TESIS DE MAESTRÍA

INGENIERÍA CIVIL

MEDICIÓN Y EVALUACIÓN DE RESILIENCIA Y CONFIABILIDAD EN DISEÑOS ÓPTIMOS DE REDES DE DRENAJE URBANO

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TABLA DE CONTENIDO

1 Introducción 2
2 Versión resumida del artículo 4
3 Referencias 22

1 INTRODUCCIÓN

Los sistemas de alcantarillado se encargan de evacuar las aguas residuales y pluviales con el fin de evitar problemas de contaminación, olores y enfermedades. A pesar de la importancia de este servicio, en el 2017, aproximadamente 2000 millones de personas en el mundo carecían de acceso a servicios básicos de saneamiento (United Nations Children's Fund (UNICEF) & World Health Organization, 2019). En el caso de Colombia, algunos departamentos están distantes de lograr una cobertura total de este servicio. Por ejemplo, según el censo del Departamento Administrativo Nacional de Estadística (DANE) del 2018, departamentos como Vichada, Guainía y Chocó tienen un cobertura de alcantarillado menor al 30% (Departamento Administrativo Nacional de Estadística (DANE), 2018).

Una de las razones principales de la falta de cobertura de alcantarillado es el presupuesto limitado, en especial en países en desarrollo. Por esta razón, es de gran importancia diseñar redes de mínimo costo que cumplan con todas las restricciones hidráulicas para una adecuada operación. La reducción de costos que puede lograr un diseño de mínimo costo es muy significativa debido a la gran cantidad de diseños posibles, incluso, se sabe que la diferencia del costo entre dos trazados diferentes de una red de alcantarillado puede variar hasta en un 50% (Saldarriaga, Cuero, Montaño, Corrales, & Luna, 2014).

Además del presupuesto limitado, en las últimas décadas, los sistemas de alcantarillado se han enfrentado a nuevos retos como el cambio climático y la urbanización, los cuales pueden aumentar la probabilidad de inundación de los sistemas. Debido a lo anterior, al momento de diseñar sistemas de alcantarillado se debe buscar obtener el diseño de menor costo, pero también garantizar que este sea resiliente y confiable.

La resiliencia y confiabilidad son dos conceptos que describen a un sistema que busca evitar fallas en su operación, que en este caso se entienden como inundaciones. Si bien ambos conceptos están relacionados, no tienen la misma definición. Según Butler et al. (2014), la confiabilidad se define como el grado en que el sistema minimiza la frecuencia de los fallos de nivel de servicio a lo largo de su vida útil cuando se somete a cargas estándar, mientras que la US National Infrastructure Advisory Council (2009) define la resiliencia como la habilidad del sistema para reducir la magnitud o duración del evento de falla.

El presente trabajo propone una metodología para evaluar la resiliencia y confiabilidad de diseños de redes de alcantarillado que busca ser una herramienta para encontrar diseños de bajo costo y alta resiliencia y/o confiabilidad. Para obtener diseños de bajo costo se utilizó la metodología de diseño optimizado de redes de alcantarillado desarrollada en el Centro de

Investigaciones en Acueductos y Alcantarillados (CIACUA) y para la medición de resiliencia y confiabilidad se utilizaron índices propuestos anteriormente en la literatura. La metodología se probó en dos redes de alcantarillado utilizadas en la literatura. Asimismo, se utilizaron dos ecuaciones de costo para modelar los costos de construcción de la red.

El trabajo se ha escrito para ser sometido a la revista "Urban Water Journal". Para respetar el código de ética de la revista, se ha preparado una versión resumida del artículo, la cuál se presenta a continuación. En la versión resumida se han omitido algunas secciones y figuras del artículo. No obstante, el trabajo completo se podrá encontrar en la revista o contactando a los autores.

2 VERSIÓN RESUMIDA DEL ARTÍCULO

Measurement and evaluation of resilience and reliability in optimal sewer networks designs

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1. Introduction

The sewer network design problem can be divided into two subproblems: the layout selection and the hydraulic design. The layout selection establishes the three-structure of the network, which indicates the flow rate and flow direction in pipes, and the hydraulic design determines the diameters and invert elevations of pipes. The objective of the sewer network design problem is to find the solution of the two subproblems that lead to the lowest cost design, i.e., the optimal design. This is a complex task due to the immense number of feasible solutions, and because of the presence of discrete variables, such as the diameter of pipes, that depend on the commercially available list of diameters.

