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Review

A Survey of Pressure Control Approaches in Water Supply Systems

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Abstract: Pressure control in water distribution networks (WDNs) provides an avenue for improving both their sustainability and reliability. The complexities of the networks make the problem more challenging as various situational operations must be accounted for to ensure that the entire system performs under recommended conditions. In general, this problem is addressed by the installation of pressure reducing valves (PRVs) in WDNs and determining their appropriate settings. Researchers have proposed the utilization of several control techniques. However, the limitations of both computational and financial resources have compelled the researchers to investigate the possibility of limiting the PRVs while ensuring their control is sufficient for the entire system. Several approaches have been put forward to mitigate this sub-problem of the pressure control problem. This paper presents a review of existing techniques to solve both the localization of PRVs and their control problems. It dwells briefly on the classification of these methods and subsequently highlights their merits and demerits. Despite the available literature, it can be noted that the solution methods are yet to be harmonized. As a result, various avenues of research areas are available. This paper further presents the possible research areas that could be exploited in this domain.

Keywords: water distribution networks; hydraulic simulation; pressure control; pressure reducing valves

1. Introduction

The bulk potable water supply network consists of reservoirs, pipes, and demands. The networks transport the water generally stored in the reservoir to the consumers. Geographical, water distribution networks (WDNs) are vast and interconnected. The effectiveness of water transportation depends primarily on the state of the networks' components. In other words, a broken pipe may result in partial or complete non-delivery of water to its intended consumers. Unfortunately, the increasing level of urbanization increases the vulnerability of WDN components and, therefore, increases the complexities in their operations [1,2].

Such complexities give rise to various abnormalities in the networks. Predominantly, these abnormalities are issues that must be dealt with in the short term (i.e., short-term problems). For instance, the varying consumer demands compel the operator to adjust the pressure in the network continuously to ensure that adequate levels are achieved and water is effectively delivered. For this problem, pumps and pressure reducing valves (PRVs) are often installed in the network,

and the adjustments as the demand changes would constitute the mitigation of the problem. To this end, various propositions have been put forward to ensure proper control of such devices.

In [3], the authors proposed a real-time remote control of variable speed pumps to control the pressure against the varying demand. The proposed approach showed improved control accuracy as compared to P-controllers. Nevertheless, a vast literature refers to the control of PRVs, and therefore, numerous approaches exist for their control. These methods include the classical control law (P-controller [4]), advanced control laws (model-predictive controllers [5], and optimal control (mixed-integer non-linear programming [6]).

Several researchers have reviewed these methods and presented their pros and cons. Their works are often limited to one or two focus points without linking the main pressure control to its sub-problems (i.e., placement of PRVs), as may be seen in Section 1.1 and Table 1. Thus, the uniqueness of this paper may be attributed to the following: (1) it accounts for diverse solution methods to pressure and classifies the approaches for easier digestion by the reader; (2) it associates the sub-problem of optimal localization of the PRVs to the global problem, and solution methods of different classes are reviewed; (3) it draws out from the literature some of the major challenges and identifies possible solution methods to deal with them.

1.1. Existing Reviews and This Review

Several works have been published to contribute to some aspects of the pressure control problem. The work in [7] covered several aspects, namely: (1) the principles of pressure control; (2) the classification of pressure control techniques; and (3) the recommendations offered in the work. The work in [8] on the review of leakage management via effective pressure management. The effect of both excessive and insufficient pressure on the network was also investigated. Model formulations for pressure reduction networks were investigated by [9]. Various solution methods were investigated to highlight both their merits and demerits. A survey of pressure management was presented in [10]. The work of [11] presented the investigation of the modeling and simulation of the problem. Various solution methods for the optimization problem were investigated. The proposed method to mitigate the computationally expensive solution to the optimization problem was also presented. The work in [12] was limited and focused on reviewing the progress on the real-time control of pressure in water distribution networks.

Despite the existence of the readily available literature reviews, various aspects are not investigated adequately or have not been reviewed before. These issues are reviewed in this paper. These issues include the placement of PRVs, the classification of control methods, and solution methods to various optimization problems. Table 1 presents the summarized version of the comparison between other reviews and this present work.

Table 1. Comparison of previous reviews/surveys in the pressure control domain. PCD, pressure control device.

Themes	References						This review
	1	2	3	4	5	6	
Effects of excessive pressure		✓					✓
Model formulation discussion			✓		✓		✓
Principles of pressure control	✓						✓
Placement of PCDs							✓
Classification of pressure control techniques	✓						✓
Pressure control valves (PCV)				✓			✓
Focused, real-time control						✓	✓
Recommendation on future works	✓	✓	✓	✓			✓

1 [7], 2 [8], 3 [9], 4 [10], 5 [11], 6 [12].

The rest of the paper is organized as follows: The derivation of some basic WDNs equations and the models of pipe elements are described in Section 2. In Section 3, the pressure control problem is reviewed, and various solution methods are presented.

2. Water Distribution and Its Basic Equations

A water distribution network is a complex and interconnected system. It is one of the most important infrastructures for water utilities. Their main purpose is to transport water from treatment plants and storage facilities to the consumers [13]. Their design and maintenance represent a significant capital investment in providing clean water to match the current improving standard of living of consumers [7,13]. Water distribution networks consist of vital components such as: (1) pipes, (2) reservoir, (3) dams, (4) pumps, and (5) valves, amongst others [9,14,15], as shown in Figure 1.

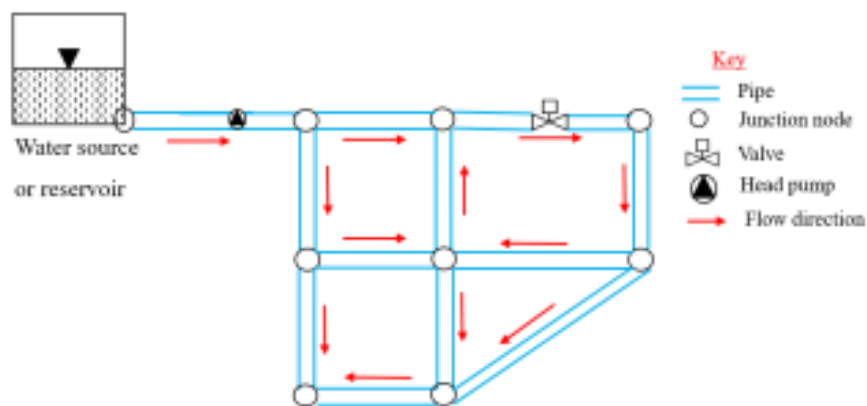


Figure 1. Basic water distribution network [7].

