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Optimal Exploitation of Urban Water Supply Networks Based on Pressure Management with the Nondominated Sorting Differential Evolution (NSDE) Algorithm

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Abstract: Urban water distribution networks are crucial infrastructures for providing essential services to society, but their exorbitant costs and limited water resources make their optimization a critical research area. Optimal management and design of these networks can help to reduce costs and enhance their efficiency while meeting technical, economic, and quality standards. In particular, the management of network pressure is critical for reducing leakage in water distribution systems. Thus, this study aimed to investigate two objective functions for optimizing the water distribution network: (i) minimizing costs while considering the number of pressure-relief valves, and (ii) minimizing network pressure by observing the optimal pressure range. To achieve this, the Nondominated Sorting Differential Evolution (NSDE) multi-objective metaheuristic algorithm was employed as the optimization tool, and a computer program was written in MATLAB software for solving the optimization models. EPANET software was also used for hydraulic simulation of the water distribution network. The efficiency and capabilities of these models were tested on the case study of the third district of Mashhad in Iran. The results indicated that the installation and adjustment of pressure-relief valves in accordance with the positions and optimal settings of the output of the proposed models significantly improved the desired goals, particularly the average pressure of the network. As an example of optimization, the study achieved a 56.12% reduction in pressure compared to the case without a plan, considering five pressure-relief valves.

Keywords: optimization; NSDE algorithm; hazard prediction; pressure-relief value; EPANET software

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1. Introduction

Iran, as a semi-arid country, has limited water resources, and it is predicted that by 2025, the world's population—including Middle Eastern countries—will be facing water tensions [1]. Water has become a strategic commodity, and its importance cannot be overstated [2]. Leakage management is critical in water management, and pressure management has been identified as the simplest, fastest, and most cost-effective method for reducing water wastage due to leakage. Pressure management is a critical aspect of water supply network operation that involves controlling and maintaining optimal pressure levels within the system. Effective pressure management is vital for ensuring network reliability, efficiency, and customer satisfaction. Pressure variations within the network can arise due to fluctuations or inconsistencies in pressure levels, leading to potential issues such as water hammer and compromised water quality. Excessive pressure variations can cause hydraulic shocks, resulting in damage to network components and infrastructure. Furthermore, pressure variations can contribute to accelerated pipe deterioration and the development or exacerbation of leaks. By implementing robust pressure management practices, including maintaining optimal pressure levels, pressure variations can be minimized, reducing the risk of water hammer and maintaining consistent water supply and quality. Additionally, effective pressure management helps mitigate leaks by avoiding excessive pressure stress on the pipes, thereby promoting network integrity and reducing water losses. The relationship between pressure management, variations, and leaks highlights the significance of implementing appropriate strategies and technologies to ensure efficient and sustainable water supply network operation [3–5]. In water supply and urban water distribution networks, various hydraulic parameters are crucial for understanding and managing the hydraulic behavior of the system. These parameters include pressure, flow rate, velocity, head loss, and hydraulic grade line. Among these parameters, pressure holds primary significance due to several reasons in both water supply and urban water distribution networks [4]. Effective management of hydraulic parameters, particularly pressure, plays a vital role in mitigating leakage within urban water distribution networks. While it is inevitable to encounter some level of leakage in such networks, proactive measures such as implementing leakage detection projects and optimizing hydraulic parameters, notably pressure, are essential for leakage reduction [3]. By closely monitoring and regulating pressure levels, water utilities can minimize excessive pressure that can contribute to leaks and pipe failures. Moreover, coupling pressure management strategies with comprehensive leakage detection initiatives allows for early identification and prompt repair of leaks, thereby minimizing water loss and optimizing the overall efficiency and sustainability of urban water distribution networks. On the other hand, pressure plays a central role as it is the driving force that propels water through the network, ensuring its delivery to consumers. Maintaining appropriate pressure levels is essential to guarantee a reliable and consistent water supply to meet consumer demands. Pressure directly influences network performance and water distribution by regulating flow rates and velocities. Proper pressure management ensures adequate flow, prevents low-pressure issues, and facilitates firefighting capabilities. It ensures that water is distributed efficiently throughout the network, even to areas with higher elevations or greater distances from the water source [5]. Intelligent pressure control is a suitable method for controlling leaks and reducing breaks caused by high pressures in the network. The loss of water from the system not only results in water wastage but also creates a hole for pollution to enter the water system, which can result in an unpleasant taste and smell and threaten the health of the citizens. Excessive pressure places stress on pipes, fittings, and components, leading to pipe bursts, leaks, and premature wear. By managing pressure within optimal ranges, the risk of infrastructure failures and leaks is mitigated, thereby promoting the longevity and efficiency of the network. Pressure also significantly impacts customer satisfaction and service quality. Adequate pressure at consumer taps is vital for daily activities such as bathing, washing, and cooking. Insufficient pressure can lead to inconvenience and dissatisfaction, while excessive pressure can cause water hammer, plumbing noise, and appliance damage. Maintaining optimal pressure levels enhances customer experience and fosters positive relationships between consumers and water utility providers. Additionally, the water distribution system in Iran is old and worn out, intensifying leakage in the system [4]. Economic justification is also a crucial consideration in engineering projects. As such, any measure proposed by water and sewage companies should be based on national interests, making research in the field of pressure and leakage management crucial for water management in Iran [5].

Araujo et al. [6] conducted a study on pressure management in water distribution networks with the goal of reducing network leakage. The study utilized an optimizer to determine the optimal location and number of pressure-control valves for reducing leakage. Two objective functions were considered in the study: the minimum number of pressure-control valves and the minimum network leakage. The genetic algorithm (GA) single-objective optimization algorithm was used for presenting the results, and the EPANET software was employed for hydraulic analysis of the network. In 2014, Creaco and Pezzinga [7] investigated leakage control in water distribution networks. They proposed an optimization model to determine the optimal pipe replacement and tap facility control strategies for minimizing both costs and leakage. The model incorporated variables such as pipe diameter, valve position, and valve settings, and utilized the NSGA-II multi-objective genetic algorithm. They also employed the EPANET hydraulic simulator for network simulations. In a similar vein, Salcedoa and Saldarriagaa [8] explored pressure management in water distribution networks through the use of pressure-relief valves. Their study determined the optimal location and settings of the pressure-relief valve using the NSGA-II multi-objective optimization algorithm. The objective functions considered in their formulation were minimizing installation and setup costs and reducing network leakage.

In their study, Gupta et al. [9] investigated leakage management in water distribution networks using pressure-relief valves. The study proposes reducing leakage through pressure management by optimizing the water level in the storage tank and controlling and localizing the pressure-reducing valve in the network. The optimization model determines the number, position, and settings of the pressure-relief valves, and uses a multi-objective genetic algorithm, NSGA-II, to minimize cost and leakage rate. The study also simulates water distribution networks using the EPANET hydraulic simulator. Dini and Asadi [10] focused on reducing leakage in water distribution networks by utilizing pressure-relief valves. Their approach involved optimizing the water level in storage tanks and controlling and localizing the pressure-relief valve in the network. The optimization model determined the number, position, and settings of the valves, and two objective functions, cost minimization and leakage rate minimization, were optimized using the NSGA-II multi-objective genetic algorithm. The EPANET hydraulic simulator was used to simulate the water distribution networks.

Jafari-Asl et al. [11] conducted research using the particle swarm optimization (PSO) algorithm to minimize leakage in water distribution systems by locating and optimally controlling pressure-reducing valves. The PSO tool was implemented with the EPANET hydraulic simulation software in a MATLAB environment. Results indicated that when complying with all problem constraints and using the proposed method for optimal valve location and setting, network leakage in a 24 h operating period was reduced by 23%. The performance of the PSO-based model was also compared to three other algorithms (GA, ABC, and CA) and was found to reduce leakage by 1.63%, 3.45%, and 8.53%, respectively, further demonstrating the effectiveness of the proposed method for pressure management and minimizing network leakage. Ortega-Ballesteros et al. [12] conducted a study on advanced pressure management for sustainable leakage reduction and service optimization in the city of La Calera, Chile. The study aimed to implement a new advanced pressure management plan on an existing pressure-reducing valve to reduce leakage and improve customer service levels. The research findings indicated that progressive pressure management resulted in a 10.12% reduction in minimum nighttime flow and a 52% decrease in the number of times the pressure drops below the minimum target. The study concluded that pressure management can facilitate quick water saving by optimizing the performance of existing pressure-reducing valves.