Due to the complexity of the problem, finding the optimal sewer network design has become a challenge for the researchers of the field. Among the first authors to propose a method to solve the problem were Li and Matthew (1990), who selected the layout of the network with the searching direction method and used discrete Differential Dynamic Programming (DDDP) for the hydraulic design. These authors also presented a sewer network that has become a popular case study in the international literature. Another approach was the proposed by Moeini and Afshar (2012, 2017, 2018) who intended using ant algorithms combined with the Tree Growing Algorithm (TGA) and Nonlinear Programming (NLP) for the layout selection and hydraulic design of sewer networks. Also, Haghighi and Bakhshipour (2015) used the loop-by-loop cutting algorithm for the layout selection and Tabu Search (TS) for the hydraulic design. Duque et al. (2020) used mixed-integer programming (MIP) for the layout selection and Dynamic programming (DP). Saldarriaga et al. (2021) included topographic criteria to the last methodology which managed to obtain the lowest cost designs published in the literature for the Li and Matthew network. Other studies that solve both subproblems of the sewer network design problem include (Diogo and Graveto 2006; Haghighi and Bakhshipour 2012; Navin and Mathur 2016; Steele et al. 2016; Alfaisal and Mays 2021).

Although it is important to minimize the cost of sewer networks, over the past years new challenges that threaten the service of sewer systems have emerged, such as climate change and urbanization. For this reason, incorporating concepts like reliability and resilience is important to provide a better service in sewer networks.

The reliability and resilience are two concepts that have positive correlation but are not the same. Alternatives that give the greatest resilience do not necessarily provide the greatest reliability (Asefa et al. 2014, as cited in Sweetapple, Fu, and Butler 2017). According to Butler et al. (2014), the reliability is defined as “the degree to which the system minimizes level of service failure frequency over its design life when subject to standard loading”, while the resilience is defined by the US National Infrastructure Advisory Council (NIAC) (2009) as “the ability to reduce the magnitude and/or duration of disruptive events.”

The reliability of sewer networks has been studied in previous works. For example Mista-Kruk (2016) analysed the reliability related to elements of pressure, vacuum and gravity systems based on data. Tee et al. (2014) estimated the reliability with respect to corrosion in pipes. Haghighi and Bakhshipour (2016) proposed a reliability index, this study is different from the others because the proposed index is meant to be consider in the design of the network. As for the resilience, many works have proposed indices to measure this concept, most of them using flooding volume (Lee and Kim 2017; Lee, Choi, and Kim 2019; Chen and Leandro 2019; Mugume et al. 2015). From these indices, the proposed by Mugume et al. stands out for its simplicity and easy implementation in any sewer network.

The present work proposes an approach to evaluate resilience, reliability, and cost in sewer networks designs obtained with an optimal design methodology. The approach aims to be a tool for finding minimum cost designs with high resilience and reliability. It also seeks to allow the analysis of the relationship between these three aspects in sewer networks. The proposed methodology was applied in two sewer networks that have been used before in the literature to test sewer network design methodologies. The methodology was also tested using two cost functions from the literature.

2. Methods

2.1. First approach: multiobjective optimization

The first approach proposed to evaluate cost and reliability in sewer networks was a multiobjective optimization model that sought to minimize cost and maximize reliability. For this purpose, the Non-Inferior Set Estimation (NISE) algorithm proposed by Medrano and Church (2015) was used. NISE consists of obtaining a single objective function from the weighting of the objective functions of interest. Such weighting is performed through Equation (1), where z_c is the new objective function, z_1 is objective function 1 (minimize cost), z_2 is objective function 2 (maximize reliability), and α is the weight.