Given a WDN as shown in Figure 1, it can be seen that its topology allows for the utilization of graph-theoretic properties to develop its mathematical representation. Assuming the network consists of N_b branches/pipes interconnected by N_n number of nodes made up of n_s number of sources and n_d number of demand nodes, the node-branch incidence matrix $C_{i,j} \in \mathbb{R}^{N_b \times N_n}$ can be expressed as [16]:

$$C_{ij} = \begin{cases} +1, & \text{if flow in branch (pipe in Figure 1) } j \text{ leaves node } i \\ -1, & \text{if flow in branch (pipe in Figure 1) } j \text{ enters node } i \\ 0, & \text{if branch (pipe in Figure 1) } j \text{ is not incident to node } i \end{cases} \quad (1)$$

The nodal balance equation may then be expressed as:

$$C_{i,j}Q = -I \quad (2)$$

where $Q \in \mathbb{R}^{N_b}$ and $I \in \mathbb{R}^{N_n}$ are vectors of the flows in the branches and nodal injections. The vector Q is primarily composed of flows as shown by the red arrows (indicating the direction of the flows) in Figure 1, whereas the vector I consists of both withdrawals and supply on junction nodes in Figure 1. Equation (2) can be decomposed to express the nodal balance for demand nodes as:

$$C_l Q = -q \quad (3)$$

C_l in (3) is an element of the decomposed $C_{i,j} = [C_s \ C_l]^T$, and q is a vector of nodal withdrawals.

The conservation of energy for the closed-loop WDNs may be expressed as:

$$\Delta h = \begin{bmatrix} C_s^t & C_l^t \end{bmatrix} \begin{bmatrix} h_s \\ h_l \end{bmatrix} \quad (4)$$

where h_s and h_l are the pressure head at the source and demand node, respectively. Δh is the pressure drop along the pipe. For each pipe i , the pressure drop can be expressed as a function of the hydraulic resistance of the pipe k .

$$\Delta h_i = k_i Q_i^\alpha = k_i Q_i |Q_i|^{\alpha-1} \quad (5)$$

In (5), k is the hydraulic resistance of the pipe and α is the pressure coefficient. Substituting Equation (5) in (4), the conservation of energy in matrix form for WDNs can be expressed as:

$$\text{diag}(k|Q|^{\alpha-1})Q - C_s^t h_s - C_l^t h_l = 0 \quad (6)$$

Defining matrix $A = \text{diag}(k|Q|^{\alpha-1})$, the hydraulic simulation model can be written in matrix form as:

$$\begin{bmatrix} A & -C_l^t \\ C_l & 0 \end{bmatrix} \begin{bmatrix} Q \\ h_l \end{bmatrix} = \begin{bmatrix} C_s^t h_s \\ -q \end{bmatrix} \quad (7)$$

The diagonal elements of matrix A depend on the element installed in the pipe. For pipe i with PRV installed as shown in Figure 1 as “Valve”, the element:

$$A(i, i) = k|Q|^{\alpha-1} + m(Q) \quad (8)$$

where $m(Q)$ is the minor loss due to the PRV. For pipes with pumps (“Head” pump in Figure 1),

$$A(i, i) = -\omega^2(h_i - k(Q_{ij}/\omega)^n)/Q_{ij} \quad (9)$$

where ω and n are the parameters depending on the type of pipes installed [17,18].

3. Pressure Control

Pressure control in water supply systems is a well investigated scheme for leakage minimization [8,19–21]. Notable works in this subject could be traced to the early 1990s [19,20]. Hindi and Hamam [19] explored the utilization of constant-outlet-pressure valves and flow-modulated valves for loss minimization in WDNs. However, the excessive computational burden prompted Hamam and Hindi [22] to utilize artificial neural networks to control the pressure. Reduced losses are observed subsequent to the implementation of this scheme. Dai and Li [23] presented an extended model for PRVs to enable the three-mode (open, normal, check valve) operation in water distribution networks for loss minimization without violating the constraints. This formulation was found to be beneficial when tested under several demand scenarios. In [21], a multi-objective strategy was formulated for pressure control and effectively reducing losses in WDNs. Under steady-state operation, the formulated strategy yielded a 6.15 L/s reduction in losses.

Although pressure control via PRVs yields satisfactory results, the energy loss as a result of head loss dissipation is a significant concern [24,25]. This affects the overall energy efficiency as the energy that could otherwise be converted into a useful form is dissipated. The utilization of PRVs jointly with pumps was proposed in [26] to improve the energy utilization of WDNs. The joint scheduling of pressure control and energy recovery based on the demand showed a reduction in leakages and the consumption of electrical energy at pumping stations. In recent times, pumps as turbines (PATs) are being used as a solution for hybrid pressure control and energy recovery. In [27], the speed and pressure control of PATs were investigated. The maximum energy recovered in the work was 23%. To select appropriate and cost-effective applications, PATs were put forward in [28,29].

3.1. Pressure Control Devices

Various pressure control devices are available for different purposes. Their deployment in water distribution networks depends on a specific need that arises. They may be used to control, limit, maintain, or break water pressure, in the pipe or a node of the network. Table 2 shows different types of such devices and their specific use.

Table 2. Pressure control elements.

Element	Use
Pressure reducing valves (PRV)	Regulation of pressure when and if it exceeds the set out values
Pressure sustaining valves (PSV)	Sustain a certain specified pressure value
Pressure control valves (PCV)	Control the pressure in the identified pressure management area
Pressure breaker valve (PBV)	Force and maintain specified pressure loss across the valve
Pumps as turbines (PATs)	Regulation of pressure when and if it exceeds the set out values and the recovery of energy.

In general, PRVs are mostly used when the problem of excessive pressure arises with the reduction of the demand in the network [8]. However, in recent times, due to the scarcity of energy, PATs have been used to recover that excess head loss and convert it into useful energy. The placement of these devices is equally as important as their control to ensure that an overall reduction in pressure is achieved [30] at a minimum operating cost.

3.2. Placement of Pressure Control Devices

Various methods have been put forward in the literature to solve the problem of the placement of PRVs. These methods could be classified into three broad categories, namely (1) the enumerative method, (2) the pressure reference method, and (3) calculus-based/optimization methods.

3.2.1. Enumerative Method

In this method, several valves are randomly inserted into the water distribution network. Optimization techniques that will eventually result in their optimum settings are applied. This method requires significant computational effort to reach the optimum solution; however, it is easier to apply. The work in [31] used successive linearization on nodal heads and pipes' flow equations to be able to use linear programming to solve the valve control problem. Three valves were inserted on the 25 node, 37 pipe network. The results obtained showed that the optimization problem took between eight and 15 iterations to yield the optimal solution.

3.2.2. Pressure Reference Method

This class of methods is based on hydraulic simulation. The reference pressure is identified, and hydraulic simulations are performed under different demand conditions. This method was proposed by [32]. For all demand patterns, the installation sites are selected as pipes that satisfy Rule 1.

$$\text{Rule 1 : if } h_i > h^{ref} \text{ and } h_j < h^{ref}$$

Pipe is selected as a PRV installation site.