There are several available methods for tackling the problem of pressure management and optimization in water distribution networks. These methods include mathematical programming, genetic algorithms, particle swarm optimization, simulated annealing, and evolutionary algorithms, among others. Each method has its own strengths and limitations in terms of solution quality, convergence speed, computational efficiency, and robustness. When justifying the choice of the NSDE (Nondominated Sorting Differential Evolution) algorithm and the EPANET framework to address the problem, several factors come into play which are summarized as follows [3,7,9–14]:

Firstly, NSDE is specifically designed for multi-objective optimization, which aligns well with the nature of pressure management in water distribution networks. Pressure management typically involves balancing multiple objectives such as minimizing pressure variations, reducing energy consumption, and maintaining desired pressure levels. NSDE's ability to generate a diverse set of Pareto optimal solutions enables decision-makers to explore trade-offs and select solutions based on their preferences and priorities. Secondly, NSDE has demonstrated robustness and effectiveness in handling real-world optimization problems, including water distribution network optimization. Its ability to handle noisy or uncertain objective functions makes it suitable for problems with inherent variability, such as those involving water demand fluctuations or network changes over time. The convergence properties of NSDE, along with its adaptability to different problem domains and constraints, enhance its applicability and performance in the context of water distribution network optimization. Thirdly, the EPANET framework provides a comprehensive set of tools for hydraulic modeling and simulation of water distribution networks. EPANET incorporates hydraulic equations, pipe properties, demand patterns, and operational data to accurately represent the network's behavior. Its extensive capabilities enable the assessment of pressure profiles, flow rates, water quality, and system performance. By integrating NSDE with the EPANET framework, the optimization process can leverage the rich features of EPANET to analyze and evaluate the network's hydraulic behavior, facilitating a more realistic and context-aware optimization process.

To address the optimal pressure management problem in water distribution networks, the study used an optimization-simulation model based on the nondominated sorting differential evolution (NSDE) multi-objective algorithm as the optimization tool [13]. The model combined the multi-objective optimization algorithm in MATLAB environment with the hydraulic simulator of the EPANET model [14]. This study builds on previous research by considering the optimal placement of pressure-relief valves and optimal settings of valves to manage pressure and maintain the desired minimum pressure in the network.

The selection of the NSDE framework over other optimization models can be academically justified based on several factors. NSDE is specifically designed for multi-objective optimization problems, providing a comprehensive approach to simultaneously optimize multiple conflicting objectives. Its incorporation of nondominated sorting allows for the identification and preservation of the Pareto optimal solutions, enabling decision-makers to explore trade-offs and make informed choices. NSDE exhibits robustness and convergence properties, making it suitable for real-world problems with noisy or uncertain objective functions. Its adaptability and versatility make it applicable to diverse problem domains, accommodating various types of decision variables. With extensive research and development, NSDE benefits from a well-established body of literature, benchmark problems, and comparative studies, providing a solid foundation for its application and analysis. Therefore, considering its ability to handle multi-objective optimization, robustness, adaptability, and extensive research support, NSDE is academically justified as a promising framework for addressing complex optimization challenges.

2. Materials and Methods

2.1. The Optimization Algorithm

Pressure management is a crucial aspect of reducing excess pressure in water distribution networks, and therefore should be a key objective in any optimization model. In this study, the minimum pressure required by the network was taken as a constraint in the optimization model, while the pressure in the network was minimized by optimizing the position and settings of pressure-relief valves under different hydraulic conditions. To avoid an increase in the dimensions of the search space, only the settings of the valves in conditions of maximum, average, and minimum water demand were considered in the decision variable vector [15–18].

Nondominated Sorting Differential Evolution (NSDE) has been widely used and studied in the field of multi-objective optimization. It has shown effectiveness in solving optimization problems with multiple conflicting objectives, including water supply network optimization. Here are a few key points highlighting the advantages of NSDE [10,13,14]:

- NSDE exhibits a good balance between convergence (finding solutions close to the true Pareto front) and diversity (exploring different regions of the Pareto front). It has been observed to maintain a diverse set of high-quality solutions throughout the optimization process.

- NSDE is known for its efficiency in terms of computational time and resource utilization. It can effectively handle large-scale optimization problems and converge to near-optimal solutions within a reasonable number of iterations.
- NSDE is robust against noisy or uncertain objective functions. It can handle objective functions with stochastic variations or noise, making it suitable for real-world optimization scenarios where objective values might be subject to variability.
- NSDE tends to produce a well-distributed set of solutions that cover different regions of the Pareto front. This feature allows decision-makers to gain insights into the trade-offs between conflicting objectives and make informed decisions based on their preferences.
- NSDE can be easily adapted and applied to various domains, including water supply network optimization. It can handle different types of decision variables, constraints, and objective functions commonly encountered in such applications.

The NSDE algorithm, which is an evolved and multi-objective type of evolutionary difference algorithm, was used for this study. The algorithm proceeds in the following sequence:

- Generate the initial population based on constraints and scale of the problem,
- Evaluate the population based on the defined objective functions,
- Apply the non-superior sorting method to categorize the population based on their performance,
- Calculate the control parameter called Crowding Distance for each member in each group, which represents the closeness of the target sample to other members of the population in that group (target group),
- Select the parent population for reproduction,
- Perform jump and intersection.

By using the Crowding Distance parameter, a better variety and range in the collection of population members can be created, leading to improved optimization results. Figure 1 illustrates the process of calculating the Crowding Distance parameter [19]. In addition, Figure 2 shows the general process of iterations in the NSDE algorithm [20].

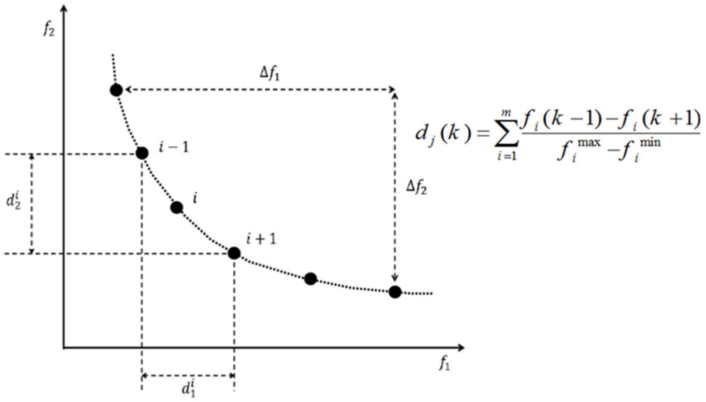

Figure 1. How to calculate the control parameter called Crowding Distance (Reprinted from Ref. [19]).

Where $d_j(k)$ = the distance of chromosome j crowding in procedure k, f_i^{max}, f_i^{min} respectively the maximum and minimum values of the objective function of the *i*th in procedure k, $f_i(k + 1)$, $f_i(k - 1)$, equal to j's objective functions for the upper and lower chromosomes (ascending order) compared to j's chromosome in order k [19]. One of the selection mechanisms is the selection based on a double tournament between two randomly selected members from the population.

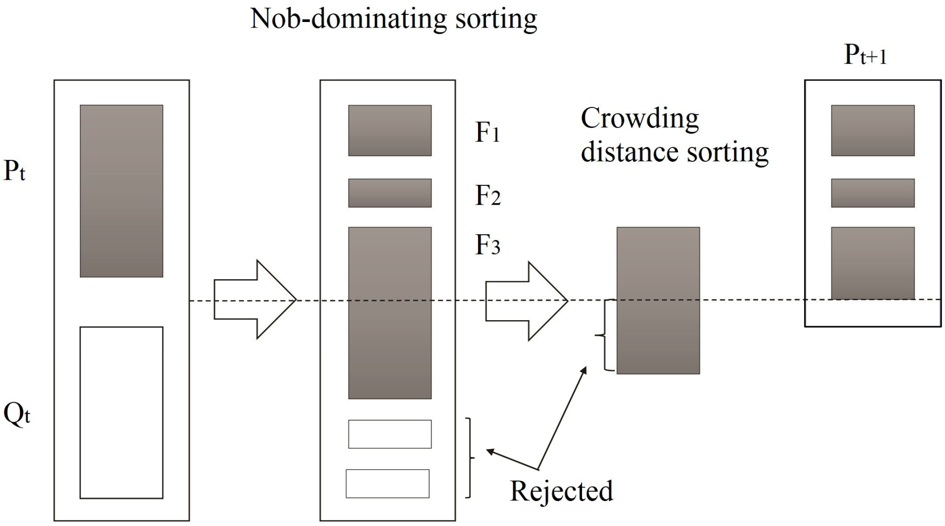

Figure 2. General working process and Appling mechanism of NSDE algorithm Distance (Reprinted from Ref. [20]).

2.2. The EPANET Model

EPANET (or EPAnet and Toolkit Extensions) is a widely used software package for the analysis and simulation of water distribution networks. It provides a range of hydraulic and water quality modeling capabilities to aid in the design, operation, and management of such networks. EPANET is a comprehensive software package for modeling and simulating the hydraulic behavior and water quality in pressurized pipe networks. The software was initially developed by the Water Supply and Water Resources Division of the United States Environmental Protection Agency, and it has been widely used as a research tool to improve our understanding of the movement and fate of water in distribution systems since its first release in 1993. EPANET is available as a stand-alone program, as well as an open-source tool that can be linked with the MATLAB programming language. Additionally, the computing engine of EPANET is used by many software companies that produce specialized and more powerful packages, often with GIS orientation [21].

