PRESSURE MANAGEMENT STRATEGIES FOR WATER LOSS REDUCTION IN LARGE-SCALE WATER PIPING NETWORKS: A REVIEW

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KEY WORDS

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ABSTRACT

In water distribution networks (WDNs), water loss through leaking pipes is inevitable, as it constitutes a major threat to the operational services of water utilities. While water utilities are keen to providing an adequate supply of water to its end users, the undermined service quality, wasted energy resources and financial loss caused by leakages are major concerns. The financial loss, among others, associated with leaky pipes is increasingly growing at an alarming rate in recent years. Therefore, monitoring pipelines health through leakage control is crucial. Nevertheless, several methods for controlling leakages in WDNs have proposed. Research efforts conducted in the past acknowledged water pressure control as an effective method for reducing losses in water piping networks. Although, adequate pressure is required in the system to meet customer's demands, it is a general agreement that reducing pressure will reduce the leakage flow rate as well as the possibility of pipe burst or crack. Several pressure management strategies have been proposed for leakage reduction in water distribution systems. In this work, we present an overview of the pressure management approaches proposed for reducing leakages in water distribution networks. Some previous and recent research efforts are outlined. Furthermore, information about leakage control, which may be useful for water utilities and pipeline engineers are provided.

1. INTRODUCTION

Water is a precious natural resource essential for human survival and nearly all modes of economic production. However, this water is not readily available for use of human as less than 3% of water on the planet is fresh water among which 80% is locked away in glaciers and ice sheets, as illustrated in Fig. 1 [1]. From this figure, it is observed that only 0.5% of all the water on the planet is accessible for human use and almost all of this is underneath the earth's surface in the form of groundwater. Consequently, to have access to this resource, operations such as drilling, pumping and treating in a water plant for storage and distribution has to be carried out by the water utility companies or the government.

Globally, increasing human population coupled with improved standard of living has forced the demand for water to increase dramatically in the past few years. As a result, this poses a threat to the scarce water resources. Futhermore, in order to meet the aforementioned increasing demand and for effective water supply to the end users, the water is usually transported through a large network of pipes as transmission mains and distribution systems. Hence a water distribution network is an essential infrastructure meant to supply autochthonous fresh water across cities. Its purpose is to deliver to the end users, sufficient amount of water under adequate pressure for various demand conditions in a large-scale network, while also generating revenue for the water utility companies and the government.

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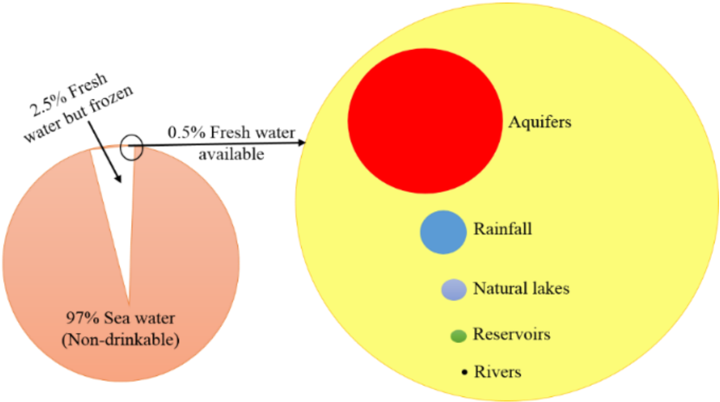
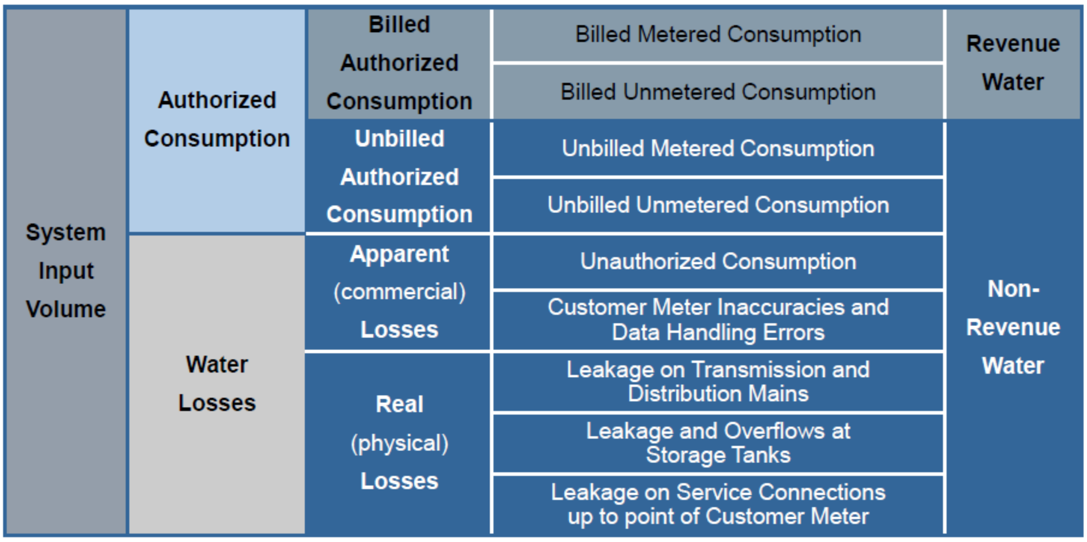