Nonetheless, the work in [21] concluded that the method suffered from the drawback that it would not consider the pipes whereby both $h_i > h^{ref}$ and $h_j > h^{ref}$ and their difference was slightly higher. Therefore, this was mitigated by the introduction of the rule that aimed to check the difference

$h_i - h_j$ and considered the pipe if it was found to be above the threshold. Rule 2 was then incorporated into the methodology proposed by [32].

$$\text{Rule 2 : if } h_i - h_j > 0.1 \times h^{ref}$$

Pipe is selected as a PRV installation site.

Further improvement on the pressure reference method was proposed in [33]. This recent improvement leveraged the nodal matrix analysis to enable the scheme to be applicable to large-scale networks.

3.2.3. Calculus-Based/Optimization Methods

This class of methods was first considered in [34] for the placement of PRVs. They proposed a scheme based on minimization of installed valves while minimizing the pressure in the systems. The resultant mixed-integer non-linear programming was linearized to realize the efficient computational scheme to solve the problem. The work in [30] formulated the problem as a mixed-integer non-linear optimization problem (MINLP). The authors proposed the approximation for pipe head loss, and their proposed approach compared favorably to EPANET. The interior point optimizer (IPOPT) was used in [6,23] to solve their hybrid localization and control problem formulated as the MINLP. Their formulation aimed to reduce the number of valves while also reducing the pressure in the network. Reduced pressure was observed after the solving of their problem scheme. The dual problem was further studied and solved using the genetic algorithm (GA) [35,36]. However, earlier in [37], a conclusion was reached that GA did not seem to offer any advantage as compared to solving the integer problem directly. Research on the development of strategies to place PATs is yet to be harmonized with a handful of works having been published. The work in Coelho and Andrade-Campos [38] proposed the utilization of numerical decision support tools to select sites for PATs optimally. This scheme was based on an optimization problem formulated to maximize the potential recoverable energy. A dual objective function was formulated in [24] to maximize the energy recovered and leakage volume reduction. Particle swarm optimization was selected to solve the optimization problem and determine optimal sites for PATs.

The pros and cons of the three classes of methods are presented in Table 3. It is worth noting that those calculus-based methods gave the optimal method at a high computation cost as compared to the enumerative method and pressure reference method.

Table 3. Brief summary of classes of methods for the placement pressure reduction valves in water distribution networks.

Method	Pros	Cons
Enumerative method [31]	Easier to apply	Optimal placement and numbers of PRVs cannot be guaranteed
Pressure reference method [21,32,33]	Less computational burden	Optimal placement of PRVs cannot be guaranteed
Calculus-based/optimization methods [6,24,30,34–38]	Optimal placement, numbers of PRVs can be guaranteed	Computationally demanding

3.3. Pressure Control Techniques

Various control strategies have been developed for pressure management in water distribution networks, and advances in control strategies have improved the ability to manage the operation and efficiency of WDN. In general, control strategies deployed in pressure control in WDNs are based on the following principles, which were reported in [7].

1. Fixed outlet pressure control

2. Time-modulated pressure control
3. Flow-modulated pressure control
4. Closed-loop pressure control
5. Optimal pressure control

Currently, efforts are geared towards real-time control schemes [39,40]. This trend of activities has led to the necessity to improve the schemes such as the expert-based one proposed in [41]. In the said expert-based scheme, pressure measurement points were defined as the state variables of the systems, while the consumer demands points were the disturbance to the system. The control variables of the expert system were the individual pumps at the pump station. The control strategy employed is shown in Algorithm 1 where *condition* is the sequence of logic comparison operation and *conclusion* is the sequence of assignments to control variables.

Algorithm 1: Expert System Control Rule

Data: System measurements.
Result: Decision for system control

```

1 Initialization;
2 while System in operation do
3   get measurements;
4   if condition is satisfied then
5     conclusion;
6   else
7     get measurements;
8   end
9 end

```

The work on the logic controller was further expanded to develop constant pressure water supply [42]. The programmable logic controller in conjunction with a frequency converter was used to achieve constant pressure water supply. The drawback of this system stemmed from the fact that water demand is not constant. Therefore, by applying constant pressure on the system, there existed a possibility of excessive or insufficient pressure in the network.

In general, the most common control techniques applied for pressure regulation may be classified into five broad categories as shown in Figure 2.

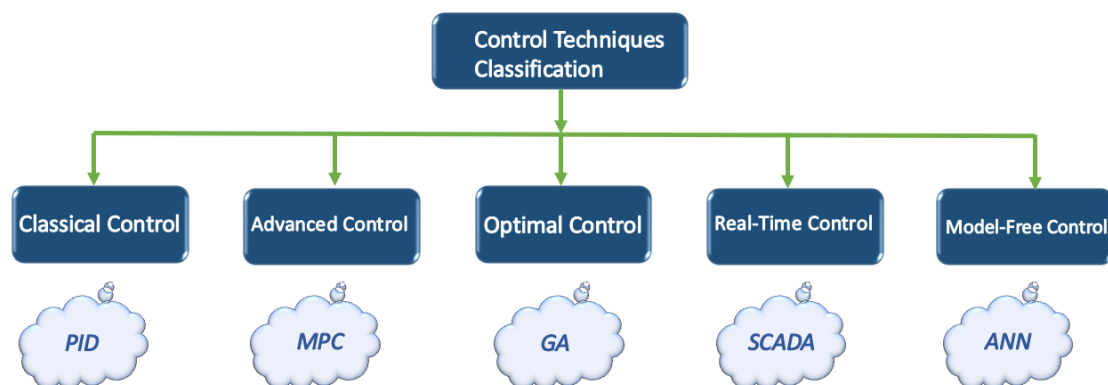


Figure 2. Classification of control techniques.

3.3.1. Classical Control Strategy

Classical control methods are based on one-at-a-time parameter control (On-Off) or PID controllers. Their application could be appropriate for small-scale systems; however, they may still be applied

in WDNs. The PID controller is a common strategy for different industrial processes. In [4], the parameterless P-controller was proposed. The P controller proposed was based on the trial and error method for tuning of the gain parameter K_0 . The classical PID controller was proposed by [43] to control the pumping system in WDN for pressure regulation. However, concerns about its control precision and capability were raised in [44]. The issue of frequency fluctuations that may lead to unsteady pressure in the pipeline was also raised in [45]. The work in [46] proposed PID to control the PRV to improve the response of the system under transients. The proposed scheme showed improvement in network response.

3.3.2. Advanced Control Strategies

As systems such as WDNs are becoming more complex, advanced control strategies with the capability of controlling several parameters at the same time may be appropriate. To advance the work done by [42], a two-dimensional fuzzy controller was proposed in [45]. The deviation between a pre-determined and measured pressure in WDN was the input to the controller, and the output was the control system commands. The fuzzy-based system was also used for operational optimization in [47]. By using these systems, valve opening and control of the pumping system were achieved. Nevertheless, it is imperative that the pre-determined pressure be adjusted as the demand in WDNs varies.