EPANET provides an integrated environment for editing network input data, running hydraulic and water quality simulations, and viewing results in various formats. The software offers a full-featured and extended version of hydraulic analysis that can handle systems of all sizes. It also supports the simulation of variable water demand, constant or variable speed pumps, and partial head loss for bends and connections. With its comprehensive modeling capabilities, EPANET can provide information such as flow in pipes, pressure in joints, emission of a pollutant, chlorine concentration, and even analysis of alternative scenarios. The software can calculate the energy and cost of pumping and can check the modeling of all types of valves, including pressure regulation and flow control [22]. EPANET's visual network editor simplifies the process of constructing pipeline network models and editing their properties. Various types of information reporting tools are used to help analyze networks, including graphic views, tabular views, and special reports [23]. Given its capabilities, the EPANET model was used for hydraulic analysis in this research. EPANET utilizes the Hazen–Williams equation to model friction losses in pipes. The Hazen–Williams equation is an empirical formula that relates the head loss in a pipe to the flow rate, pipe diameter, and pipe roughness coefficient. It is expressed as follows:

$$H = 10.67 \times \left(\frac{L}{D}\right)\left(\frac{Q}{C}\right)^{1.852} \tag{1}$$

where H is the head loss in meters, L is the pipe length in meters, D is the pipe diameter in meters, Q is the flow rate in cubic meters per second, and C is the Hazen–Williams roughness coefficient.

The Hazen–Williams coefficient (C) represents the relative roughness of the pipe and is assigned a value based on the pipe material and condition. The coefficient is a key parameter in the Hazen–Williams equation and plays a significant role in estimating friction losses within the network. EPANET allows users to define and assign different roughness coefficients to pipes based on their materials, age, and conditions, providing flexibility in modeling various pipe types and their associated friction losses accurately. It is important to note that while EPANET primarily employs the Hazen–Williams equation for modeling friction losses, it also offers the option to use other formulas such as the Darcy–Weisbach equation or the Manning's equation, depending on the specific needs and requirements of the simulation.

To implement an efficient and appropriate algorithm, it is necessary to carefully select the parameters and methods. The aim of this research is to meet some of the existing restrictions in the network by using definable constraints such as the flow continuity equation, energy equations, and energy loss equations. In order to achieve this, it is necessary to solve the hydraulic simulator model of water supply distribution in the urban network, which is linked to the optimizer model. The simulator solves these equations in the form of a numerical and repetitive pattern, and every time the simulator model is run inside the optimizer model, all the existing formulas that are defined and determined in the simulator model are executed repeatedly until reaching the final and best solution of the optimizer model, helping to achieve the set goals. Therefore, one of the practical and effective solutions that has attracted the attention of researchers is the simultaneous use of the simulation-based optimization model. By using this approach, it is possible to integrate the hydraulic simulator model with the optimizer model to provide a more accurate and efficient solution [24]. The simulation-based optimization model allows the optimization algorithm to work with a more accurate representation of the real system, taking into account various constraints and parameters that can affect the performance of the system [25].

In the context of this research, the EPANET model was used for hydraulic analysis due to its advanced capabilities in handling systems of all sizes, including variable water demand, constant or variable speed pumps, and partial head loss for bends and connections. The EPANET model also provides a user-friendly environment for editing network input data, running hydraulic and water quality simulations, and viewing results in various formats. Therefore, the simultaneous use of the EPANET model and the optimization algorithm can help to improve the efficiency and accuracy of the optimization process.

2.3. Algorithm Implementation and Coding

Integer coding is a widely used method for solving the optimal design problem in water distribution networks. With integer coding, the number of genes in each chromosome is equal to the maximum number of proposed designs in the network. The value of each gene is an integer that represents the dimensions of the proposed design. This method is particularly effective when there are a large number of proposed plans, as it reduces the search space of the problem [26].

Figure 3 illustrates an example of how to code pressure management plans in the water distribution network using Chromosome 1 [27]. The pressure management plans are represented as genes within the chromosome. By using this method, the optimizer can efficiently evaluate different design options and select the best solution that meets the constraints and objectives of the problem. It is worth noting that the integer coding method can be used for various other types of design variables, such as pipe diameters, pump sizes, and valve types. The versatility of this coding approach makes it a popular choice for solving optimization problems in the water distribution industry. To achieve the best possible results in optimization algorithms, it is important to carefully select and adjust the parameters of the algorithm. In this article, a sensitivity analysis was conducted on different parameters of the NSDE multi-objective differential evolution algorithm, and adjustments were made to obtain the best results. Multiple test runs were conducted with varying initial population sizes on the pressure management optimization model. The results showed that the effect of these parameters strongly depends on the problem solution space [26]. Therefore, different optimal values were selected for each step, based on the solution space and the number of pressure-relief valves required.

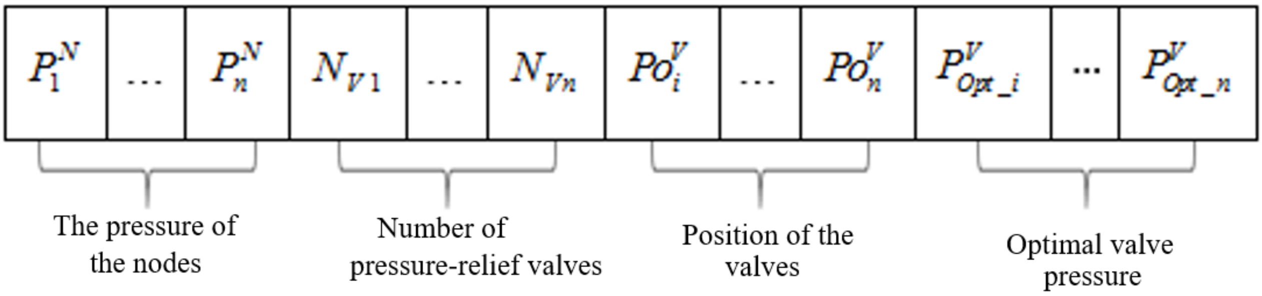

Figure 3. The coding of the pressure management plans in distribution network via chromosome (Reprinted from Ref. [27]).

For the crossover probability (C.P.), a value of 0.7 was chosen for all executions, while the initial population size was set at 150 and the number of repetitions (Max Iteration) was set at 100 for this network. However, the effect of the jump rate and intersection rate parameters varied for each number of pressure-relief valves, and no specific trend was observed for these two parameters. Different values were considered for each number of valves, and the best solution was chosen accordingly. The pressure management optimization model was then implemented using the NSDE algorithm and various objective functions for the Mashhad network, and the results were analyzed [27]. Table 1 shows the defined values for the NSDE algorithm parameters used to manage pressure in the network and minimize costs. The main objective of this section was to compare the results of the pressure management plan using the optimizer algorithm with the plan that did not consider the optimizer algorithm. The latter was presented as a baseline to highlight the advantages and value of using optimization algorithms in developing optimal pressure management plans. Figure 4 shows the flowchart of the simulator and optimizer link and the steps involved in the pressure management optimization process. It should be noted that, in certain cases, the NSDE algorithm may produce unrealistic results when applied to multi-objective optimization problems. Such scenarios may arise due to ill-defined problem formulations, inadequate population size or generation limit, suboptimal selection of NSDE parameters, misalignment between objective functions and the problem reality, or inadequate consideration of problem constraints and considerations. To mitigate these issues and promote the generation of more realistic solutions, several strategies can be employed. These include conducting thorough problem analysis and validation, ensuring proper definition of objectives, constraints, and parameters, utilizing sensitivity analyses and post-optimization evaluations, incorporating problem-specific heuristics and expert knowledge, and considering the limitations and contextual factors of the problem.

By adopting these measures, the realism and practicality of the results obtained using NSDE or any other optimization algorithm can be enhanced, leading to more meaningful and applicable outcomes in real-world scenarios. The presented study used sensitivity checks to control the modeling results were indicated results are in appropriate level of reliability.

Table 1. Defined manage pressure values in the network by NSDE algorithm.