$$z_c = \alpha * z_1 + (1 - \alpha) * z_2 \tag{1}$$

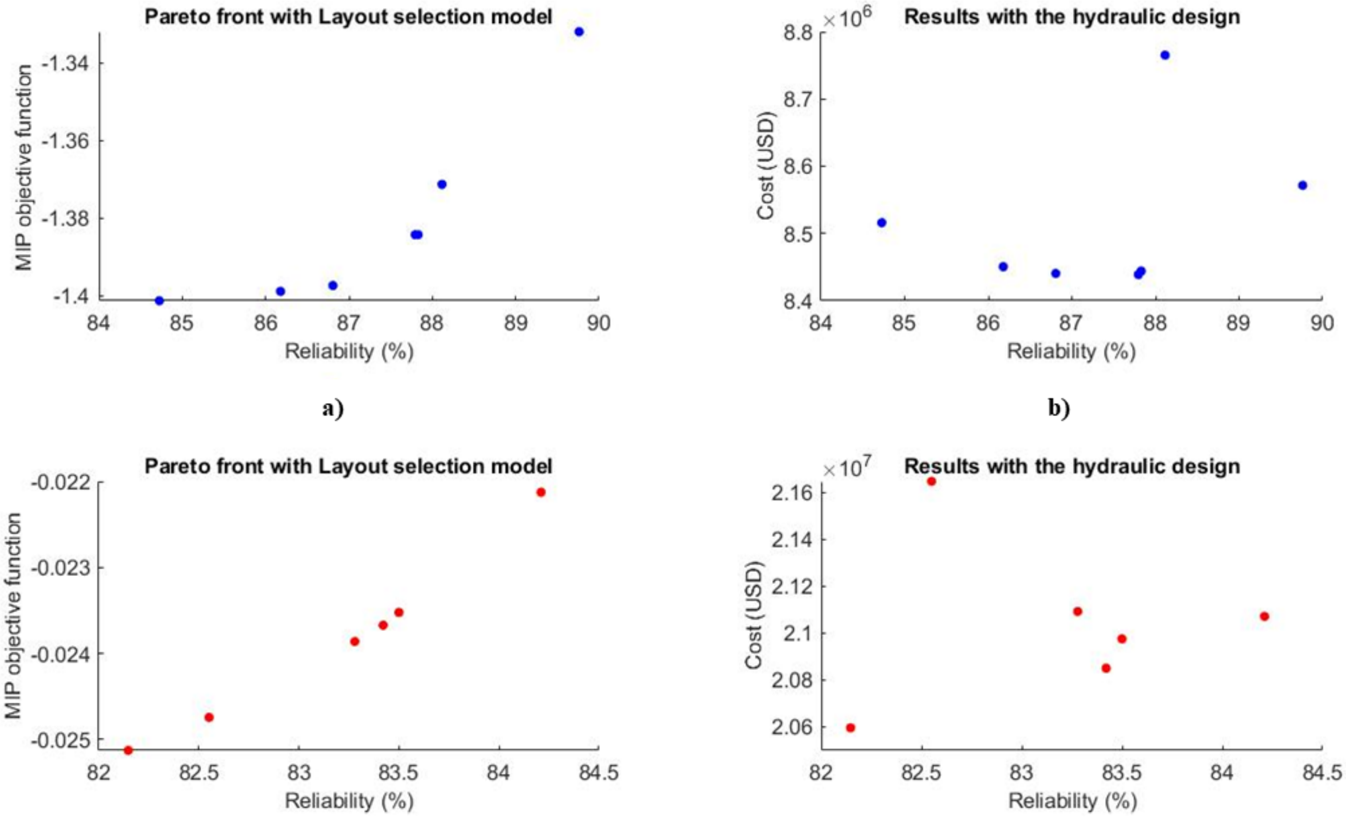
The NISE algorithm starts by assigning the value of 1 to α to find a solution that only considers objective function 1, then α takes the value of 0 to find the solution that only considers objective function 2. Subsequently, α is calculated with Equation (2) to find new solutions iteratively until it is not possible to find solutions that have higher reliability and lower cost than the existing ones. In Equation (2), σ_i and σ_j correspond to previous solutions.

$$\alpha = \frac{z_2(\sigma_i) - z_2(\sigma_j)}{\left(z_2(\sigma_i) - z_2(\sigma_j)\right) + \left(z_1(\sigma_j) - z_1(\sigma_i)\right)} \tag{2}$$

Using multiobjective optimization in sewer design is challenging because the problem is divided into two subproblems. Given that the reliability index relies exclusively on layout variables, the multiobjective methodology was applied in the layout selection model (i.e., MIP model). Thus, the MIP objective function and the reliability index are the objective functions to optimize in the multiobjective algorithm.

The multi-objective optimization produces a Pareto front, where each solution corresponds to a different layout with its own MIP objective function and reliability. Because the cost of the network is unknown in the layout, the optimal hydraulic design was calculated for each layout that composes the Pareto front. In this way, the cost and reliability of various designs of the same network were obtained.