Fuzzy PID controllers were also exploited for pressure management in [44]. Inputs to the fuzzy PID controller were the error e and change in error de/dt , as shown in Figure 3. The self-adaptive gain parameters K_p , K_i , and K_d were used by the controller to find a relationship between PID parameters and input parameters.

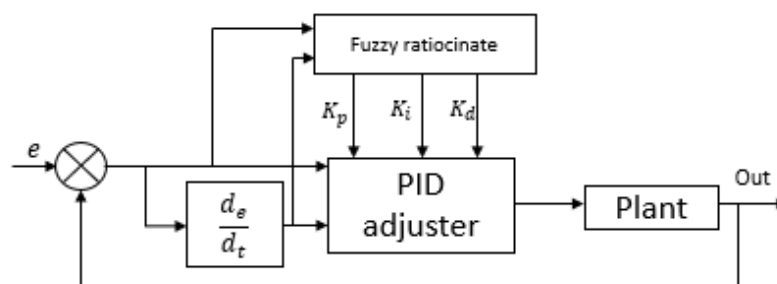


Figure 3. Basic model predictive scheme [44].

Adaptive reference control was proposed in [32,48] to achieve constant pressure at the critical node of the system. Various authors have proposed model predictive control (MPC) for pressure management in WDNs. To a great degree, MPC has been a useful control technique in various industrial processes. This is due to its ability to re-develop a control problem into an optimization problem [49] and its usefulness in real-time application [50,51]. Figure 4 shows the basic MPC proposed by [14]. The proposed scheme used the pressure-driven model to simulate the dynamics of the WDN.

From the measurements that were taken in the WDN flow rate, pressure and outflow rate were estimated [5] and integrated with the optimizer. The optimizer found the optimal pressure settings by minimizing the objective function:

$$\begin{aligned} & \text{minimize} && f(q) \\ & \text{subject to} && 0 < u_k < 1 \\ & && h_i \geq h^{min} \end{aligned} \quad (10)$$

where u_k is the PRV control position index, h_i is the pressure associated with node i , h^{min} is its minimum pressure allowed, and q is the flow in the pipe. An improved MPC was designed by [52] with an improved predictor model. In their earlier work, an extended period simulation was used as the predictor model. However, in the latter work, a quasi-steady-state model was used. In [53], reliable

fault-tolerant MPC was proposed. The design of the controller was done such that, after a fault occurred, the optimization and predictive capability was not affected.

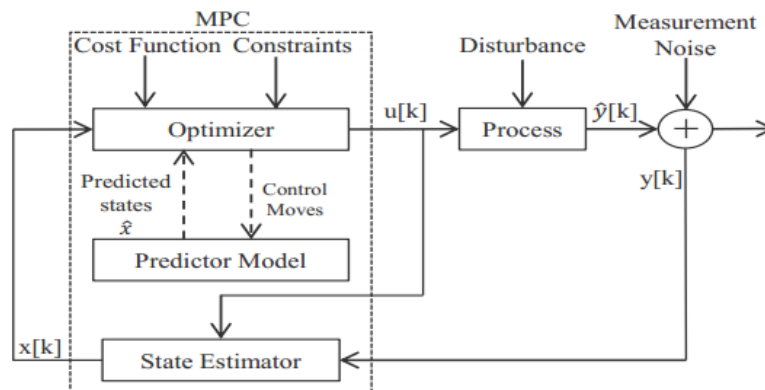


Figure 4. Basic model predictive scheme [14].

3.3.3. Optimal Control

Optimal pressure control in a water distribution network is desired to ensure the minimization of leakages [54]. Often, the optimization is formulated to minimize the pressure under multiple demands [35,55,56]. The work in [19] formulated the pressure reduction problem as a non-linear, non-convex optimization problem. Two separate programming schemes were proposed to approximate non-linearly as an approximated linear programming problem. Their approach saw an improvement in computational efficiency in obtaining the solution. Recently, in [57], the same strategy was applied to enable the response to different demand schedules. In [30], the problem of optimal pressure control by proposing the quadratic approximation of the pipe friction was addressed. The resultant non-linear problem was linearized, and the obtained solution showed a 1% deviation when compared to the commonly used EPANET [17]. It is worth noting that the linearization of the problem would ultimately reduce the accuracy of the solution.

The problem of pressure control in WDNs was solved as the non-linear optimization problem in [58]. It was observed that the increment of PRVs in the network resulted in the increased computational burden required to solve the problem. The interior point optimizer (IPOPT) was used in [6,23] to solve the MINLP problem for pressure control. A decrease in pressure was observed, and the optimizer took ≈ 4.93 seconds. Strictly feasible sequential convex programming for control of pressure reducing valves was proposed in [59]. The proposed methodology was used to solve the formulated NLP problem. The results showed a reduction of 3.7% in pressure reduction. An MINLP problem was formulated to maximize the recovered energy and control the pressure in the WDN [60]. The scheme was tested on a 25 node benchmark test case. The results in [60] showed that optimization could aid decision making in the installation of PATs.

Some researchers have favored the utilization of meta-heuristic techniques to solve pressure control problems. Conventional genetic algorithms (GA) were used to find optimal pressures in WDN [61]. The algorithm searched for a solution using adaptive mechanisms, and it was non-deterministic. The work in [62] used GA to solve the optimization of PRV problem formulated as the minimization of the difference between the maximum and the minimum pressure in the WDN. Their results showed that it was possible to control the abnormal surges in pressure by the optimal setting of the PRV parameters. The work in [63] incorporated the weighted penalty in the GA in order to optimize the operation of the WDNs. The optimization procedure for energy recovery and leakage reduction utilizing GA was developed in [64]. The objectives of the optimization procedure were set to maximize the amount of energy recovered and the percentage of loss reduction. In [65], a hybrid genetic algorithm was used to solve derivative-free non-linear programming for the optimal setting of PATs for pressure control. The results showed that the scheme was able to maximize the energy

produced by PATs. The non-dominated sorted genetic algorithm was used in [21,36,66] to solve the multi-objective optimization problems. The optimization problems were formulated to reduce the number of valves used and to also determine their optimal operation. However, since these were heuristic approaches, global optimality could never be guaranteed.

The music-inspired approach was to obtain the optimal setting of the PRVs in [67]. This methodology showed improved performance as compared to the genetic algorithms. The technique showed computational time and leakage reductions. Another scheme that showed a reduction in computational effort was the tabu-search metaheuristic approach proposed in [68].

3.3.4. Real-Time Control

Research investments in real-time control of pressure in WDN have been gaining momentum recently [4,69]. In contrast to pressure settings during the operation of the network, these methods aim to determine the best pressure setting from continuous measurements that are taken. From the measurements, the pressure control devices (PCDs) in WDNs are adjusted appropriately taking into account the demand that must be met. Real-time pressure control strategies may be based on classical or advanced control strategies.