Figure 1: The global water availability [1].

However, the smooth running of large-scale water supply networks is still a major engineering challenge [2]. This is because not all the water produced at the water treatment plants reaches the end users and generate revenue for water industries and the government. Instead, a significant portion of this water is lost and does not reach the end user. This lost water is sometimes refered to as non-revenue water (*NRW*) [1] and is expressed by the International Water Association (IWA) as in the water balance shown in Fig. 2 [1],



System Input Volume	Authorized Consumption	Billed Authorized Consumption	Billed Metered Consumption	Revenue Water
			Billed Unmetered Consumption	
		Unbilled Authorized Consumption	Unbilled Metered Consumption	Non-Revenue Water
			Unbilled Unmetered Consumption	
	Water Losses	Apparent (commercial) Losses	Unauthorized Consumption	
			Customer Meter Inaccuracies and Data Handling Errors	
		Real (physical) Losses	Leakage on Transmission and Distribution Mains	
			Leakage and Overflows at Storage Tanks	
			Leakage on Service Connections up to point of Customer Meter	

Figure 2: The IWA water balance [1].

$$NRW = W_{losses} + UAC \tag{1}$$

$$W_{losses} = \mathrm{Re}\,al_{losses} + Apparent_{losses} \tag{2}$$

where *UAC* denotes the unbilled authorised consumption and W_{losses} represents the water loss. By substituting (2) into (1), a major component of the *NRW* corresponds to the real losses due to leakages from the pipes, joints and fittings. The apparent losses are due to customer's meter's inaccuracies and illegal consumption [1]. In most water utilities, reducing the *NRW* is a major issue. In South Africa, the *NRW* threatens the financial viability of the municipal water services with an estimated loss of around R7 billion annually [3]. Due to the huge economic impact of water losses, several approaches dealing with this problem have been proposed. However, traditional approaches to solving water loss problems are not enough to make a significant improvement. To respond to this problem, new approaches involving increased automation and monitoring are needed [4]. Certainly, reducing the *NRW* will give the water industries access to self-generating cash flow for investing in new infrastructure and operational maintenance. It will also provide better value and improved water service to its users [1].