However, when the multiobjective optimization was performed, it was discovered that the MIP objective function is not proportional to the network cost, i.e., layouts with a low MIP objective function do not correspond to low-cost networks. As a result, when using the first approximation, a Pareto front was obtained for the layout selection model, but no relationship between network cost and reliability was discovered. In other words, the most expensive designs were not necessarily the most reliable. Figure 1 shows the results obtained using the first approximation, which show the aforementioned. The Chicó network's results are shown in blue, while the Li and Matthew network's results are shown in red.



a) **b)**

c) **d)**

Figure 1. Results of the first approach. a) Pareto front of the layout selection and b) cost and reliability of the designs of the Chicó network. c) Pareto front of the layout selection and d) cost and reliability of the designs of the Li and Matthew's network.

Based on the results of the first approach, it was determined that there is no trade-off between the network's cost and reliability; that is, a network with higher reliability is not necessarily more expensive. As a result, it was decided to develop a second approach in which multi-objective optimization was not used, but instead, a reliability measurement on a variety of designs for the same network was performed. The relationship between cost and reliability was examined, and low-cost and high-reliability designs were sought without the use of a multi-objective algorithm. Furthermore, the concept of resilience was included in the analysis because it integrates reliability with the magnitude and/or duration of a failure event.

2.2. Final approach: Evaluation of resilience and reliability in sewer networks designs

The second approach was to evaluate the resilience and reliability of various low-cost sewer network designs. New designs were obtained by modifying b_{ijt} in the objective function of the layout selection.

Initially, the four designs corresponding to the iterations of the original methodology of Saldarriaga et al. were made. From these, new designs were obtained by modifying the parameter b_{ijt}. The modifications were made depending on how the parameter was originally calculated. In the case of the designs found with criterion 1 or 2, the modification consisted of changing the value of the penalty µ. In the case of criterion 3 and the fourth iteration, the way in which the distance and excavation costs were calculated were modified, respectively.

When parameter b_{ijt} was changed, it was discovered that there was no relationship between the magnitude of the change and the cost of the resulting design. Furthermore, it was found that a design could be achieved many times using different modifications in b_{ijt}. As a result, the value of the changes made in b_{ijt} was randomized until the desired number of designs was obtained.

Moreover, we attempted to obtain a range of costs in the new designs in order to investigate the relationship between cost, resilience, and reliability. To search for low-cost designs, the designs of iterations with lower costs were used as a basis, and vice versa, to search for high-cost designs, the designs of iterations with higher costs were used as a basis.

After obtaining the desired number of designs, the resilience calculation was performed. To do this, the design was first modeled in SWMM. Then, the flood volume obtained by clogging each of the inner-branch pipes of the network was calculated. Next, the resilience of each pipe was calculated with the flood volume and inflow volume of the network. Finally, the resilience of the network was calculated as the average of the resilience of the inner-branch pipes. After that, reliability was calculated for these same designs using the Haghighi and Bakhshipour index. The results were organized into two graphs, one of cost vs. resilience and the other of cost vs. reliability.

3. Case studies

The methodology was tested in two sewer networks previously used in the literature as case studies. The first one is labelled *Chicó* and is part of the real sewer network of Bogotá, Colombia. This sewer network is composed of 109 manholes and 160 pipes, and it only has one outfall with a total flow rate of 1.525 m^3/s. The other sewer network is the one proposed by Li and Matthew, which is composed of 57 manholes, 79 pipes, and one outfall with a total flow rate of 0.338 m^3/s.

The sewer network design methodology must comply with the required hydraulic constraints to ensure proper operation of the network. In the present work, the constraints proposed by Li and Matthew (1990) were used, which are presented in Table 1.

Table 1. Hydraulic constraints

Constraint	Value	Condition
Minimum diameter	0.2 m	Always
Maximum filling ratio	0.6	$d \leq 0.3$ m
	0.7	$0.35 \text{ m} \leq d \leq 0.45\, m$
	0.75	$0.5 \text{ m} \leq d \leq 0.9\, m$
	0.8	$d \geq 1\, m$
Minimum velocity	0.7 m/s	$d \leq 0.5$ m and Flow rate $> 0.015 \text{ m}^3/s$
	0.8 m/s	$d > 0.5$ m and Flow rate $> 0.015 \text{ m}^3/s$
Maximum velocity	5 m/s	Always
Minimum gradient	0.003	Flow rate $< 0.015\, m^3/s$
Minimum depth	1 m	Always

The list of commercially available diameters used is: {0.2, 0.25, 0.3, 0.35, 0.38, 0.4, 0.45, 0.5, 0.53, 0.6, 0.7, 0.8, 0.9, 1.0, 1.05, 1.20, 1.35, 1.4, 1.5, 1.6, 1.8, 2, 2.2, 2.4} in meters, and the material used for pipes was concrete with a Manning's n equal to 0.014.