The work in [69] proposed a logic control algorithm to mitigate excessive and insufficient pressure that may exist in the network. Their control strategy assumed that a desired set-point value of piezometric height h_{sp} was known. The deviation of piezometric height $h(t)$ from the set-point was then used to calculate the variation $\Delta a(t)$ of closure setting a of the valve.

Remote real-time control of the pressure control valve (PCV) is currently an advanced method of pressure management in WDN [4,40]. This technique enables the data collection from all the nodes in the network including isolated/remote nodes. Proportional (P) controllers were used in [3,4,70], while in [40], programmable logic control was used to achieve remote real-time pressure control. Integral controller (I) $C(s) = \frac{K_i}{s}$ was used in [71] to regulate the pressure by controlling PRVs in WDN. Laboratory experiments were used to validate the capability of the said controller.

Supervisory control and data acquisition systems (SCADA) [72] in conjunction with a genetic algorithm were a scheme proposed in [39,73] to ensure that the pressure levels were maintained within acceptable limits. The proposed scheme was used in real time with application to WDN.

3.3.5. Model-Free Control

Model-free control (MFC) is a concept that encapsulates techniques often employed to control complex systems by using the ultra-local model of the network (simplified representation) [74]. An MFC scheme does not need an explicit solution of the model to control the manipulated variables of the systems. In general, they are employed to avoid complex computations that are related to the non-linear system, which are often expensive to evaluate [74]. Hamam and Hindi [22] proposed to leverage the ability of neural nets (NN) to describe non-linearity and developed the emulator for an optimization procedure. This showed a reduced computational burden to control the PRV for pressure minimization, and a substantial reduction in leakage was also observed. The approach adopted in [75,76] was to mimic the hydraulic solution of WDNs. The resultant emulator was then coupled to GA to determine the appropriate settings of the PRVs. Though the schemes [22,75,76] were able to control PRVs without an explicit solution of the hydraulic model, the change in the topology of the system would render them absolute.

3.3.6. Summary and Comparison of Research Outputs

Table 4 shows the summary of the control techniques. The summary includes the limitations of the schemes and their suitable applications. In Table 5, contributions from some of the reviewed literature are shown. The various aspects covered include the control strategy, the periods' studies, and the inclusion of uncertainties. It can be seen from Table 5 that the evaluation of the control models has not considered the uncertainties of demand.

Table 4. Brief summary of control techniques commonly employed in pressure control of water distribution networks.

Technique	Operation Strategy	Remarks	Limitation	Application	Classification
Classical Control [4,43–46]	Based on one-at-a-time parameter control (On-Off) or PID controllers	Cost-effective and easy implementation, however not suitable for large-scale WDN	One parameter control at a time	Suitable for small-scale systems	Physical model-driven
Advanced Control [14,32,40,48,50,51]	A model is required to mimic the behavior of the system. Based on prior knowledge of the requirements in the system, these controllers adjust the controlled variable to reduce the error between the reference and required quantities.	Their implementation is cumbersome, and the accuracy of the model will determine the accuracy of the results.	Difficulty in their implementation	Suitable for large-scale networks	Physical model-driven
Optimal Control [19,36,58–61,67]	Based on the principles of calculus, the best operating parameters are selected. These parameters may be selected under various constraints or no constraints at all.	The computational requirements of this class of methods have proven to be very cumbersome. Therefore, this method may not be ideal for real-time applications.	Computational resources limit the number of control variables in time constraint applications	For large-scale networks	Physical model-driven
Real-Time Control [4,72,73]	Based on the measurements obtained in real time, through the SCADA or other application, a control law is applied, and necessary adjustment instructions are produced	A sizable capital investment is required to get these systems running	Control laws that may be applied are limited by the available processing power	Can be used in any systems where real-time infrastructure is available	Physical model-driven
Model-Free Control [22,75,76]	Based on the utilization of emulators to mimic the model of the chosen control law	Requires a large training dataset to realize an accurate emulator	Challenges in adapting the said emulator as the topology of the network changes	Suitable to a network with minimal changes in the topological design	Data-driven

Table 5. Comparison of the research.

Reference	Control	Single-Periods	Multi-Periods	Transients	Uncertainty
[4]	P		✓		✗
[43,45,46]	PID		✓	✓	✗
[14,51,52]	MPC				
[19,20,30,31]	NLP → LP	✓			✗
[6,21,23,35,36,39,55]	NLP		✓		✗
[22,75,76]	NN		✓		✗

4. Discussion and Suggestion for Future Works

In the past three decades, the pressure control problem has been addressed by various scholars. Predominantly, researchers have favored the utilization of an optimization method to solve the problem. Their advantages include the ability to control more than one element at a time. As a result, the problem formulation has evolved over the years; from the rather presumptive propositions in [19] to models including the holistic modeling of the pressure reducing valves [23]. Two prominent issues arose from the review: (1) computational requirements for optimal solutions; and (2) the methodologies presented were not tested under uncertainties in the WDNs. For the former, linearization on the non-linearity is ordinarily performed. However, the cost of this in the accuracy has not yet been put forward, therefore leading to the possibility of a trade-off between accuracy and computation. On the latter issue, multi-period simulations have been done before [3,31]. However, the demand patterns used in the studies were predetermined. Although the control schemes yield satisfactory results, the performance of the schemes has not been tested under uncertain conditions.

Furthermore, it is evident that most of the methods rely on the accuracy of the model to produce accurate control settings of the PRVs. It is worth noting that elements of the WDNs are exposed to various environmental conditions. As a result, the parameters of the WDN elements (i.e., hydraulic resistance) will inevitably be affected, consequently causing a mismatch between the real system and its model. Therefore, relying on the model to produce appropriate control settings of the PRVs may result in inaccurate adjustments of the real WDN systems.

Although outstanding achievements have been reported in the formulation of the pressure control problem, further improvement could still be attained in the face of various conditions that the WDNs operate under. In the context of uncertainties in demand patterns, computation of the optimization solution and possible mismatches between the model and the real system, the following can be considered as future studies.

1. Incorporating the demand uncertainties into the control problem to evaluate its robustness
In [77,78], various methods for modeling the predictive uncertainty of water were put forward. These schemes could be incorporated in the formulation of the control problem so that the robustness of the control scheme could be evaluated under uncertainties.
2. Deployment of the emulators in pressure control
Despite the existence of the literature [22,75,76] in this aspect, it can be noted that the niche is yet to be harmonized. This stems from [22] developing the emulator for the optimization procedure, whereas [75,76] developed the emulator for the hydraulic model. It is worth noting that all these works deployed back-propagation neural nets to develop the emulators. The strength of this method lies in the computations required to evaluate the model once it is trained. However, thousands of measurements have to be available for training of the model to increase its accuracy. The advances in the machine learning field offer some opportunities for improvement of MLPs in terms of their training and accuracy. The learning rate of these techniques could be investigated as related to WDN applications. Deep neural networks (DNNs) are paradigms that could be deployed and their suitability investigated in WDNs applications.
3. Reinforcement learning (RL)-based controllers
Owing to the advance mentioned in Item 2, RL-based controllers could be explored for pressure

control in WDNs. The strength of this scheme could be based on the fact that prior knowledge of the system is not required to develop the controller. The RL-based controller learns from its experience as it interacts with the environment. This could be beneficial as the accuracy of the controller would not be lost as a result of estimating the parameters of the model.