Water losses through leaking pipes are inevitable in water distribution systems and water utilities have to continuously make efforts in order to reduce losses in them. Reducing water losses in the distribution system is not an easy task and requires the development of a proactive leakage detection technique as well as speedy repairs of leaky pipes. In the past, numerous leakage detection techniques have been developed. Unfortunately, most of these techniques are only effective for some type of leakage flow [5]. For background leakage such as outflow through creeping or deteriorated joints, detection is a major issue. More so, background leakages are hidden and because they are diffuse flows, which are difficult to detect by measuring instruments, thus posing a major threat to water utility companies. 90% of water losses is caused by *small, hidden leaks* [6]. Owing to this, a hydraulic model for leakage detection and estimation could be a promising approach for detecting small, continuous background and burst leakages in WDNs [7]. In WDNs, leakage outflows are sensitive to pressure in the pipe, therefore, several pressure control approaches have been proposed as an effective means of reducing such type of leakages in large-scale water distribution networks.

In this chapter, an overview of the pressure management scheme adopted for leakage control in WDNs is presented. Some past and recent research efforts in this domain are also discussed. The importance and operational capabilities of these techniques are highlighted. The rest of the paper is organised as follows. Section 2 presents an overview of WDNs topology, leakage and leakage—pressure relationship. In Section 3, the pressure control concept and some previous research works are briefly discussed while Section 4 concludes the paper.

2. WATER DISTRIBUTION NETWORK

A water distribution network (WDN) such as the one shown in Fig. 3 comprises of a set of interconnected pipes, each pipe with a defined length, diameter and friction resistance coefficient. Each pipe intersects at a point of consumption (demand) where water flow enters or exit the network. This point is known as a junction node. Each pipe can also contain network elements such as pumps, fittings and valves. The pump is used to deliver sufficient pressure to meet customer's demand at the junction nodes. A WDN may also have a fixed grade node such as a reservoir or storage tank, where the head or pressure is known. In the design of WDNs, hydraulic models play a critical role in the planning and management of the system parameters. A steady-state hydraulic model [8] provides insight in the state estimate of a network [9] and understanding of the pipe network and its associated components in order to address potential adverse incidents. Dynamic hydraulic models [4] use the real-time sensed data from sensor node attached to WDN component such as water meter [10] to evaluate the current conditions of the network, and automatically send control signals to various network components. This will adjust the water distribution network (WDN) performance and make it more efficient.

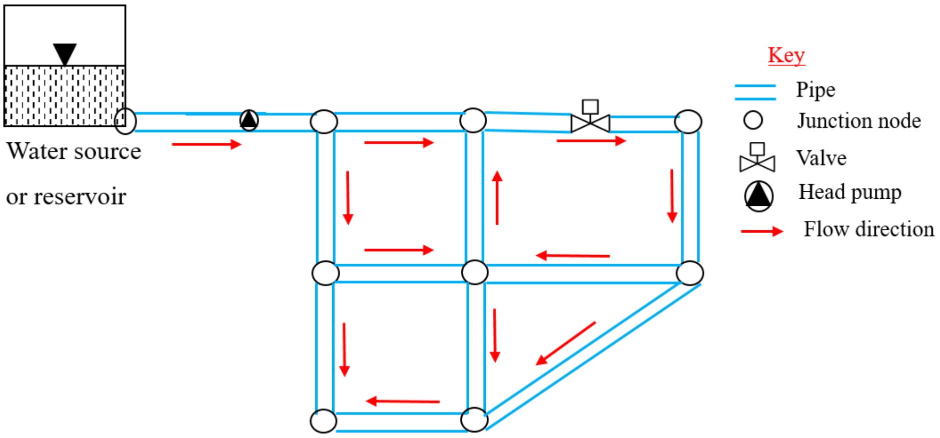


Figure 3: Schematics of a water distribution network.

In WDNs, losses are unpredictable and can occur through leakage at the junction nodes as well as along the pipes. In most cases, a significant volume of water is lost through the pipes in the networks. To reduce network leakage outflows, some basic leakage management strategies have been proposed for use by the water utilities. These strategies are illustrated in Fig. 4.

