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Flow rate redistribution: Methodology and case study in an irrigation system

Redistribución de caudales: Metodología y caso de estudio en un sistema de riego

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Technological innovation: Methodology for redistributing flow rates in open-network irrigation systems.

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Resumen

El estado de Zacatecas, ubicado en la república mexicana, es una región principalmente agrícola que ha sufrido sequías severas en los últimos años, afectando la producción local y resaltando la necesidad de un uso eficiente del agua. En respuesta, la adopción y optimización de sistemas de riego se han vuelto esenciales para apoyar la agricultura y minimizar la escasez de agua. Este artículo presenta una metodología novedosa para redistribuir los caudales en sistemas de riego organizados en red abierta mediante el ajuste de los diámetros de los orificios de salida. Este trabajo emplea principios de mecánica de fluidos, específicamente en el flujo interno y viscoso, para calcular con precisión los tamaños de orificios necesarios que permitan una distribución uniforme y efectiva del agua en toda la red de riego. La metodología se aplica a un caso de estudio en una red abierta con 14 salidas, donde el objetivo fue lograr un flujo homogéneo de agua para satisfacer las necesidades de riego de cultivos al tiempo que se conserva el agua.

Utilizando ecuaciones para la pérdida de carga y la determinación de caudales, junto con cálculos iterativos, el estudio permitió obtener los diámetros de los orificios de salida requeridos para obtener una caudal uniforme en los extremos del sistema de riego. Además, la metodología ofrece flexibilidad para adaptarse a diferentes configuraciones de red y presiones variables, lo que la hace aplicable a una amplia variedad de sistemas de riego agrícola. Los hallazgos de este estudio son relevantes para investigadores y profesionales interesados en mejorar la gestión del agua en áreas agrícolas, especialmente en regiones propensas a la escasez de agua. Este enfoque también tiene potencial para aplicaciones más amplias en sistemas hidráulicos donde se desea una distribución uniforme del flujo.

Palabras clave: Sistema de riego, Sistemas abiertos de tuberías, Mecánica de fluidos aplicada.

Abstract

The state of Zacatecas, located in the Mexican Republic, is a primarily agricultural region that has experienced severe droughts in recent years, affecting local farming and highlighting the need for efficient water use. In response, the adoption and optimization of irrigation systems have become essential for supporting agriculture and minimizing water scarcity. This article presents a novel methodology for redistributing flow rates in open-channel irrigation systems by adjusting the diameters of the outlet orifices. The proposed methodology leverages principles from fluid mechanics, particularly internal and viscous flow, to accurately calculate the necessary orifice sizes that allow for a uniform and effective distribution of water across the entire irrigation network. The methodology is applied to a case study involving an open network with 14 outlets, where the goal was to achieve a homogeneous water flow to meet crop irrigation needs while conserving water. Using equations for head loss and flow rate determination, along with iterative calculations for orifice sizing, the study demonstrates how water flow redistribution can be effectively implemented in irrigation systems with fixed pipe diameters. Additionally, the methodology offers flexibility to adapt to different network configurations and variable pressures, making it applicable to a wide range of agricultural irrigation systems. The findings of this study are relevant to researchers and practitioners aiming to enhance water management in agricultural areas, particularly in regions prone to water scarcity. This approach also has potential for broader applications in hydraulic systems where uniform flow distribution is desired.

Keywords: Irrigation System, Open network system, Applied fluid mechanics.

1. INTRODUCTION

Agriculture is one of the most critical activities for human survival and also one of the most vulnerable to climate change [1,2,13]. Irrigation systems play a crucial role in mitigating this vulnerability by reducing dependence on rainfall. Researchers worldwide are actively exploring methods to optimize the use of water resources in irrigation. For instance, Su Ki Ooi et al. [3] developed a tool for designing decentralized controls for irrigation channels. Mareels et al. [4] present a framework for automated irrigation systems using control theory principles, enabling on-demand water delivery and improving overall distribution efficiency.

Given the complexity of hydraulic calculations, personal computers and other technologies are essential tools in this field [5], [6]. This study focuses on achieving uniform flowrate distribution in open-network irrigation systems with fixed pipe diameters. While various methods exist for designing pipelines [7], [8], this work addresses the specific challenge of non-adjustable diameters. Here, using orifices (holes) of varying sizes at each system outlet to achieve uniform flow rates is proposed. Intuitively, the size of the orifice should increase with distance from the water source.