5. Conclusions

Efficient pressure control in the water distribution network is essential to improve its performance. The effective implementation of pressure could see improvement of the sustainability of the WDNs. This paper investigated the pressure control solution methods that are often applied in WDNs. Methods commonly employed in the literature may be categorized as: (1) classical control, (2) advanced control, (3) optimal control, (4) real-time control, and (5) model-free control. It was evident from this paper that several methods have been put forward to control the pressure in WDNs adequately. However, shortcomings exist in the proposed methodologies. In the classical control case, the first deficiency is its ability to manipulate multiple variables at the same time, and the second concerns the fluctuations observed by researchers. The complexity of computations that must be solved in advanced and optimal control methods are major concerns raised in the literature. However, they do eliminate the issue of multiple manipulations of variables. In real-time control, the classical PID controllers are augmented and deployed. As a result, the deficiency of multi-variable manipulation remains. Model-free control proposed in the literature relies only on the prior knowledge of the WDN. They are rigid and cannot be used should the topology of the network change. Furthermore, it is not clear whether these schemes could still yield a favorable outcome should they be tested under uncertain conditions.

Owing to the shortcomings identified, it is clear that more work has to be done to reach harmonized solutions. To that end, this work suggests that future works can explore: (1) the incorporation of uncertainties in the control problem to evaluate the robustness of the control, (2) the utilization of computationally efficient emulators, and (3) the deployment of RL-based controllers.

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References

1. Bello, O.; Abu-Mahfouz, A.M.; Hamam, Y.; Page, P.R.; Adedeji, K.B.; Piller, O. Solving management problems in water distribution networks: A survey of approaches and mathematical models. *Water* **2019**, *11*, 562. [[CrossRef](#)]
2. Adedoja, O.S.; Hamam, Y.; Khalaf, B.; Sadiku, R. Towards development of an optimization model to identify contamination source in a water distribution network. *Water* **2018**, *10*, 579. [[CrossRef](#)]
3. Page, P.R.; Abu-Mahfouz, A.M.; Mothetha, M.L. Pressure Management of Water Distribution Systems via the Remote Real-Time Control of Variable Speed Pumps. *J. Water Resour. Plan. Manag.* **2017**, *143*, 04017045. doi:10.1061/(ASCE)WR.1943-5452.0000807. [[CrossRef](#)]
4. Page, P.R.; Abu-Mahfouz, A.M.; Yoyo, S. Real-time Adjustment of Pressure to Demand in Water Distribution Systems: Parameter-less P-controller Algorithm. *Procedia Eng.* **2016**, *154*, 391–397. doi:10.1016/j.proeng.2016.07.498. [[CrossRef](#)]
5. Kumar, S.M. Monitoring and Control of Water Distribution Networks. Ph.D. Thesis, Indian Institute of Technology Madras, Chennai, India, 2008.
6. Dai, P.D. Efficient Optimization of Pressure Regulation in Water Distribution Systems Using a New-Relaxed Pressure Reducing Valve Model. *Vietnam J. Sci. Technol.* **2018**, *56*, 503–514.

7. Adedeji, K.B.; Hamam, Y.; Abe, B.T.; Abu-Mahfouz, A.M. Pressure management strategies for water loss reduction in large-scale water piping networks: A review. In *Advances in Hydroinformatics*; Springer: Singapore, 2018; pp. 465–480.
8. Puust, R.; Kapelan, Z.; Savic, D.; Koppel, T. A review of methods for leakage management in pipe networks. *Urban Water J.* **2010**, *7*, 25–45. [[CrossRef](#)]
9. De Corte, A.; Sörensen, K. Optimization of gravity-fed water distribution network design: A critical review. *Eur. J. Oper. Res.* **2013**, *228*, 1–10. [[CrossRef](#)]
10. Xu, M.; Yang, J.; Hughes, D.M.; Lechevallier, M.W. Survey of pressure management in water distribution systems. *J.-Am. Water Work. Assoc.* **2014**, *106*, E518–E524. [[CrossRef](#)]
11. Kanakoudis, V.; Tsitsifli, S. Potable water security assessment—A review on monitoring, modeling and optimization techniques, applied to water distribution networks. *Desalin. Water Treat* **2017**, *99*, 18–26. [[CrossRef](#)]
12. Creaco, E.; Campisano, A.; Fontana, N.; Marini, G.; Page, P.; Walski, T. Real time control of water distribution networks: A state-of-the-art review. *Water Res.* **2019**, *161*, 517–530. [[CrossRef](#)]
13. Keedwell, E.; Khu, S.T. A novel evolutionary meta-heuristic for the multi-objective optimization of real-world water distribution networks. *Eng. Optim.* **2006**, *38*, 319–333. [[CrossRef](#)]
14. Sankar, G.S.; Narasimhan, S.; Narasimhan, S. Online model predictive control of municipal water distribution networks. In *Computer Aided Chemical Engineering*; Elsevier: Amsterdam, The Netherlands, 2012; Volume 31, pp. 1622–1626.
15. Wang, Y.; Cembrano, G.; Puig, V.; Urrea, M.; Romera, J.; Saporta, D.; Valero, J.G.; Quevedo, J. Optimal Management of Barcelona Water Distribution Network Using Non-Linear Model Predictive Control. *Ifac-Papersonline* **2017**, *50*, 5380–5385. [[CrossRef](#)]
16. Hamam, Y.; Brameller, A. Hybrid method for the solution of piping networks. *Proc. Inst. Electr. Eng.* **1971**, *118*, 1607–1612. [[CrossRef](#)]
17. Rossman, L.A. *EPANET 2 Users Manual*; United States Environmental Protection Agency: Washington, DC, USA, 2000.
18. Todini, E. Towards realistic extended period simulations (EPS) in looped pipe network. In Proceedings of the Water Distribution Systems Analysis Symposium 2006, Cincinnati, OH, USA, 27–30 August 2006; pp. 1–16.
19. Hindi, K.; Hamam, Y. Pressure control for leakage minimization in water supply networks Part 1: Single period models. *Int. J. Syst. Sci.* **1991**, *22*, 1573–1585. [[CrossRef](#)]
20. Hindi, K.; Hamam, Y. Pressure control for leakage minimization in water supply networks: Part 2. Multi-period models. *Int. J. Syst. Sci.* **1991**, *22*, 1587–1598. [[CrossRef](#)]
21. 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.* **2016**, *7*, 1528–1534.
22. Hamam, Y.; Hindi, K. Optimised on-line leakage minimization in water piping networks using neural nets. In Proceedings of the IFIP Working Conference, Dagschul, Germany, 28 September–1 October 1992; Volume 28, pp. 57–64.
23. Dai, P.D.; Li, P. Optimal Localization of Pressure Reducing Valves in Water Distribution Systems by a Reformulation Approach. *Water Resour. Manag.* **2014**, *28*, 3057–3074. doi:10.1007/s11269-014-0655-6. [[CrossRef](#)]
24. Lima, G.M.; Junior, E.L.; Brentan, B.M. Selection and location of Pumps as Turbines substituting pressure reducing valves. *Renew. Energy* **2017**, *109*, 392–405. [[CrossRef](#)]
25. Lima, G.M.; Brentan, B.M.; Luvizotto, E., Jr. Optimal design of water supply networks using an energy recovery approach. *Renew. Energy* **2018**, *117*, 404–413. [[CrossRef](#)]
26. Shao, Y.; Yu, Y.; Yu, T.; Chu, S.; Liu, X. Leakage Control and Energy Consumption Optimization in the Water Distribution Network Based on Joint Scheduling of Pumps and Valves. *Energies* **2019**, *12*, 2969. [[CrossRef](#)]
27. Alberizzi, J.C.; Renzi, M.; Righetti, M.; Pisaturo, G.R.; Rossi, M. Speed and Pressure Controls of Pumps-as-Turbines Installed in Branch of Water-Distribution Network Subjected to Highly Variable Flow Rates. *Energies* **2019**, *12*, 4738. [[CrossRef](#)]
28. Marchiori, I.N.; Lima, G.M.; Brentan, B.M.; Junior, E.L. Effectiveness of methods for selecting pumps as turbines to operate in water distribution networks. *Water Supply* **2019**, *19*, 417–423. [[CrossRef](#)]