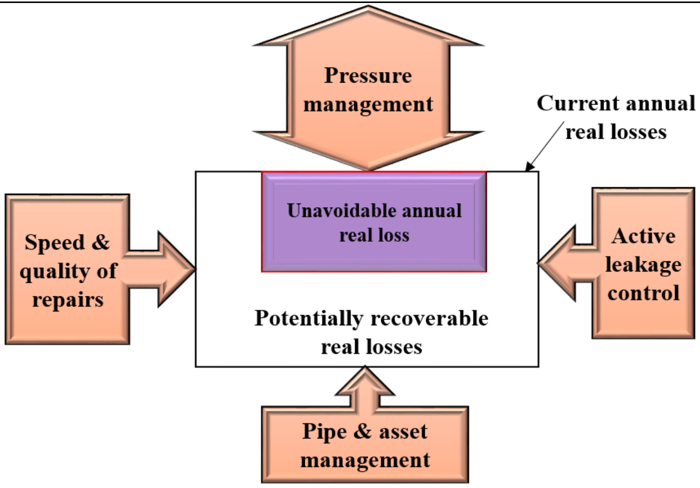


Figure 4: The basic leakage management strategy [1].

Observing Fig. 4, it may be seen that pressure management is one of the fundamental elements of a leakage management strategy. This is because previous research efforts revealed that a relationship between network leakage and pressure exist [11-14]. By representing leakages as a flow through an opening in the pipe, the leakage—pressure relationship is expressed as [12-15]

$$q_l = kP^n \tag{3}$$

where q_l is the leakage flow rate, k represents the leakage coefficient, P is the pressure head in the pipe while n denotes the leakage exponent. The value of n range from 0.5 to 2.5 depending on the type of leaks [12,14]. From (3), it follows, therefore, that higher pressure leads to high leakage flow rate and vice versa. It is obvious from (3) that leakage flow will be very sensitive to pressure changes when $n>1$. Although, the leakage flow behaviour is a complex phenomenon and the understanding of leakage hydraulics is necessary for better representation of the leakage—pressure relationship. A more comprehensive representation is based on the use of fixed area and variable area discharge (FAVAD) concept proposed by May [11]. This concept is based on the fact that leak openings varies along the pipe length. Therefore, the leakage—pressure relationship is further expressed as

$$Q_l = C_d A_l^f \sqrt{2gH} + C_d A_l^v \sqrt{2gH} \tag{4}$$

where Q_l denotes the leakage flow rate, C_d is the leakage discharge coefficient, A_l^f, the fixed area of leak opening, A_l^v, the variable area of leak opening. H represents the pressure head produced by pump while g is the acceleration due to gravity. In both representations of the leakage flow rate expression, one can conclude that leakage flow is sensitive to pressure variations.

From both leakage representations, it is obvious that reducing the network pressure will greatly reduce leakage flow rate. Therefore, in WDNs, pressure management strategy is recognised as one of the most efficient and cost effective policy to reduce leakages [16]. Apart from minimising leakages in WDNs, the water utilities can also benefit from pressure management by reducing the risks of pipe burst and consequently extends the pipe service life [17,18]. This will in no small measure, reduce the cost of maintenance and repairs allocated to pipelines and its associated components.

In a water distribution system, the head pump must deliver adequate pressure to meet customer demands at the junction nodes. However, higher pressure can lead to pipe burst, especially for small diameter pipes. Therefore, in a WDN, the probability of a pipe breakage in the network as a result of the system pressure variations may be estimated using a model proposed by Swamee *et al*. [19] as

$$\mathrm{Pr}_k = \frac{0.0021e^{-4.35D_k} + 21.4{D_k}^8 e^{-3.73D_k}}{1+10^5 {D_k}^8} \tag{5}$$

where Pr_k denotes the probability of breakage in pipe k and D_k represents its diameter. From (5), it may be deduced that the probability of breakage in a pipe is a decreasing function of the pipe diameter under the influence of water pressure variations. The rate at which new leaks occur is greatly influenced by pressure surges and high pressures [12]. Additionally, the rate of water demand cannot be overlooked. Water demand is stochastic in nature; the major pipe burst tends to occur during the late evening and early morning periods when the system pressure are at their highest values [20]. A noteworthy evidence is that the operational pressure control is an effective means of reducing leakage over networks, and for reducing the risk of further leaks by smoothing pressure variations.