This article presents a methodology for calculating orifice sizes to achieve uniform flow across all outlets. A case study demonstrates the application of the proposed methodology.

2. METHODOLOGY

The objective of this work is to determine the size of the orifices that will allow the achievement of the desired flow rates at each outlet of an irrigation system, regardless of whether the flow rates need to be uniform or not. With this in mind, the proposed methodology takes the desired flow rates at each outlet of the system as input data. Therefore, the first step is to apply the continuity equation at each node or branch of the system in order to determine the flow through each section of pipeline.

With the flow rates for the pipelines determined, the head loss can then be calculated using Darcy-Weisbach's equation (1).

$$h_{LP} = f\,\frac{L}{D}\frac{V^2}{2g} \qquad \textbf{(Eq. 1)}$$

Where:
f = Frictional resistance (dimensionless).
L = Length of the pipe (m).
V = Velocity of incompressible fluid (m/s).
D = Pipeline diameter (m).
g = Acceleration due to gravity (g = 9.8 m/s^2).
h_{LP} = Head loss pipeline (m).

Whenever the flow velocity changes direction or magnitude in a conduit (e.g., at fittings, bends, and other appurtenances), additional turbulence is induced. The energy associated with this turbulence is eventually dissipated into heat and produces a minor head loss, also known as local (or form) loss. The local (minor) loss associated with a particular fitting can be evaluated by Equation 2.

$$h_{LS} = K\left(\frac{V^2}{2g}\right) \qquad \textbf{(Eq. 2)}$$

Where:
h_{LS} = Head loss pipeline due to turbulence (m).
K = Loss coefficient for the particular fitting involved (dimensionless).

Once the frictional head losses are known, the total piezometric head at each outlet of the irrigation system can be determined by subtracting the frictional head loss from the piezometric head of the preceding node. To illustrate this, the diagram in Figure 1 is provided.

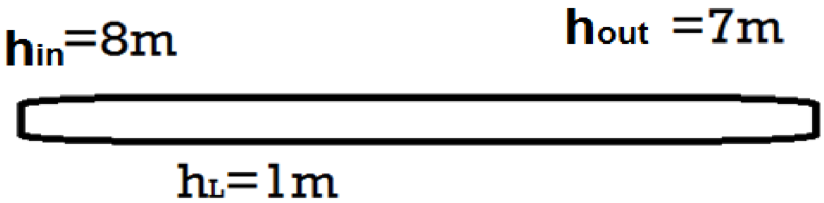

Figure 1. Head reduction due to friction.

This way, the total head at each node of the irrigation system can be calculated. The total head at a node is determined by subtracting the head loss (h_L) between it and the previous node. This process is repeated iteratively until the total head is calculated for all outlets. The flow velocity at the outlet is directly related to the available piezometric head; a higher piezometric head results in a greater fluid velocity. The outlet flow velocity is then determined by the available total head at that point, as described by Torricelli's equation (3), which relates the fluid velocity to the square root of the head.

$$V_s = \sqrt{2gh} \qquad \textbf{(Eq. 3)}$$

Where:
V_S = Speed of outflow (m/s).
h = Available head (m).

Finally, once the flow rates and velocities at the outlet are known, the outlet hole diameter can be calculated using the well-known equation V = Q / A. Alternatively, this can be achieved by applying the continuity equation between the flow through the pipe and the flow at the outlet hole, and solving for the outlet hole diameter. The diameter of each outlet's orifice is calculated using Equation (4). This calculation relates the orifice diameter to the flow velocity in the pipeline and the pipeline diameter.

$$D_0 = \sqrt{\frac{V_T}{V_s} D_p^2} \qquad \textbf{(Eq. 4)}$$

Where:
D_0 = Diameter of outlet's orifice (m).
D_p = Pipeline's diameter (m).
V_T = Outflow speed through outlet hole (m/s).
V_s = Fluid velocity through main pipe.