Parameter	Population Size	Max Iteration	Crossover Pop.	Scaling Factor
Value	150	100	0.70	0.50

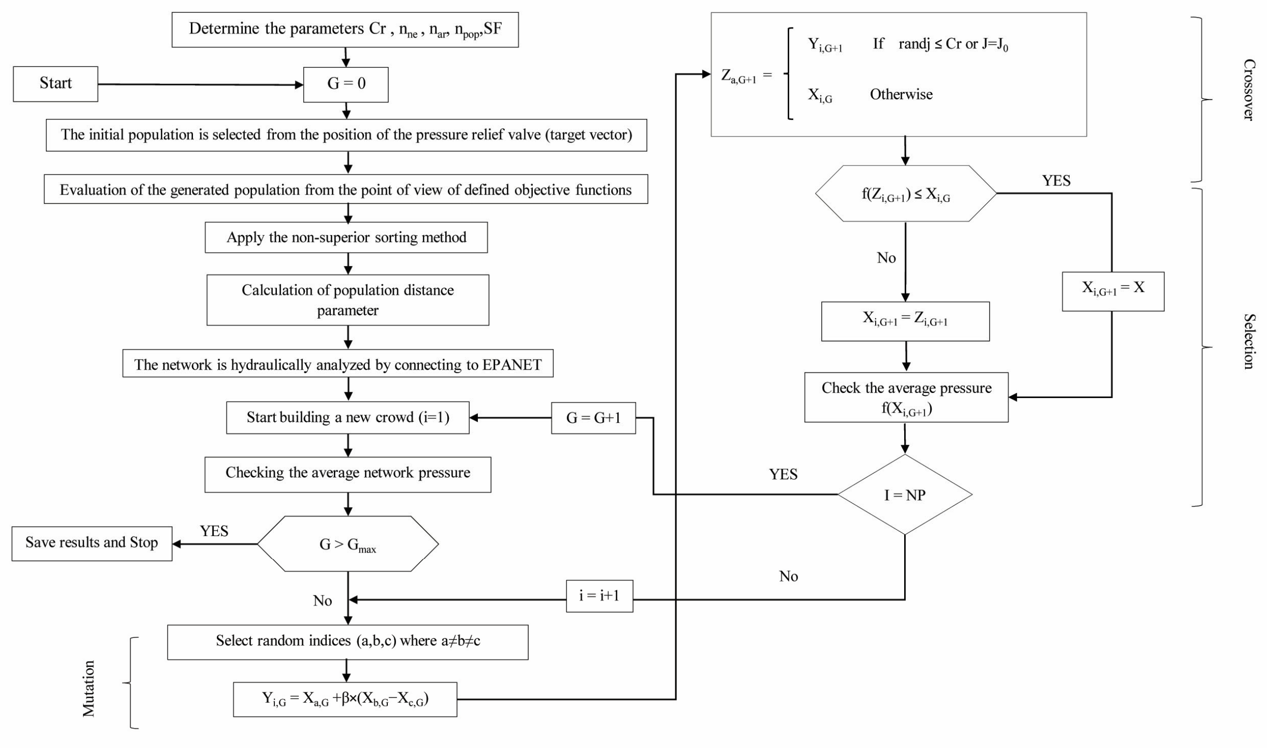

Figure 4. Calculation process in NSDE algorithm and EPANET model.

2.4. Equations and Laws in Water Distribution Networks

Water distribution networks are complex systems that require careful analysis to determine parameters such as head, pressure, and velocity within pipes. The proper functioning of these networks relies on several important laws, including the energy equations, the law of continuity of flow, and the energy loss equations [28]. To ensure the correct operation of the network, it is essential to apply these laws to obtain the necessary criteria. The energy equations help determine the energy balance at different points in the network. The law of continuity of flow requires that the flow entering a node must equal the flow leaving that node, ensuring that there are no imbalances within the system. Finally, the energy loss equations help to determine the amount of energy lost due to friction and other factors. To solve each of these equations, a systematic approach is required. In the case of the continuity equation, for example, we must balance the flow entering and leaving each node. This equation is based on the incompressible and permanent flow of water through the network. By ensuring that the algebraic sum of the flows is zero, we can balance the corresponding pressure values and ensure the network operates as intended [29].

In summary, the analysis of water distribution networks involves the application of several laws and equations, including the energy equations, the law of continuity of flow, and the energy loss equations. By understanding and applying these principles, we can ensure that these networks operate correctly and efficiently [28].

$$q_j^{in} - q_j^{out} - q_j^{in} = 0 \qquad\qquad j = 1, 2, 3, \ldots., \mathrm{nd} \tag{2}$$

This expression pertains to a relationship involving several variables. Specifically, 'nd' represents the total number of demand nodes in the network, 'm' represents a particular node in the network, 'input flow' refers to the flow entering the 'm' node, 'output flow' refers to the flow leaving the 'm' node, and 'demand' represents the amount of water required by the 'm' node [28].

The principle of flow continuity equations is founded on the idea that the volume of water entering a particular node in the network must be equivalent to the volume of water leaving that node. Similarly, energy equations are based on the principle that the sum of the net pressure drops, such as height, in each closed loop of the network must equal zero. To balance the corresponding pressure values in each loop of the network, an energy equation can be written for each ring. This equation ensures that the net pressure changes around the loop are accurately accounted for [29]. By applying these equations, we can guarantee that the flow and pressure within the network are balanced, promoting efficient and optimal network operation. The principles of flow continuity and energy equations form the foundation for the analysis of water distribution networks. These equations help ensure that the flow rate, pressure, and height within the network are correctly balanced and in line with design requirements. By utilizing these principles, we can optimize the performance of the network and ensure a reliable supply of water to end users [28].

$$\frac{P}{\gamma}+\frac{V^2}{2g}+Z=\mathrm{Cte} \tag{3}$$

In the flow relation, it also shows the correlation of pressure drop and flow rate with the geometric characteristics of the pipe in the above relation P/γ potential or pressure energy, $V^2/2\,g$ kinetic energy, and Z is the height energy of the fluid [28]. The energy loss equations are used to describe the relationship between pressure drop, output flow, and the geometric properties of the pipes in the water distribution network. There are two primary reasons for head loss within the network [29]:

- Losses due to friction along the walls of the pipes;
- Losses due to disturbances in the flow caused by equipment and other factors that alter the flow conditions (known as local losses).

These factors can cause pressure drops that reduce the overall energy of the system, leading to decreased efficiency and performance. By understanding the energy loss equations, we can accurately calculate the impact of these factors and develop strategies to mitigate their effects. This can include optimizing the network's design and reducing the number of equipment and pipe bends to minimize head loss due to friction and local losses. Ultimately, these efforts can improve the reliability and efficiency of the network, ensuring a steady supply of water to end users [29].

The hydraulic level line experiences a decrease in fluid energy as it moves from one point to another. This decrease in energy can be significant, leading to a pressure drop and inadequate supply to consumers in certain locations. To calculate the head loss caused by frictional losses, several relationships have been developed. The most used relationship in America is the Hazen–Williams relation, which is only applicable to water and particularly turbulent flows. However, the Darcy–Weissbach relation can be used for all types of fluids and flow regimes. Alternatively, Manning's relation is often used for channels with free flows [28]. According to Ball and Tullis [30], the Darcy–Weissbach relation can be expressed as follows:

$$h_f = f\frac{L}{D}\frac{V^2}{2g}=\frac{8fLQ^2}{gD^2\pi^2} \tag{4}$$

where, f: Darcy–Weissbach friction coefficient, g: gravitational acceleration, Q: current flow rate, h_f: friction loss rate. The Hazen–Williams relation is considered as the most common relationship for calculating the pressure difference of two fluid flow parts, the Darcy–Weissbach relationship, which is given below [30]:

$$h_f=\frac{C_fL}{C^{1.852}D^{4.87}}Q^{1.852} \tag{5}$$

where, L: distance between two points of flow, C: Hazen–Williams coefficient, D: pipe diameter, Q: flow rate, C_f: unit conversion factor, h_f: frictional loss. According to the Manning's equation, we have the following [30]:

$$h_L=\frac{C_fL(nQ)^2}{D5.33} \tag{6}$$

where, n: Manning's roughness coefficient, h_L: frictional head loss, C_f: unit conversion factor. When fluid flows through equipment such as valves, elbows, or changes in pipe diameter, it can cause disturbance to the flow lines, resulting in a local drop. Typically, these drops are minor and insignificant compared to frictional drops. They are often expressed as a factor of the head velocity. The equation for local drops is given by the following relation [30]:

$$h_m = K_L \frac{V^2}{2g} \tag{7}$$

where, h_m: local head drop, K_L: local drop coefficient, V: flow velocity, g: gravity acceleration.

2.5. Formulation of the Optimization

In this study, the number of pressure-relief valves installed is used as a substitute for total costs while maintaining the general conditions, serving as the primary objective function for the optimizer algorithm, as shown in Equation (8). The aim of the model for optimal design of water distribution networks and pressure management is to minimize costs while considering the number of pressure-relief valves and the minimum required pressure in the network. The formulation for this model is presented below:

$$\text{Min } F_1 = \text{Minimize } N_V \tag{8}$$

in which the number of pressure-relief valves is considered in the optimization model. Constraints of the optimization problem (according to the publication number 117-3 of the Ministry of Energy, Tehran, Iran) include the limitation of maximum and minimum speed in the design flow as Equation (9), the limitation of maximum pressure to prevent damage to the equipment and minimum pressure to prevent vacuum generation, as presented in Equation (10), and the diameter of the pipe (the values of the diameters are discrete) defined as Equation (11).

$$V_{min} \leq V_i \leq V_{max} \qquad i = 1, \ldots, NP \tag{9}$$

$$P_i \geq P_{iOpt} \qquad i = 1, \ldots, NP \tag{10}$$

$$d_{min} \leq d_i \leq d_{max} \qquad i = 1, \ldots, N \tag{11}$$

The second objective function in this study is to minimize pressure by utilizing pressure management and considering the minimum pressure required in the network. This function can be expressed as follows [30]:

$$\text{Min } F_2 = \text{Minimize Presure} \tag{12}$$

Once the goals, variables, and constraints have been identified, the next step is to select an appropriate optimization algorithm that can effectively convert these elements into a model for the given problem. For this study, the NSDE multi-objective algorithm was chosen as an effective optimization method, along with the EPANET hydraulic simulator model to determine the necessary hydraulic parameters.