29. García, I.F.; Novara, D.; Mc Nabola, A. A Model for Selecting the Most Cost-Effective Pressure Control Device for More Sustainable Water Supply Networks. *Water* **2019**, *11*, 1297. [[CrossRef](#)]
30. Eck, B.J.; Mevissen, M. *Valve Placement in Water Networks: Mixed-Integer Non-Linear Optimization With Quadratic Pipe Friction*; Report No RC25307 (IRE1209-014); IBM Research: Armonk, NY, USA, 2012.
31. Jowitt, P.W.; Xu, C. Optimal valve control in water-distribution networks. *J. Water Resour. Plan. Manag.* **1990**, *116*, 455–472. [[CrossRef](#)]
32. Liberatore, S.; Sechi, G.M. Location and Calibration of Valves in Water Distribution Networks Using a Scatter-Search Meta-heuristic Approach. *Water Resour. Manag.* **2009**, *23*, 1479–1495. doi:10.1007/s11269-008-9337-6. [[CrossRef](#)]
33. Gupta, A.; Bokde, N.; Kulat, K.; Yaseen, Z.M. Nodal Matrix Analysis for Optimal Pressure-Reducing Valve Localization in a Water Distribution System. *Energies* **2020**, *13*, 1878. [[CrossRef](#)]
34. Hindi, K.; Hamam, Y. Locating pressure control elements for leakage minimization in water supply networks: An optimization model. *Eng. Optim.* **1991**, *17*, 281–291. [[CrossRef](#)]
35. Nicolini, M.; Zovatto, L. Optimal location and control of pressure reducing valves in water networks. *J. Water Resour. Plan. Manag.* **2009**, *135*, 178–187. [[CrossRef](#)]
36. Nicolini, M. Optimal pressure management in water networks: increased efficiency and reduced energy costs. In Proceedings of the Defense Science Research Conference and Expo (DSR), Singapore, 3–5 August 2011; pp. 1–4.
37. Hindi, K.; Hamam, Y. Locating pressure control elements for leakage minimization in water supply networks by genetic algorithms. In *Artificial Neural Nets and Genetic Algorithms*; Springer: Vienna, Austria, 1993; pp. 583–587.
38. Coelho, B.; Andrade-Campos, A. Energy recovery in water networks: Numerical decision support tool for optimal site and selection of micro turbines. *J. Water Resour. Plan. Manag.* **2018**, *144*, 04018004. [[CrossRef](#)]
39. Shamir, U.; Salomons, E. Optimal real-time operation of urban water distribution systems using reduced models. *J. Water Resour. Plan. Manag.* **2008**, *134*, 181–185. [[CrossRef](#)]
40. Laucelli, D.; Berardi, L.; Ugarelli, R.; Simone, A.; Giustolisi, O. Supporting Real-Time Pressure Control in Opegård Municipality with WDNNetXL. *Procedia Eng.* **2016**, *154*, 71–79. [[CrossRef](#)]
41. Coulbeck, B.; Ulanicki, B.; Rance, J.P.; Deviatkov, V.V.; Kosov, S.; Glukhovskiy, I. Pressure control of a Moscow water supply system using expert system technology. *Trans. Inst. Measur. Control* **1996**, *18*, 193–201. [[CrossRef](#)]
42. Yang, Z.; Wu, L.; Dong, X. Control System Design for Constant-pressure Water Supply. In Proceedings of the 2010 Second International Conference on Multimedia and Information Technology (MMIT), Kaifeng, China, 24–25 April 2010; Volume 2, pp. 55–57.
43. Lei, Z.; Jing, Z. Implement of increment-model PID control of PLC in constant-pressure water system. In Proceedings of the 2007 8th International Conference on Electronic Measurement and Instruments, Xi'an, China, 16–18 August 2007; pp. 4–336.
44. Wang, D.L.; Wang, A.M. The Pressure Control on Non-negative Pressure Water Supply Based on the Fuzzy PID Control. In Proceedings of the 2009 International Joint Conference on Artificial Intelligence, Hainan Island, China, 25–26 April 2009; pp. 140–143.
45. Peng, X.; Xiao, L.; Mo, Z.; Liu, G. The variable frequency and speed regulation constant pressure water supply system based on PLC and fuzzy control. In Proceedings of the 2009 International Conference on Measuring Technology and Mechatronics Automation, Zhangjiajie, China, 11–12 April 2009; Volume 1, pp. 910–913.
46. Prescott, S.L.; Ulanicki, B. Improved control of pressure reducing valves in water distribution networks. *J. Hydraul. Eng.* **2008**, *134*, 56–65. [[CrossRef](#)]
47. Bezerra, S.; da Silva, S.; Gomes, H. Operational optimization of water supply networks using a fuzzy system. *Water* **2012**, *38*, 565–572. [[CrossRef](#)]
48. Kallesoe, C.S.; Jensen, T.N.; Wisniewski, R. Adaptive reference control for pressure management in water networks. In Proceedings of the 2015 European Control Conference (ECC), Linz, Austria, 15–17 July 2015; pp. 3268–3273.
49. Bello, O.; Hamam, Y.; Djouani, K. Coagulation process control in water treatment plants using multiple model predictive control. *Alex. Eng. J.* **2014**, *53*, 939–948. [[CrossRef](#)]