This process is repeated at each outlet hole, thus completing the algorithm for calculating the diameters. In this work, the equations resulting from the described formulations are implemented using the Engineering Equation Solver (EES) software, which, as its name suggests, is designed to solve engineering equations.

Figure 2 illustrates the algorithm used to calculate the diameters of the irrigation system's exit orifices.

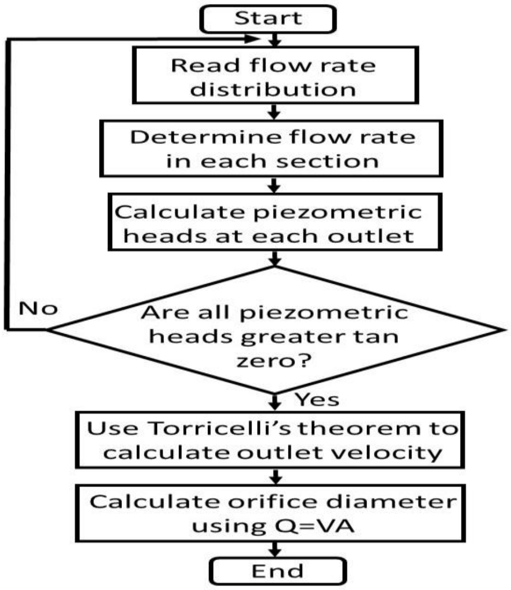

Figure 2. Flowchart of the proposed methodology.

If the flow rates aren't predefined, the algorithm can be used by setting a target flow rate based on empirical knowledge or experience. The target flow rate can be gradually increased in small increments, typically by tenths of a liter per minute, and the maximum value will be the highest one that ensures no zero or negative flow values at any outlet.

The dimensionless friction factor (f) can be estimated for a pipe having surface roughness $\in$ (m) using the Colebrook-White equation:

$$\frac{1}{f^{1/2}} = -2.0\log\left(\frac{\in / D_p}{3.7} + \frac{2.51}{\text{Re}\, f^{1/2}}\right) \quad for\, \text{Re} \geq 2100$$

(Eq. 5)

$$\frac{64}{\text{Re}} \quad for \quad \text{Re} < 2100$$

(Eq. 6)

Where:
D_p = Pipeline diameter.
Re = Reynolds number.

In Equation (5), the friction factor f appears on both sides of the equation, and there is no explicit solution for it. The calculation of this factor requires an iterative procedure. The EES software provides a built-in function that can be easily called within the code to perform this calculation.

The commonly accepted criteria for Newtonian fluids in laminar flow is that the Reynolds number is less than 2,100, while turbulent flow is characterized by Re exceeding 4,000. However, Freeman [9] suggests a transitional region between 1,225 and 3,000, and Merkle [10] indicates that laminar flow can only re-establish if Re falls below 1,150. Due to the absence of an explicit equation for calculating the friction factor in the transition zone, the approach shown in Equations (5) and (6) is adopted. These equations are plotted in Figure 3 for a material surface roughness of 3×10^{-7} m, which is typical for plastic pipes. This assumption is conservative, as it may lead to a slight overestimation of the friction factor and, consequently, the head loss. This approach is preferred, as underestimating the friction factor could result in inadequate water delivery to the farthest outlets of the irrigation system.

