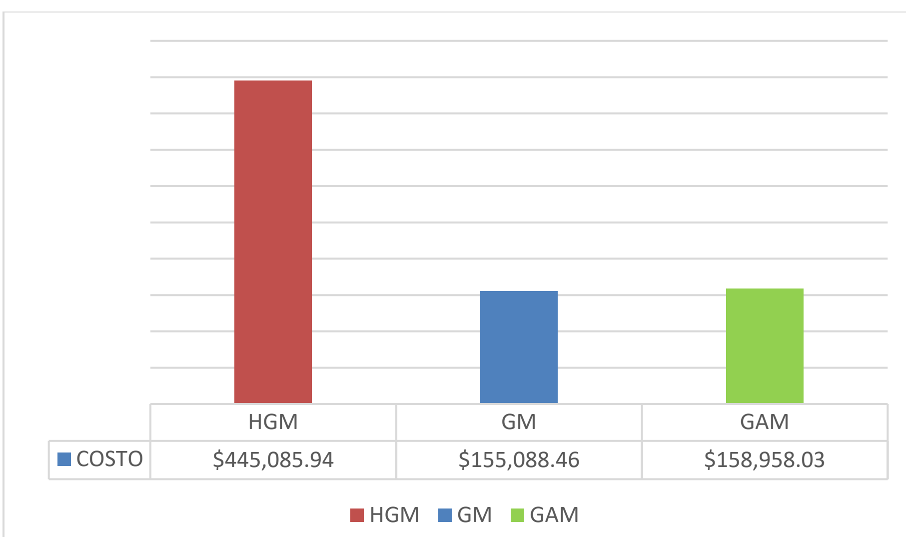

Fig. 5: Cost of hydraulic design of network R1, with the three methods used

4. Conclusions

The resulting hydraulic design of the R1 study network using the hydraulic gradient method, the Granados method, and and the genetic algorithm method satisfies the flow velocity restrictions and the set point pressure specified in the design. The reduction in hydraulic design cost of the R1 study network using the Granados (GM) and Genetic Algorithm (GAM) optimization methods is 24% and 26%, respectively, compared to the conventional Hydraulic Gradient (HGM) method. The The design result with the Granados and Genetic Algorithm methods shows an economic difference of 1.07%, which reflects that the use of Genetic Algorithms in hydraulic design results in lower costs compared to the Granados method.

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