3. PRESSURE CONTROL

Water pressure regulations in pipes have been proven to be an important tool for long term reduction of losses in water distribution networks. Therefore, pressure management scheme is an important aspect of water networks and has been a topic of discussion in the past years. In most networks, active pressure control for loss minimisation through the reduction of excess water pressure is essential [21]. There are a number of methods for regulating pressure in the WDNs. These include the use of variable speed pump controllers such as the Aquavar e-ABII manufactured by Xylem Gould Water Technology [22] and the use of break pressure tanks [1]. In addition, regulating the water pressure in distribution networks is usually achieved by partitioning the complex networks into a smaller sub-networks known as the district meter areas (DMAs) or the pressure management areas (PMAs) [1,17,21,23]. The water pressure in these areas is regulated by installing network elements such as control valves at the inlet of the zone(s). Several high level control valves have been developed which are being deployed to the pipes either to control the water pressure or flow at some specific points in the networks. These control valves include, but are not limited to;

i. Pressure reducing valves (PRV), used to limit the pressure in pipe links;
ii. Pressure sustaining valves (PSV), used to maintain pressure at a specific value;
iii. Pressure controlling valves (PCV), used to control the pressure in a specific zone in the water networks;
iv. Pressure breaker valve (PBV), which is used to force a specified pressure loss across the valve.

The recent proliferation in control technology leading to the new paradigm in valve control, the option for more sophisticated pressure control have increased drastically in recent years. The water pressure in the network is usually managed by installing control valves, mostly the PRVs at the inlet of the PMAs or DMAs or other areas that are experiencing high burst frequencies or high leakage levels. A comprehensive discussion of this can be found in [17]. As a result, the water pressure in the zone can be regulated by operating the PRVs.

Numerous research works are available in the literature that confirm the use of PRVs for loss reduction. The research work of Kalanithy and Lumbers [24] affirmed that the use of PRVs can adversely reduce the leakage flow rate in WDNs as illustrated in Fig. 5.

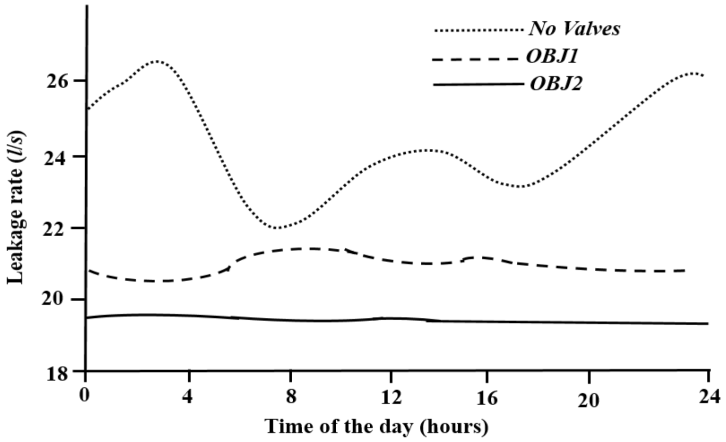


Figure 5: Leakage flow rate comparison with and without pressure regulating valves [24].

Observing the results obtained in their research work, it may be seen that the hourly distribution of the leakage flow rate is high when no pressure reducing valves was installed in the system. However, with the installation of valves at lines OBJ1 and OBJ2 in the network, the profile of the leakage flow distribution is reduced drastically. Even the leakage distribution is almost constant (at a reduced level) for the installed valve at line OBJ2 in the network.

In a general conclusion, pressure management adoption either through the installation of PRVs at some strategic network zones or other use of other pressure control elements can adversely reduce leakage flow rate. It is therefore recognised as an effective means and an intervention tool for reducing the most difficult leak flow and all types of leakage (background, unreported and reported) without replacing existing infrastructure [18]. For each leakage type illustrated in Fig. 6, it may be seen that the pressure reduction method is a common intervention tool for leakage flow rate reduction.