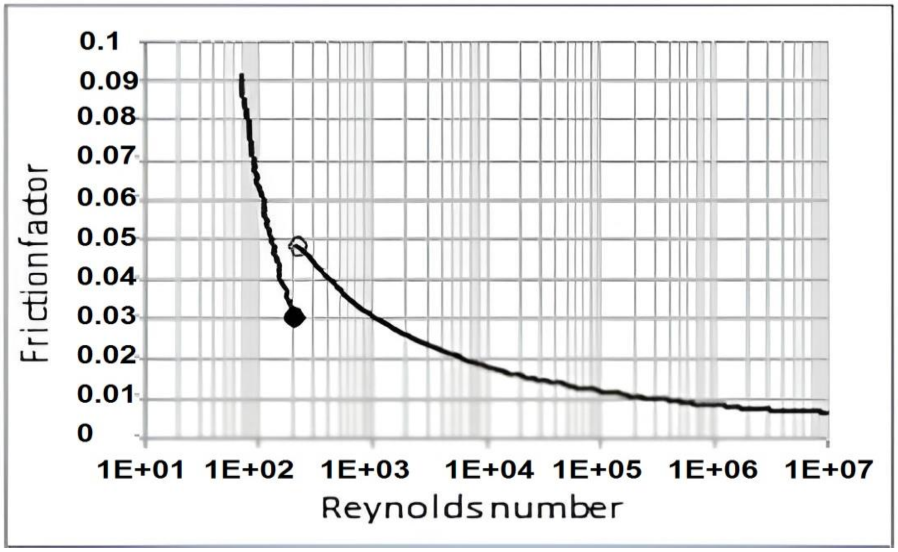

Figure 3. Friction factor calculation.

3. CASES OF STUDY.

A theoretical and real-world case study will be presented in this section.

Figure 4 illustrates the structure of the theoretical case, featuring a main pipeline with four branches, each branching into three or four outlets. The lengths of the network depicted in figure 4 are provided in Table 1. The diameter of all the pipes is 0.0254 m.

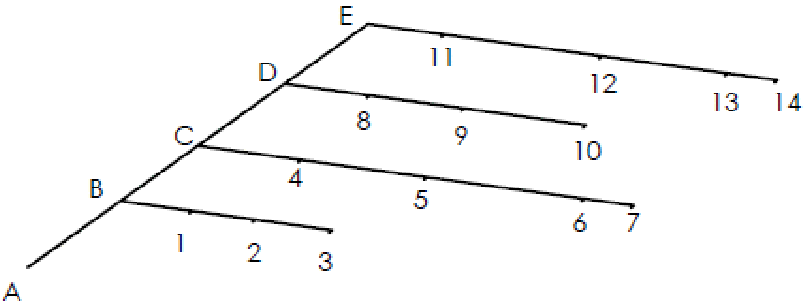

Figure 4. Open-channel irrigation network for the theoretical case of study.

Table 1. Dimensions for the theoretical irrigation system.

Section	Lenght (m)	Section	Length (m)
A-B	30	5-6	35
B-C	25	6-7	11
C-D	28	D-8	19
D-E	27	8-9	21
B-1	16	9-10	27
1-2	14	E-11	17
2-3	17	11-12	35
C-4	23	12-13	28
4-5	28	13-14	11

The water inlet is located at point A. The methodology is applied considering various pressures at point A. For this simplified example, each outlet is treated as a single perforation with a specified diameter. All pipes in this theoretical case study have a nominal diameter of 1 inch.

On the other hand, Figure 5 presents a sketch of a real case located in Zacatecas, Zacatecas, México for a fruit tree irrigation system. The methodology outlined in the previous section is applied to this open-channel irrigation network. Table 2 summarizes the required dimensions for defining the network geometry. A water reservoir, located five meters above the irrigation system's elevation, supplies the water. Head loss due to accessories, including one pipe inlet, six standard elbows, and three globe valves, between the reservoir and the first irrigation system node was also considered. The pipes as well as the accessories are made from PVC.

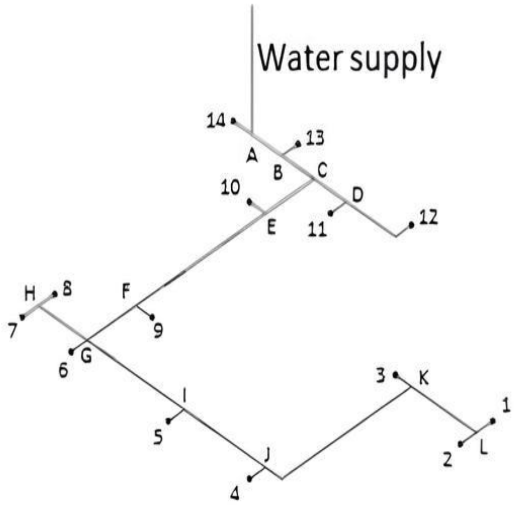

Figure 5. Open-channel irrigation network.

Table 2. Dimensions for the irrigation system.