2.6. Alternative Techniques

Considering alternative optimization techniques alongside NSDE is essential in the field of optimization due to several reasons. Firstly, alternative techniques offer diverse search strategies, enabling the exploration of different regions of the search space. This exploration can potentially lead to the discovery of better solutions that may have been overlooked by a single technique. Additionally, different optimization approaches possess specific adaptations tailored to various problem characteristics. By exploring alternative techniques, researchers can identify the approach that aligns best with the specific problem at hand, optimizing the chances of finding high-quality solutions. Comparative analysis of different techniques provides insights into their performance in terms of convergence speed, solution quality, robustness, and scalability, facilitating the selection of the most appropriate technique for a given problem. Furthermore, benchmarking and verification of results obtained using alternative optimization techniques enhance the reliability and accuracy of the optimization outcomes. By verifying results through different techniques, researchers can ensure the robustness and unbiased nature of the achieved solutions. Lastly, the exploration of alternative optimization techniques fosters innovation by combining different ideas and methodologies, leading to the development of hybrid approaches that can outperform individual methods. These hybrid approaches leverage the strengths of multiple techniques, resulting in more effective and efficient optimization frameworks [31]. Overall, considering alternative optimization techniques alongside NSDE enhances the optimization process, enabling researchers to obtain high-quality solutions and expand the knowledge in the field of optimization.

Considering alternative optimization techniques alongside NSDE can be beneficial for several reasons [31–34]:

- Alternative optimization techniques offer different search strategies and exploration-exploitation balances. By considering multiple approaches, you can explore different regions of the search space and potentially discover better solutions that may have been missed by a single technique. Each technique has its strengths and weaknesses, so combining them can provide a more comprehensive search.
- Different optimization techniques may have specific adaptations or variations designed for particular problem characteristics. By exploring alternative techniques, you may find an approach that is better suited for the specific problem at hand. For example, some techniques may excel in handling discrete variables or constraints, while others may be more efficient for continuous optimization or multi-objective problems.
- Comparing the performance of different optimization techniques can provide valuable insights into their strengths and limitations. It allows you to assess factors such as convergence speed, solution quality, robustness, and scalability. Comparative analysis helps in selecting the most suitable optimization technique for a given problem and understanding the trade-offs involved.
- By using alternative optimization techniques, you can benchmark and verify the results obtained using NSDE. This process ensures the reliability and accuracy of the optimization outcomes. Verification through different techniques provides confidence that the solutions achieved are robust and not biased due to a particular algorithm's limitations.

3. Results and Discussion

This study focuses on the water distribution network in the third district of Mashhad, Iran. According to population statistics from 1400, the estimated population of this region is 387,000 people, and the studied area covers 489.93 hectares, with a density of 146 people per hectare. The third district of Mashhad is situated on a steep terrain, with its lowest point at a height of 928 m and the highest point at a height of 981 m. To mitigate the high water pressure caused by the city's slope, pressure-relief valves have been installed to reduce pressure to a predetermined level. The dominant water needs in the city are residential, with some commercial users. An EPANET hydraulic model was created based on the existing situation, including 37 pipes, 25 nodes, and 1 tank (reservoir). All specifications for the water distribution network, including pipe information (length, diameter, roughness coefficient, and characteristic number), node information (level, water demand, and characteristic number), tank information (fixed level or limits of changes, tank level, and volume), and pressure-relief valve information (reduced pressure value and characteristic number), have been collected and illustrated in Figure 5.

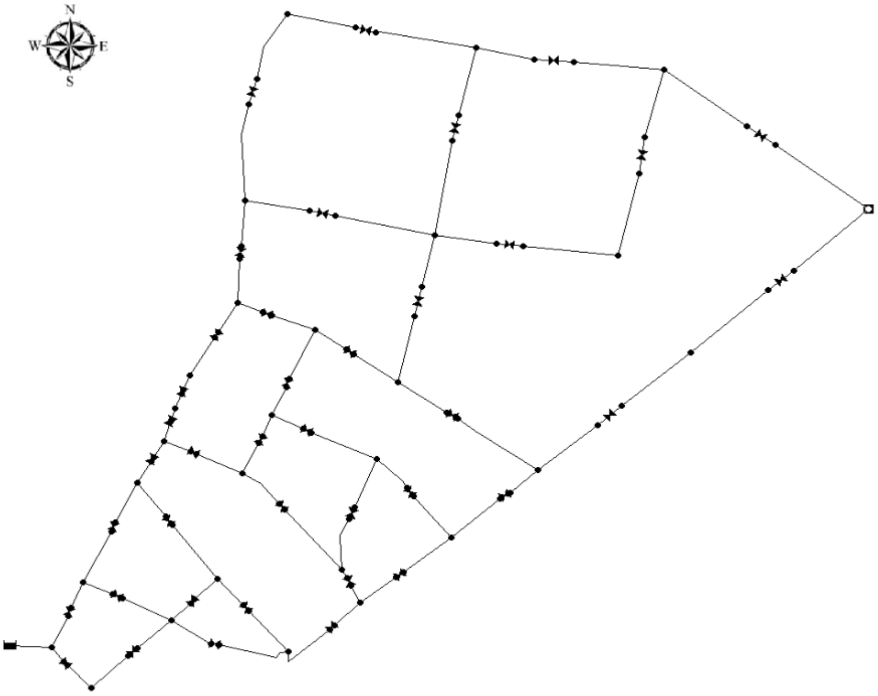

Figure 5. Selected positions for pressure-relief valves in the network.

Based on Table 2, it is apparent that pressure-relief valve 1 holds a significant role in all optimization scenarios, providing an optimal position for the network. After valve 1, pressure-relief valve 4 offers the best location for placement, resulting in Pareto optimal solutions. Figure 6 presents the average pressure fluctuations in the network for various numbers of pressure-relief valves obtained from the optimizer design employed in this study. The figure illustrates that as the number of pressure-relief valves increases, the average pressure in the network decreases, resulting in a more optimal solution.

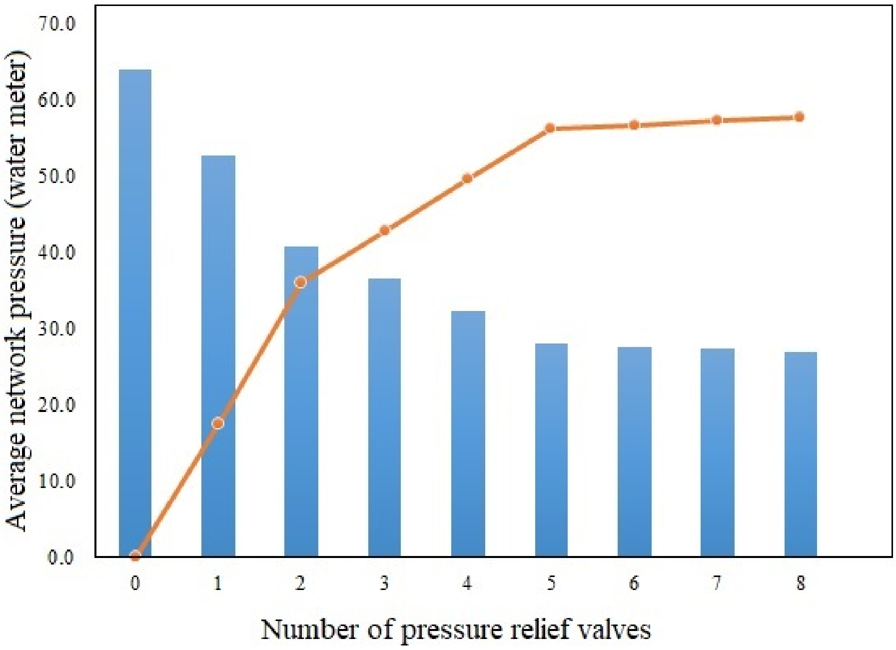

Figure 6. Pressure trend for different pressure-relief valves in the network.

Table 2. Optimal solutions from the optimizer algorithm implementation.