As for the equations to model the construction cost of the sewer networks, two equations that have been previously used in the literature were implemented. One of them was proposed by Maurer, Wolfram, and Anja (2010) and is presented in Equation (3), where C is the construction cost of one pipe in U.S. dollars, d is the diameter of the pipe in meters, L is the length of the pipe in meters, h is the average depth of the pipe in meters, and m_α, m_β, n_α, and n_β are constants defined by the authors. The values of these constants are in Table 2.

$$C = \left((m_\alpha d + n_\alpha)h + (m_\beta d + n_\beta)\right) * L \qquad (3)$$

Table 2. Constants of the equation of Maurer, Wolfram, and Anja.

Constant	**Value**	**Units**
m_α	110	$\text{USD} * \text{m}^{-3}$
m_β	1200	$\text{USD} * \text{m}^{-2}$
n_α	127	$\text{USD} * \text{m}^{-2}$

n_β	-35	$\mathrm{USD} * \mathrm{m}^{-1}$

The other cost equation was proposed by Li and Matthew (1990) and is presented in Equations (4), and (5) where f_p and f_m are the construction cost of a pipe and a manhole in yuan, respectively; *d* is the diameter of the pipe in meters (the downstream pipe in the case of Equation (5)), *L* is the length of the pipe in meters, and *h* is the depth in meters.

$$f_p = \begin{cases} (4.27 + 93.59d^2 + 2.86dh + 2.39h^2)L & if\ d \leq 1\,m\ and\ h \leq 3\,m \\ (36.47 + 88.96d^2 + 8.70dh + 1.78h^2)L & if\ d \leq 1\,m\ and\ h > 3\,m \\ (20.50 + 149.27d^2 - 58.96dh + 17.75h^2)L & if\ d > 1\,m\ and\ h \leq 4\,m \\ (78.44 + 29.25d^2 + 31.80dh - 2.32h^2)L & if\ d > 1\,m\ and\ h > 4\,m \end{cases} \tag{4}$$

$$f_m = \begin{cases} 136.67 + 166.19d^2 + 3.50dh + 16.22h^2 & if\ d \leq 1\,m\ and\ h \leq 3\,m \\ 132.91 + 790.94d^2 - 280.23dh + 34.97h^2 & if\ d \leq 1\,m\ and\ h > 3\,m \\ 209.74 + 57.53d^2 + 10.93dh + 19.88h^2 & if\ d > 1\,m\ and\ h \leq 4\,m \\ 210.66 - 113.04d^2 + 126.43dh - 0.60h^2 & if\ d > 1\,m\ and\ h > 4\,m \end{cases} \tag{5}$$

To resume, four scenarios were evaluated varying the sewer network and the cost function. These scenarios are summarized in Table 3.

Table 3. Evaluated scenarios

Scenario	Sewer network	Cost function
1	Chicó	Maurer, Wolfram, and Anja
2	Chicó	Li and Matthew
3	Li and Matthew	Maurer, Wolfram, and Anja
4	Li and Matthew	Li and Matthew

4. Results

4.1. Scenario 1: Chicó network with the cost function of Maurer, Wolfram, and Anja.

Figure 2 present the cost, resilience, and reliability of 15 designs of a sewer network. In this figure, a) presents the cost against resilience of the designs, and b) presents the cost against reliability of the same designs.

The design labelled as “MIP and DP” correspond to the design achieved with the methodology of Duque et al. (2020). The 4 designs referenced as “MIP and DP extension” correspond to the solution of the 4 iterations of the methodology proposed by Saldarriaga et al. (2021). The remaining 10 designs correspond to those obtained with the strategies of the present work.

Also, the design considered as the “Best design” is marked with an X. The best designs are considered the ones with the lowest cost and highest resilience, or reliability. Selecting which design is the best can be subjective. It depends on how much cost the decision maker is willing to accept to increment the resilience or reliability. In the present work, the best designs were chosen with the authors criterion to illustrate an example of how the methodology can be useful to select designs with low cost and high resilience/ reliability.