Section	Lenght (m)	Section	Length (m)
A-14	0.15	H-7	0.3
A-B	0.5	H-8	0.3
B-13	0.26	G-6	0.3
B-C	0.87	G-I	2.01
C-D	1.32	I-5	0.3
D-11	0.3	I-J	2.21
D-12	1.45	J-4	0.3
C-E	1.1	J-K	3.08
E-10	0.8	K-3	0.21
E-F	2.62	K-L	1.21
F-9	0.81	L-2	0.29
F-G	1.06	L-1	0.71
G-H	2.17		

Each outlet was equipped with a set of pipes and fittings, as shown in Figure 6. This set includes a standard elbow, a 30 cm vertical pipe section, a 10 cm horizontal pipe section and a cap with an orifice (diameter to be calculated). All pipes in this real case study have a nominal diameter of ½ inch.

Figure 6. Irrigation system outlet pipeline.

4. RESULTS.

The algorithm was tested using the system shown in Figure 4 and the flow rates specified at Table 3. At point A, the system's inlet, a piezometric head of 4 meters is available.

Table 3. Requested caudal distribution.

Outlet number	Caudal Liters/minute	Outlet number	Caudal Liters/minute
1	0.5	8	1
2	1	9	0.5
3	1	10	1
4	1.5	11	1.5
5	0.5	12	1.5
6	1	13	1.5
7	2	14	1.5

Following the steps of the algorithm, the volumetric flow rates are calculated for each section of the irrigation system using the desired outlet flow rates. This volumetric flow rates are shown in Table 4.

Table 4. Volumetric flow rates.

Section	Flow rate	Section	Flow rate
A-B	16	5-6	3
B-C	13.5	6-7	2
C-D	8.5	D-8	2.5
D-E	6	8-9	1.5
B-1	2.5	9-10	1
1-2	2	E-11	6
2-3	1	11-12	4.5
C-4	5	12-13	3
4-5	3.5	13-14	1.5

Then, the energy losses due to friction are calculated, which are shown in Table 5.

Table 5. Energy losses due to friction.

Section	Head loss(m)	Section	Head loss (m)
A-B	1.317	5-6	0.05831
B-C	0.7841	6-7	0.003667
C-D	0.3528	D-8	0.007916
D-E	0.1719	8-9	0.00525
B-1	0.00667	9-10	0.0045
1-2	0.00467	E-11	0.1083
2-3	0.002833	11-12	0.1274
C-4	0.1027	12-13	0.04665
4-5	0.06271	13-14	0.00275

Using these data, the total piezometric head at each point of interest in the system can be calculated. These results are shown in Table 6.

Table 6. Available head at each outlet.

Node	Available head	Node	Available head
1	2.676	11	1.266
2	2.672	12	1.139
3	2.669	13	1.136
4	1.796	14	1.133
5	1.734	A	4
6	1.675	B	2.683
7	1.672	C	1.899
8	1.538	D	1.546
9	1.533	E	1.374
10	1.529		

Finally, the diameters of the outlet orifices are calculated based on the desired flow rates and the piezometric heads. These calculations are repeated for piezometric heads at the inlet of 3 m and 2.6 m. The required outlet diameters are presented in Figure 7, where the horizontal axis represents the outlet number and the vertical axis represents the outlet diameter. By applying the proposed methodology, the outlet diameters were calculated. As expected, a larger flow rate requires larger outlet diameters. Additionally, it is observed that the required outlet diameters increase as the available head decreases. This explains why the blue line in Figure 7 diverges from the orange line. In this specific case, a minimum head of 2.6 meters is required to achieve the desired flow rates.