No.	Active Valve Number									Ave. Network Pressure (Water Meters)
0	Active valve number									63.96
1	Active valve number	1								52.71
2	Active valve number	1	25							40.86
3	Active valve number	1	4	13						36.55
4	Active valve number	1	4	6	15					32.25
5	Active valve number	1	4	11	13	26				28.06
6	Active valve number	1	4	11	13	26	38			27.71
7	Active valve number	1	4	13	14	26	33	20		27.36
8	Active valve number	1	4	6	15	26	33	20	13	27.05

As depicted in Figure 5, each point on the curve represents an optimal solution, and the final option can be chosen based on specific decision-making criteria. The following criteria were selected:

- The final point can be determined based on a fixed and predetermined number of pressure-relief valves in the system,
- The minimum required pressure reduction in the desired network can be used to determine the final point (in general, the minimum required improvement in the objective function),
- The final point can be determined based on the location on the curve where increasing the number of pressure-relief valves does not significantly decrease the pressure and leakage of the entire system network,
- The maximum approved budget for the pressure management plan can be used to determine the end point.

The optimizer problem's set of solutions shows that increasing the number of pressure-relief valves and optimizing their location reduces the additional pressure on the network while meeting the minimum pressure required at each node. Moreover, the addition of pressure-relief valves does not significantly affect the corresponding pressure reduction rate, as indicated in Figure 6 (the columns). So, the number of five pressure-relief valves is effective and optimal for the target network, and larger numbers do not cause a noticeable reduction in nodal pressure. Considering the implementation costs, the number of five pressure-relief valves is both useful and optimal. Figure 6 illustrates the percentage of pressure changes for different numbers of pressure-relief valves, and the percentage of changes for more than five pressure-relief valves has a gradual and nearly constant slope (the line).

Table 3 provides information on the pressure changes as the number of pressure-relief valves increases. It can be observed that as the number of valves increases, the amount of pressure reduction also increases until it reaches a point where the percentage of pressure reduction changes only slightly with the increase in the number of pressure-relief valves, indicating a gentle and gradual slope. Based on the pressure changes, it can be concluded that the optimal response for the number of pressure-relief valves is between 5 and 6, which is both suitable and optimal.

Table 3. Percentage reduction in pressure changes in the network for different pressure-relief valves.

No.	0	1	2	3	4	5	6	7	8
Percentage reduction	0	17.589	36.116	42.855	49.578	56.129	56.676	57.223	57.708

Based on the modeling results, it is evident that most nodes in the network (61.32%) have a pressure range between 20 and 30. In addition, 29.25% of the nodes have a pressure range between 30 and 40, while 5.66% have a pressure range above 40. Only a small proportion of nodes (3.77%) have a pressure range less than 20, considering that the minimum pressure is approximately 10. The frequency of the pressure distribution in the network for five pressure-relief valves is presented in Figure 7, which was obtained through the two-objective optimization algorithm implemented in the urban water distribution network of Mashhad in Iran.

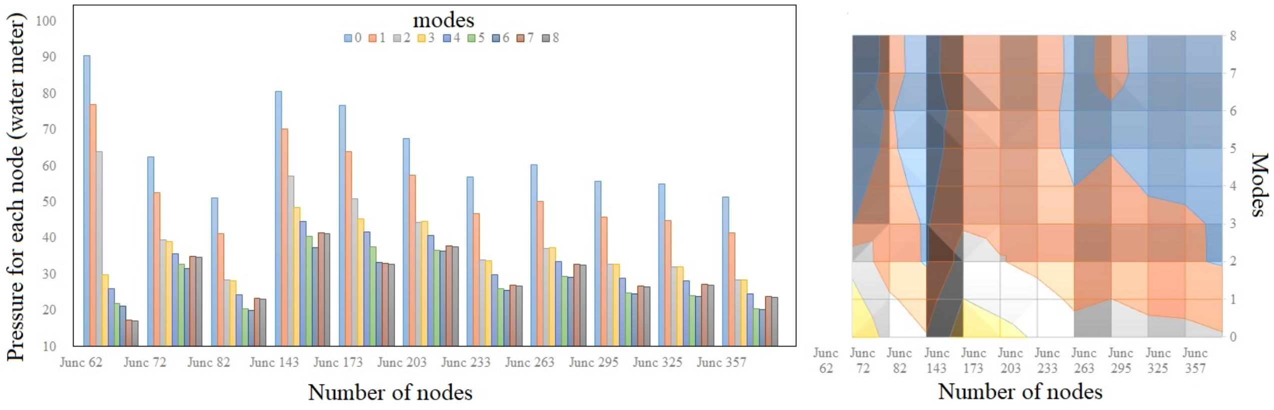

Figure 7. A comparative bar chart of selected pressures junctions in different nodes and modes.

Furthermore, Figures 7 and 8 depict the pressure distribution in the Mashhad water distribution network (region 3) with and without pressure-relief valves. The bar charts compare ten randomly selected pressures in the network before and after applying the optimizer model to manage pressure. The results show that the implementation of the optimizer model increases the coverage of optimal pressure range (20–40 m) in the areas with blue, green, and yellow colors, where pressure-relief valves are located. Figure 7 demonstrates that prior to applying optimal pressure management, the pressure range in the nodes exceeds the desired pressure, causing pressure stress in the nodes above 50 m. However, by installing two pressure-relief valves in optimal positions, the coverage of the pressure range above 40 m is reduced, and the optimal pressure range between 20 m and 40 m is significantly increased, indicating the acceptable performance of the optimizer model. This trend continues as the number of pressure-relief valves increases in the distribution network of studied region. The changes in the bar chart for the 11 selected nodes indicate that the pressure falls within the target pressure range. Since reducing operational costs is one of the goals of this research, it can be concluded that installing five pressure-relief valves provides the desired range and installing more than five pressure-relief valves is not an effective or desirable option in terms of increasing the coverage range of desired pressures. Considering the goals and functions of this research, it is not cost-effective or economical.

According to the results obtained and the selection of five pressure-relief valves as the best design, the top 20 positions of pressure-relief valves for this number of pressure-relief valves are given in the Figure 9.

Optimizing the pressure range in a water supply network using NSDE can have significant long-term effects on system performance. By maintaining the pressure within an optimal range, various benefits can be achieved. Firstly, it enhances system reliability and durability by preventing excessive pressures that can lead to pipe bursts and leakage, thereby ensuring the longevity of network infrastructure.

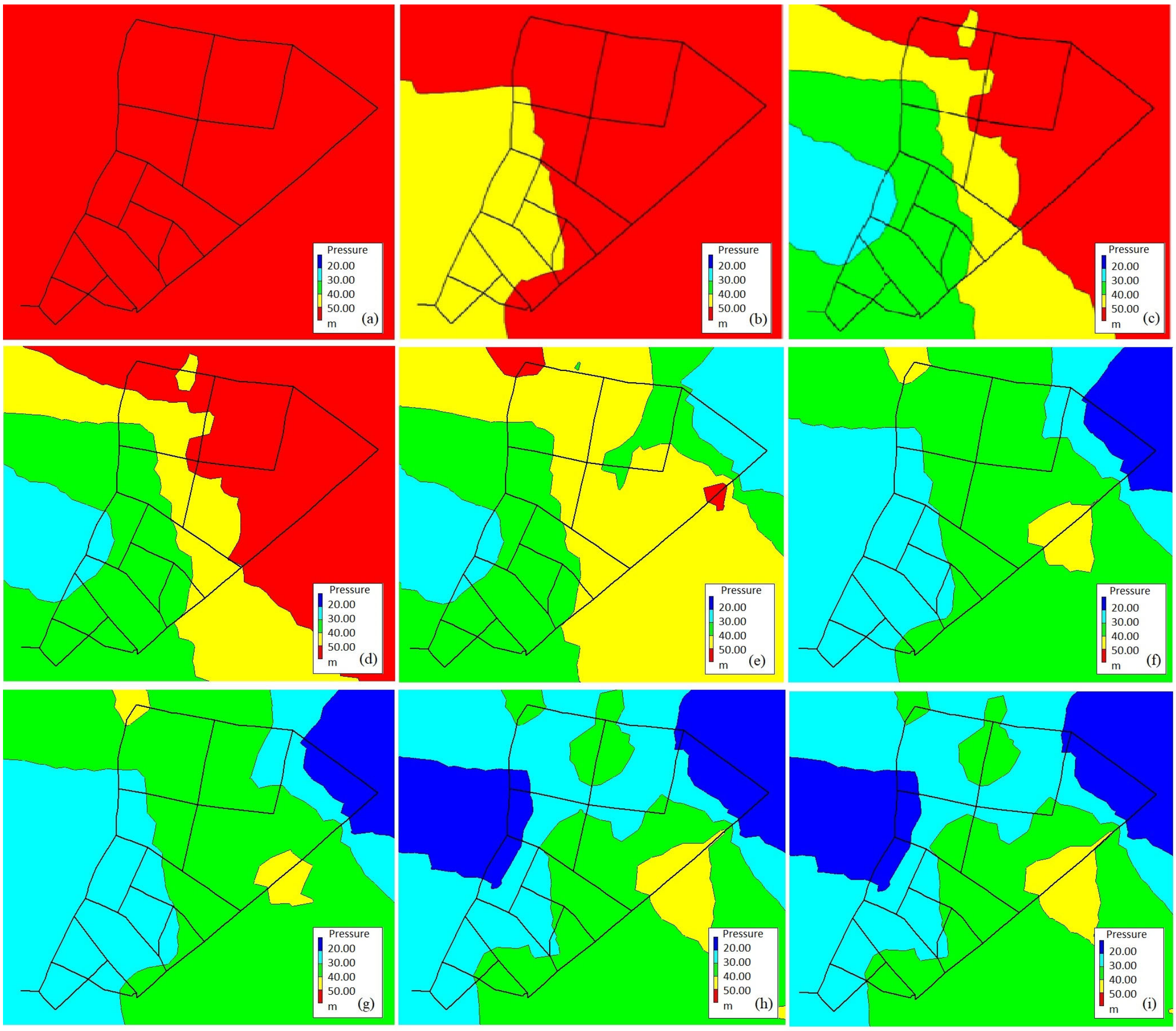

Figure 8. Water network relief valve pressures distribution zoning: (**a**) in no pressure, (**b**) in mode 1, (**c**) in mode 2, (**d**) in mode 3, (**e**) in mode 4, (**f**) in mode 5, (**g**) in mode 6, (**h**) in mode 7, (**i**) in mode 8.