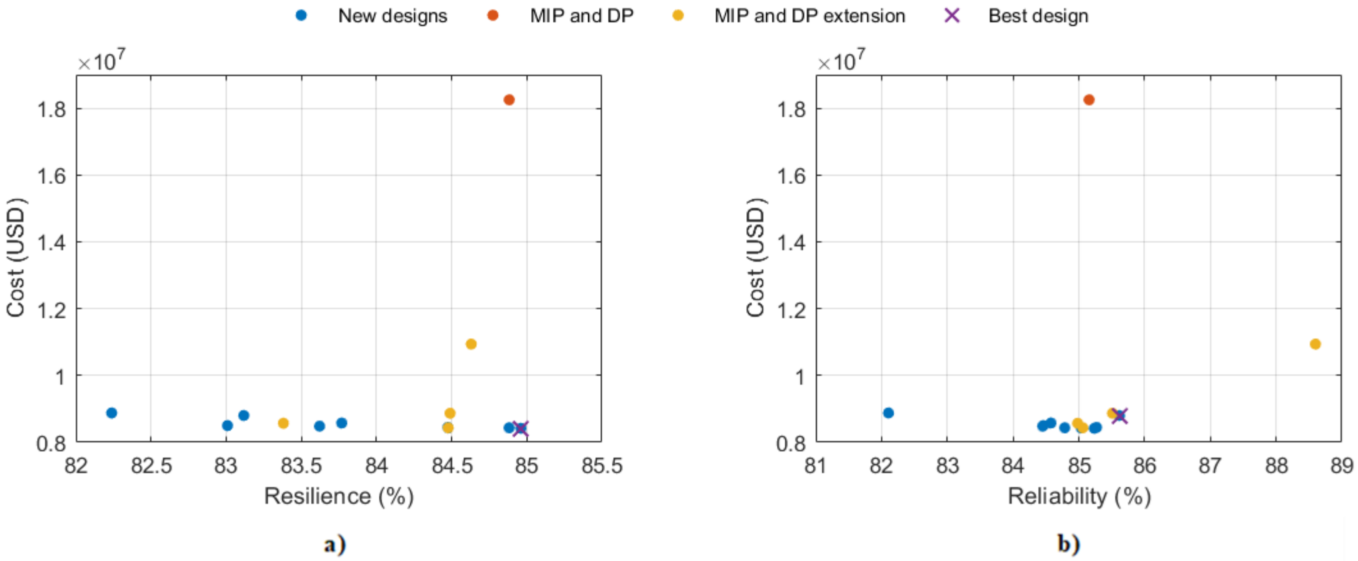


Figure 2. Cost vs. a) resilience and b) reliability in near-optimal designs of the scenario 1.

Also, since from the first approach it was concluded that the reliability index used and the cost did not have a positive correlation as expected, it was decided to analyse the correlation coefficient between the cost, resilience, and reliability of the designs. Table 4 presents these results for the case of the Chicó network and the cost function of Maurer, Wolfram, and Anja.

Table 4. Correlation matrix between the cost, resilience, and reliability of the scenario 1.

	Cost	**Resilience**	**Reliability**
Cost	1		
Resilience	0.285	1	
Reliability	0.193	0.562	1

5. Conclusions

This paper proposes a methodology to evaluate the cost, resilience and reliability of sewer network designs obtained with optimized design methodologies. The following conclusions are presented based on the results obtained:

- Significantly more expensive designs have higher resilience but not necessarily higher reliability. In contrast, when the cost difference between two designs is not very large, the design with higher resilience is not necessarily the more expensive one.
- The methodology allowed finding designs that were more resilient and less expensive than those that had already been published. This shows that inexpensive networks can be very resilient, in some cases even more than expensive designs.
- Although the correlation between resilience and reliability is positive, it is not very high. Resilience is recommended over reliability if one must choose between the two as a criterion to determine which design is better since this concept takes both reliability and the magnitude of the failure event into account. Furthermore, reliability is less sensitive to modifications in network design.

From the findings regarding the relationship between cost, resilience, and reliability in sewer networks, it is suggested to use cost and resilience as criteria to determine which sewer network design is preferable. It is also recommended for future studies to use an algorithm that automates the process of finding new designs in order to take advantage of computer resources to explore a larger number of designs.

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