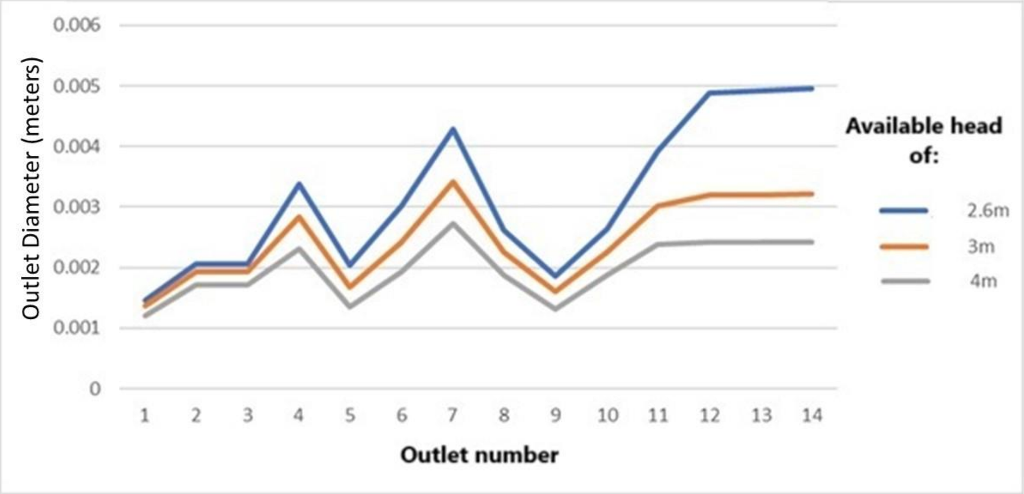

Figure 7. Outlet diameters for different available head.

Additionally, the algorithm can be used to determine the maximum uniform flow rate for a given available head at the inlet. This can be achieved by iteratively increasing the desired flow rate at each outlet until a zero or negative value is obtained for the piezometric head at one of the outlets. Figure 8 illustrates the maximum flow rate as a function of the available hydraulic head at point A. This can also be used to calculate the necessary head for a specific uniform flow rate at each outlet. It is important to note that the flow rate does not increase linearly with the head at point A due to the nonlinear increase in pipeline head losses. However, Hower-Cuevas [11] and Echegorri [12] also found a nonlinear relation between flow rate and head loss.

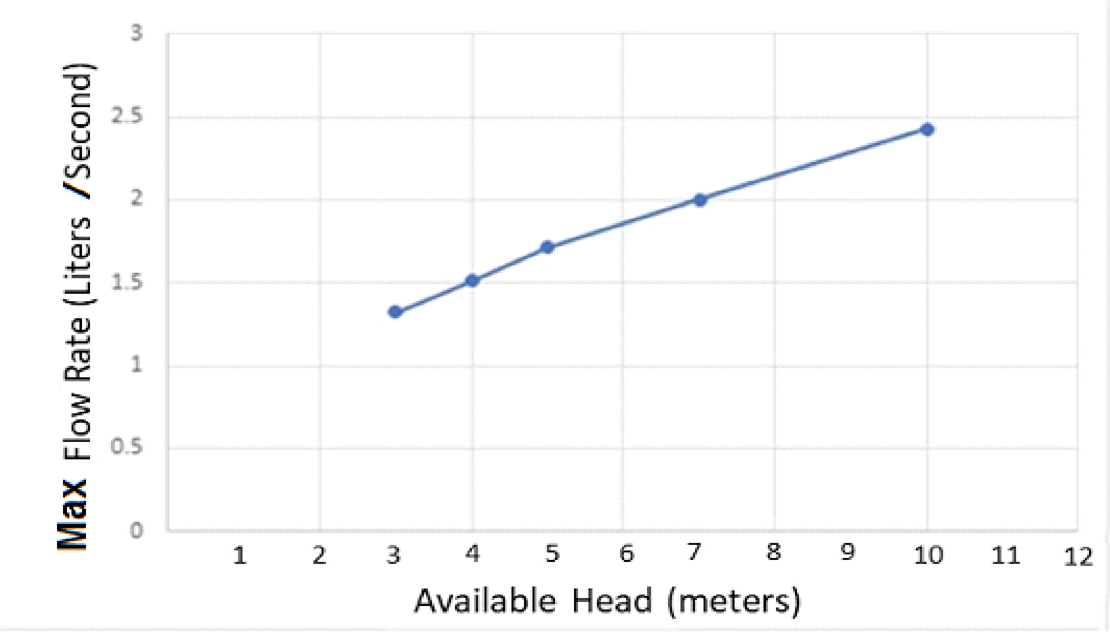

Figure 8. flow rate as a function of the available hydraulic head.