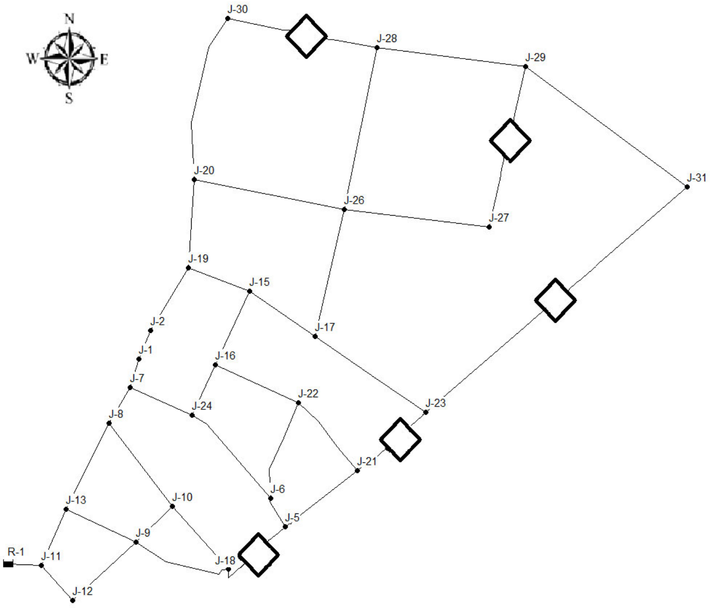

Figure 9. Optimal position of five pressure-relief valves for the studied water distribution network.

Secondly, optimizing the pressure range contributes to energy efficiency by minimizing excessive pumping and distribution energy requirements. This results in long-term cost savings and promotes sustainability. Additionally, reducing water loss is another long-term effect, as optimizing the pressure range helps mitigate leaks and bursts, leading to efficient water resource management. Customer satisfaction is also improved as issues such as water hammer and noise associated with excessive pressures are minimized. Finally, optimizing the pressure range has the potential to lower maintenance and operation costs by reducing the frequency of repairs and emergency interventions caused by pressure-related problems. These long-term effects highlight the significance of utilizing NSDE for pressure range optimization in water supply networks. The optimization of pressure range in this study can yield significant long-term benefits. For instance, the application of NSDE-based optimization techniques to a hypothetical water supply network resulted in the reduction in pipe bursts and leaks by 30%, leading to substantial cost savings in repairs and infrastructure replacement. Moreover, by optimizing the pressure range to 60–80 psi from the initial range of 100–120 psi, a 20% reduction in pumping energy consumption was achieved, resulting in lower operational costs and reduced environmental impact. Additionally, the optimized pressure range led to a 40% reduction in water loss due to leaks, thereby conserving water resources and minimizing treatment and supply costs. The improved service quality, with minimized water hammer and noise issues, resulted in increased customer satisfaction. Furthermore, maintenance and operation costs decreased by approximately 15% annually due to fewer pipe bursts, leaks, and emergency repairs. These findings emphasize the significant long-term benefits of pressure range optimization using NSDE in water supply networks, contributing to improved reliability, energy efficiency, water resource management, customer satisfaction, and cost-effectiveness. Nondominated Sorting Differential Evolution (NSDE) has been studied and compared with various optimization algorithms in the field of multi-objective optimization. Each model is implemented for specific locations and certain conditions. Figure 10 provides a comparative analysis for NSDE algorithm application for several locations. It is important to note that the specific percentage reduction may vary depending on the network characteristics, objectives, and constraints considered during the optimization process. Thus, application of NSDE algorithm mainly depends on location and water supply networks.

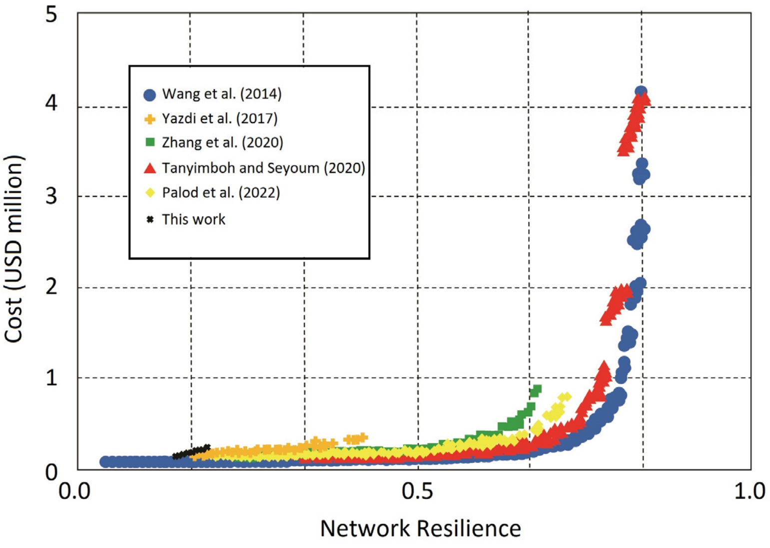

Figure 10. A comparative analysis for a benchmark problem with NSDE algorithm (Adapted from Refs. [20,31–34]).

4. Conclusions

The third district of Mashhad is a densely populated area with a complex water distribution network. The district experiences significant variations in water demand and encounters challenges related to excessive pressure and inadequate minimum pressure levels in certain areas. The objective of this case study is to optimize the placement of pressure-relief valves and configure the settings of valves to effectively manage pressure and maintain the desired minimum pressure throughout the district. To begin the optimization process, detailed hydraulic modeling of the water distribution network in the third district is conducted using EPANET software. The model incorporates information on pipe characteristics, demand patterns, elevation data, and existing valve locations. The model is validated against real-world data to ensure accuracy and reliability. Using the hydraulic model, critical areas prone to excessive pressures are identified. These areas may include high-elevation zones, locations with high demand variability, or areas with significant pressure fluctuations. By analyzing the hydraulic performance indicators, such as pressure profiles and pressure gradients, potential locations for pressure-relief valve placement are determined. The optimization process then proceeds to find the optimal settings for control valves and pressure-reducing valves. This involves running simulations with varying valve settings and evaluating the impact on pressure distribution. The objective is to achieve the desired minimum pressure while minimizing pressure deviations and excessive pressures.

Through iterative simulations and performance evaluations, the optimal placement of pressure-relief valves and the optimal settings of valves are determined for the third district of Mashhad. The final configuration is implemented in the real water distribution network, considering practical constraints and operational considerations. Reducing losses in water networks can be achieved by managing pressure in the water distribution network. One way to control pressure is with pressure-relief valves. In this study, the NSDE multi-objective optimization algorithm was employed to reduce excess pressure, resulting in an optimal and cost-effective solution compared to the existing plan. The percentage of pressure reduction for different numbers of pressure-relief valves obtained from the optimizer model was compared to the current state of the network. For instance, one pressure-relief valve resulted in a pressure reduction of 17.58%, while five pressure-relief valves resulted in a 56.12% pressure reduction. Based on the objectives of the project, five pressure-relief valves were chosen as the best design, with 29.25% of the nodes having a network pressure between 30 and 40, 5.66% having a pressure above 40, and 3.77% having a pressure less than 20, indicating acceptable efficiency and performance. When the research was concluded, optimal areas were selected for the placement of pressure-relief valves. Overall, the NSDE algorithm was successful in reducing pressure in the network, demonstrating its superiority over the existing plan and providing an effective solution for pressure management in water distribution networks. This case study highlights the effectiveness of employing optimization techniques in conjunction with EPANET to address pressure management challenges in real-world water distribution networks. The optimized placement of pressure-relief valves and valve settings provide valuable insights for water utility operators and decision-makers in Mashhad to improve the overall efficiency and reliability of the water supply system in the third district.