50. Zeilinger, M.N.; Raimondo, D.M.; Domahidi, A.; Morari, M.; Jones, C.N. On real-time robust model predictive control. *Automatica* **2014**, *50*, 683–694. [[CrossRef](#)]
51. Bangura, M.; Mahony, R. Real-time model predictive control for quadrotors. *IFAC Proc. Vol.* **2014**, *47*, 11773–11780. [[CrossRef](#)]
52. Sankar, G.S.; Mohan Kumar, S.; Narasimhan, S.; Narasimhan, S.; Murty Bhallamudi, S. Optimal control of water distribution networks with storage facilities. *J. Process. Control.* **2015**, *32*, 127–137. [[CrossRef](#)]
53. Robles, D.; Puig, V.; Ocampo-Martinez, C.; Garza-Castañón, L.E. Reliable fault-tolerant model predictive control of drinking water transport networks. *Control. Eng. Pract.* **2016**, *55*, 197–211. [[CrossRef](#)]
54. Jose, N.; Sumam, K. Optimal Water Distribution Network Design Accounting for Valve Closure. *Procedia Technol.* **2016**, *24*, 332–338. [[CrossRef](#)]
55. Nicolini, M.; Giacomello, C.; Deb, K. Calibration and optimal leakage management for a real water distribution network. *J. Water Resour. Plan. Manag.* **2010**, *137*, 134–142. [[CrossRef](#)]
56. Pecci, F.; Abraham, E.; Stoianov, I. Mathematical Programming Methods for Pressure Management in Water Distribution Systems. *Procedia Eng.* **2015**, *119*, 937–946. [[CrossRef](#)]
57. Oikonomou, K.; Parvania, M.; Khatami, R. Optimal demand response scheduling for water distribution systems. *IEEE Trans. Ind. Inform.* **2018**, *14*, 5112–5122. [[CrossRef](#)]
58. Vasudevan, D. Water Distribution Networks: Leakage Management Using Nonlinear Optimization of Pressure. Master's Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2018.
59. Wright, R.; Abraham, E.; Parpas, P.; Stoianov, I. Optimized control of pressure reducing valves in water distribution networks with dynamic topology. *Procedia Eng.* **2015**, *119*, 1003–1011. [[CrossRef](#)]
60. Corcoran, L.; McNabola, A.; Coughlan, P. Optimization of water distribution networks for combined hydropower energy recovery and leakage reduction. *J. Water Resour. Plan. Manag.* **2016**, *142*, 04015045. [[CrossRef](#)]
61. Araujo, L.S.; Ramos, H.; Coelho, S.T. Pressure Control for Leakage Minimisation in Water Distribution Systems Management. *Water Resour. Manag.* **2006**, *20*, 133–149. [[CrossRef](#)]
62. El-Ghandour, H.A.; Elansary, A.S. Optimal selection of pressure relief valve parameters for surge pressure control in water distribution systems. *Urban Water J.* **2019**, *16*, 269–276. [[CrossRef](#)]
63. Van Dijk, M.; van Vuuren, S.J.; Van Zyl, J.E. Optimising water distribution systems using a weighted penalty in a genetic algorithm. *Water* **2008**, *34*, 537–548. [[CrossRef](#)]
64. Bonthuys, G.J.; van Dijk, M.; Cavazzini, G. Energy Recovery and Leakage-Reduction Optimization of Water Distribution Systems Using Hydro Turbines. *J. Water Resour. Plan. Manag.* **2020**, *146*, 04020026. [[CrossRef](#)]
65. Cimorelli, L.; D'Aniello, A.; Cozzolino, L.; Pianese, D. A Derivative Free Non-Linear Programming Method for the Optimal Setting of PATs to Be Used in a Hybrid Genetic Algorithm: A Preliminary Work. *Proceedings* **2018**, *2*, 684. [[CrossRef](#)]
66. Saldarriaga, J.; Salcedo, C.A. Determination of optimal location and settings of pressure reducing valves in water distribution networks for minimizing water losses. *Procedia Eng.* **2015**, *119*, 973–983. [[CrossRef](#)]
67. De Paola, F.; Giugni, M.; Portolano, D. Pressure management through optimal location and setting of valves in water distribution networks using a music-inspired approach. *Water Resour. Manag.* **2017**, *31*, 1517–1533. [[CrossRef](#)]
68. Fanni, A.; Liberatore, S.; Sechi, G.; Soro, M.; Zuddas, P. Optimization of water distribution systems by a tabu search metaheuristic. In *Computing Tools for Modeling, Optimization and Simulation*; Springer: Boston, MA, USA, 2000; pp. 279–298.
69. Creaco, E.; Franchini, M. A new algorithm for real-time pressure control in water distribution networks. *Water Sci. Technol. Water Supply* **2013**, *13*, 875–882. [[CrossRef](#)]
70. Page, P.R.; Abu-Mahfouz, A.M.; Yoyo, S. Parameter-Less Remote Real-Time Control for the Adjustment of Pressure in Water Distribution Systems. *J. Water Resour. Plan. Manag.* **2017**, *143*, 04017050. [[CrossRef](#)]
71. Fontana, N.; Giugni, M.; Glielmo, L.; Marini, G.; Verrilli, F. A lab prototype of pressure control in water distribution networks. *Ifac-Papersonline* **2017**, *50*, 15373–15378. [[CrossRef](#)]
72. Cheng, W.; Yu, T.; Xu, G. Real-Time Model of a Large-scale Water Distribution System. *Procedia Eng.* **2014**, *89*, 457–466. doi:10.1016/j.proeng.2014.11.212. [[CrossRef](#)]
73. Kang, D. Real-time optimal control of water distribution systems. *Procedia Eng.* **2014**, *70*, 917–923. [[CrossRef](#)]
74. Sira-Ramírez, H.; Luviano-Juárez, A.; Ramírez-Neria, M.; Zurita-Bustamante, E.W. *Active Disturbance Rejection Control of Dynamic Systems: A Flatness Based Approach*; Butterworth-Heinemann: Oxford, UK, 2018.

75. Rao, Z.; Alvarruiz, F. Use of an artificial neural network to capture the domain knowledge of a conventional hydraulic simulation model. *J. Hydroinform.* **2007**, *9*, 15–24. [[CrossRef](#)]
76. Rao, Z.; Salomons, E. Development of a real-time, near-optimal control process for water-distribution networks. *J. Hydroinform.* **2007**, *9*, 25–37. [[CrossRef](#)]
77. Anele, A.O.; Hamam, Y.; Abu-Mahfouz, A.M.; Todini, E. Overview, comparative assessment and recommendations of forecasting models for short-term water demand prediction. *Water* **2017**, *9*, 887. [[CrossRef](#)]
78. Anele, A.O.; Todini, E.; Hamam, Y.; Abu-Mahfouz, A.M. Predictive uncertainty estimation in water demand forecasting using the model conditional processor. *Water* **2018**, *10*, 475. [[CrossRef](#)]



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