- Based on the preceding results, it can be concluded that the model performs accurately and will be valuable for comparing theoretical and experimental results in the subsequent case study. This second case study aimed to achieve a uniform flow rate distribution across all 14 irrigation system outlets (shown in Figure 4), while maximizing the flow rate for each outlet for a 4-meter available head at the inlet. The proposed methodology was applied iteratively, incrementing the flow rate by 0.05 liters per minute, until a negative total head was encountered at an outlet. The maximum flow rate was defined as the highest flow rate with a non-negative total head at all outlets. The calculated outlet diameters for various flow rates are presented in Figure 9. These results reveal the following:

- **Uniform Outlet Diameters at Low Flow Rates**: At low flow rates, the calculated outlet diameters are consistent across all outlets. In this specific case, the maximum achievable uniform diameter is 1 mm, corresponding to a flow rate of 0.35 L/min.
- **Maximum Achievable Flow Rate**: The proposed methodology enables the calculation of the maximum flow rate that can be delivered to each irrigation system outlet. For this specific case, the maximum achievable flow rate is 0.51 L/min.
- **Diverging Diameters at High Flow Rates**: As the targeted flow rate approaches the maximum achievable value, the calculated outlet diameters begin to diverge significantly.

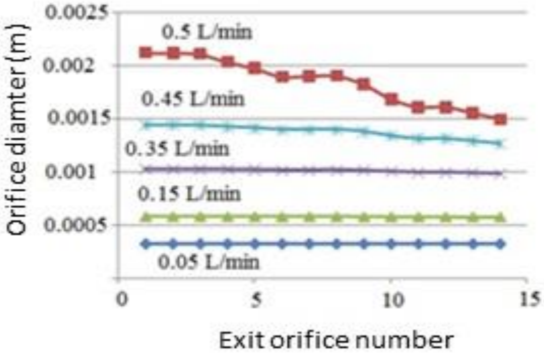

Figure 9. Diameters of the outlet openings for different flow rates.

As previously noted, the maximum achievable flow rate is 0.51 L/min. As a result, the flow rate within the pipeline network ranges from 7 L/min in the main feed pipe to 0.51 L/min at each outlet. The calculations also reveal that the main feed pipe accounts for 76% of the total head loss, while each outlet of the system contributes only 0.1% of the pressure drop. Table 7 summarizes the calculated and implemented orifice diameters, along with the achieved flow rates.

Table 7. Obtained flow rate.

Outlet number	Calculated diameter (mm)	Actual diameter (mm)	Flow rate (L/min)
1	2.68	2.5	0.51
2	2.67	2.5	0.53
3	2.64	2.5	0.58
4	2.44	2.5	0.52
5	2.31	2.5	0.55
6	2.15	2	0.52
7	2.16	2	0.49
8	2.16	2	0.48
9	2.03	2	0.52
10	1.81	2	0.51
11	1.71	2	0.44
12	1.71	2	0.45
13	1.64	1.5	0.43
14	1.56	1.5	0.44

The targeted flow rate in this case study is 0.51 L/min. However, table 7 shows that only exits 1 and 10 deliver the exact targeted flow rate. The remaining exits deliver flow rates ranging from 0.43 to 0.58 L/min. This discrepancy between the calculated and the achieved flow rates can be attributed to several factors:

- **Discrepancy between calculated and implemented diameters**: Minor differences may exist between the calculated orifice diameters and the actual implemented diameters due to manufacturing tolerances or limitations.
- **Transitional flow regime**: From node 5 onwards, the flow likely enters the transitional regime (2000 < Re < 4000). In this regime, calculating the friction factor and consequently, the head loss becomes more complex due to the unpredictable flow behavior.
- **Potential impurities**: The presence of impurities within the pipeline, such as glue residue, could introduce additional friction and potentially affect the flow rate.

5. CONCLUSIONS

The proposed methodology demonstrates its effectiveness in redistributing flow rates in situations where pipe diameters cannot be modified, such as in existing or pre-purchased systems. For low flow rates, uniform orifice diameters can be achieved. However, to maximize flow rates, orifices with varying diameters are required.

Predicting energy losses within the transitional flow regime (2000 < Re < 4000) and the limitations in manufacturing precise orifice diameters contribute to a ± 15% discrepancy between calculated and actual flow rates.

Using equations (5) and (6) to calculate the friction factor remains appropriate for this application, as the majority of head loss occurs in the initial sections of the network, where turbulent flow dominates.

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