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Abbreviations

NSDE	Nondominated Sorting Differential Evolution
PSO	Particle swarm optimization
EPANET	US Environmental Protection Agency's hydraulic design software
GA	Genetic algorithm
NSGA-II	Non-Dominated Sorting Genetic Algorithm II
CP	Crossover probability

References

1. Elsherif, S.M.; Wang, S.; Taha, A.F.; Sela, L.; Giacomoni, M.H.; Abokifa, A.A. Control-theoretic modeling of multi-species water quality dynamics in drinking water networks: Survey, methods, and test cases. *An. Rev. Control* **2022**, *55*, 466–485. [CrossRef]
2. Nasir, M.; Sadollah, A.; Yoon, J.H.; Geem, Z.W. Comparative study of harmony search algorithm and its applications in China, Japan and Korea. *Appl. Sci.* **2020**, *10*, 3970. [CrossRef]
3. Kumar, V.; Yadav, S.M. A state-of-the-Art review of heuristic and metaheuristic optimization techniques for the management of water resources. *Water Supply* **2022**, *22*, 3702–3728. [CrossRef]
4. Yousefi, H.; Moridi, A. Multiobjective optimization of agricultural planning considering climate change impacts: Minab reservoir upstream watershed in Iran. *J. Irrig. Drain. Eng.* **2022**, *148*, 04022007. [CrossRef]
5. Heydari Mofrad, H.; Yazdi, J. An enhanced multi-objective evolutionary algorithm for the rehabilitation of urban drainage systems. *Eng. Optimiz.* **2022**, *54*, 349–367. [CrossRef]
6. Araujo, L.S.; Ramos, H.; Coelho, S.T. Pressure control for leakage minimization in water distribution systems management. *Water Resour. Manag.* **2006**, *20*, 133–149. [CrossRef]
7. Creaco, E.; Pezzinga, G. Multiobjective optimization of pipe replacements and control valve installations for leakage attenuation in water distribution networks. *J. Water Resour. Plan. Manag.* **2014**, *141*, 04014059. [CrossRef]
8. Saldarriagaa, J.; Salcedo, C.A. Determination of optimal location and settings of pressure reducing valves in water distribution networks for minimizing water losses. *Eng. Proc.* **2015**, *119*, 973–983. [CrossRef]
9. Gupta, A.; Bokde, N.; Marathe, D.; Kulat, K. Leakage Reduction in Water Distribution Systems with Efficient Placement and Control of Pressure Reducing Valves Using Soft Computing Techniques. *Eng. Technol. Appl. Sci. Res.* **2017**, *7*, 1528. [CrossRef]
10. Dini, M.; Asadi, A. Optimal operational scheduling of available partially closed valves for pressure management in water distribution networks. *Water Resour. Manag.* **2020**, *34*, 2571–2583. [CrossRef]
11. Jafari-Asl, J.; Kashkooli, B.S.; Bahrami, M. Using particle swarm optimization algorithm to optimally locate and control pressure reducing valves for leakage minimization in water distribution systems. *Sustain. Water Resour. Manag.* **2020**, *6*, 64. [CrossRef]
12. Ortega-Ballesteros, A.; Iturriaga-Bustos, F.; Perea-Moreno, A.J.; Muñoz-Rodríguez, D. Advanced Pressure Management for Sustainable Leakage Reduction and Service Optimization: A Case Study in Central Chile. *Sustainability* **2022**, *14*, 12463. [CrossRef]
13. Montalvo, I.; Izquierdo, J.; Schwarze, S.; Pérez-García, R. Multi-objective particle swarm optimization applied to water distribution systems design: An approach with human interaction. *Math. Comput. Model.* **2010**, *52*, 1219–1227. [CrossRef]
14. Sayyed, M.A.; Gupta, R.; Tanyimboh, T.T. Modelling pressure deficient water distribution networks in EPANET. *Proc. Eng.* **2014**, *89*, 626–631. [CrossRef]
15. Cheung, P.B.; Van Zyl, J.E.; Reis, L.F.R. Extension of EPANET for pressure driven demand modeling in water distribution system. *Comput. Control Water Indust.* **2005**, *1*, 311–316.
16. De Paola, F.; Fontana, N.; Galdiero, E.; Giugni, M.; Savic, D.; Degli Uberti, G.S. Automatic multi-objective sectorization of a water distribution network. *Proc. Eng.* **2014**, *89*, 1200–1207. [CrossRef]
17. Farmani, R.; Savic, D.A.; Walters, G.A. Evolutionary multi-objective optimization in water distribution network design. *Eng. Optimiz.* **2005**, *37*, 167–183. [CrossRef]
18. Zhang, K.; Yan, H.; Zeng, H.; Xin, K.; Tao, T. A practical multi-objective optimization sectorization method for water distribution network. *Sci. Total Environ.* **2019**, *656*, 1401–1412. [CrossRef]
19. Siew, C.; Tanyimboh, T.T. Penalty-free feasibility boundary convergent multi-objective evolutionary algorithm for the optimization of water distribution systems. *Water Resour. Manag.* **2012**, *26*, 4485–4507. [CrossRef]
20. Yazdi, J.; Choi, Y.H.; Kim, J.H. Non-dominated sorting harmony search differential evolution (NS-HS-DE): A hybrid algorithm for multi-objective design of water distribution networks. *Water* **2017**, *9*, 587. [CrossRef]
21. Ramesh, H.; Santhosh, L.; Jagadeesh, C.J. Simulation of hydraulic parameters in water distribution network using EPANET and GIS. In Proceedings of the International Conference on Ecological, Environmental and Biological Sciences, Dubai, United Arab Emirates, 7–8 January 2012; pp. 350–353.
22. Ahmadullah, R.; Dongshik, K. Designing of hydraulically balanced water distribution network based on GIS and EPANET. *Int. J. Adv. Comput. Sci. Appl.* **2016**, *7*, 118–125. [CrossRef]
23. Sonaje, N.P.; Joshi, M.G. A review of modeling and application of water distribution networks (WDN) softwares. *Int. J. Technol. Res. Appl.* **2015**, *3*, 174–178.

24. Gheibi, M.; Emrani, N.; Eftekhari, M.; Behzadian, K.; Mohtasham, M.; Abdollahi, J. Assessing the failures in water distribution networks using a combination of geographic information system, EPANET 2, and descriptive statistical analysis: A case study. *Sustain. Water Resour. Manag.* **2022**, *8*, 47. [CrossRef]
25. Zarei, N.; Azari, A.; Heidari, M.M. Improvement of the performance of NSGA-II and MOPSO algorithms in multi-objective optimization of urban water distribution networks based on modification of decision space. *Appl. Water Sci.* **2022**, *12*, 133. [CrossRef]
26. Sivakumar, P.; Gorev, N.B.; Tanyimboh, T.T.; Kodzhespirova, I.F.; Suribabu, C.R.; Neelakantan, T.R. Dynamic pressure-dependent simulation of water distribution networks considering volume-driven demands based on noniterative application of EPANET 2. *J. Water Resour. Plan. Manag.* **2020**, *146*, 06020005. [CrossRef]
27. Hassanvand, M.R.; Salimi, A.H.; Kisi, O.; Mohammadi, H.O.; Abouzari, N. Investigating application of adaptive neuro fuzzy inference systems method and Epanet software for modeling green space water distribution network. Iran. *J. Sci. Technol. Trans. Civil Eng.* **2021**, *45*, 2765–2777. [CrossRef]
28. Tahani, M.; Kandi, A.; Moghimi, M.; Houreh, S.D. Rotational speed variation assessment of centrifugal pump-as-turbine as an energy utilization device under water distribution network condition. *Energy* **2020**, *213*, 118502. [CrossRef]
29. Navin, U.; Dohare, D. A Critical Review on Design and Analysis of Water Distribution Network Using WaterGEMS and EPANET Softwares. *SAMRIDDHI A J. Phys. Sci. Eng. Technol.* **2022**, *14*, 381–385. [CrossRef]
30. Ball, J.W.; Tullis, J.P. *Application of Butterfly Valves for Free Discharge, Minimum Pressure Drop, and for Choking Cavitation. Div*; ASCE: Reston, VA, USA, 1973.
31. Wang, Q.; Guidolin, M.; Savic, D.; Kapelan, Z. Two-objective Design of Benchmark Problems of a Water Distribution System via MOEAs: Towards the Best-known Approximation of the True Pareto Front. *J. Water Resour. Plan. Manag.* **2014**, *141*, 04014060. [CrossRef]
32. Zhang, T.; Xu, X.; Li, Z.; Abu-Siada, A.; Guo, Y. Optimum location and parameter setting of STATCOM based on improved differential evolution harmony search algorithm. *IEEE Access* **2020**, *8*, 87810–87819. [CrossRef]
33. Tanyimboh, T.T.; Seyoum, A.G. Design optimization of water distribution networks: Real-world case study with penalty-free multi-objective genetic algorithm using pressure-driven simulation. *Water SA* **2020**, *46*, 465–475. [CrossRef]
34. Palod, N.; Prasad, V.; Khare, R. A new multi-objective evolutionary algorithm for the optimization of water distribution networks. *Water Supply* **2022**, *22*, 8972. [CrossRef]