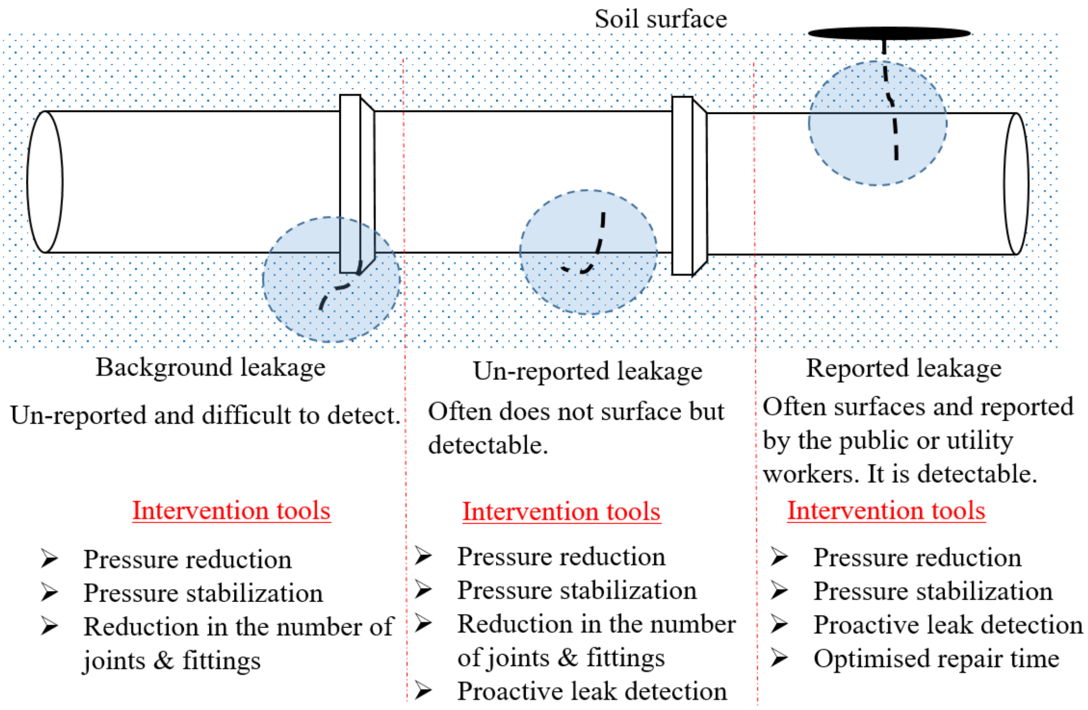


Figure 6: Leakage types and intervention tools [25].

The following are the benefits of controlling pressure in water distribution networks;

(i) It reduces surges and excess pressures; Pressure control also;
(ii) Lowers pipe failure rate;
(iii) Extends pipe service lives;
(iv) Improve water distribution management;
(v) Lowers water loss through leaking pipes;
(vi) Saves water and energy cost.

3.1 Pressure Control Strategies

Numerous techniques for achieving the pressure control is available in the literature. Among the notable technique include the use of the fixed outlet pressure control [26-30], the time-modulated pressure control [26-28], the flow modulated pressure control [26-30], closed loop pressure control [26,31], parameter-less P-controller [32-35], and the optimisation approach [36-43].

Fixed outlet pressure control technique (FOPC): In this technique, the use of network element usually a pressure reducing valve, that can provoke head loss due to the friction of the flow of water with the pipe wall is used. In this approach shown in Fig. 7, the PRV is installed to control the maximum pressure entering a zone in the water pipe networks. This zone is usually the pressure zones or areas of high pressure occurrence in the network. Fixed outlet pressure control approach is simple to use and cost effective as it does not require the installation of an additional device in the network. However, the flexibility of adjusting water pressures to suit demand variations at different times of the day cannot be achieved [26-30].

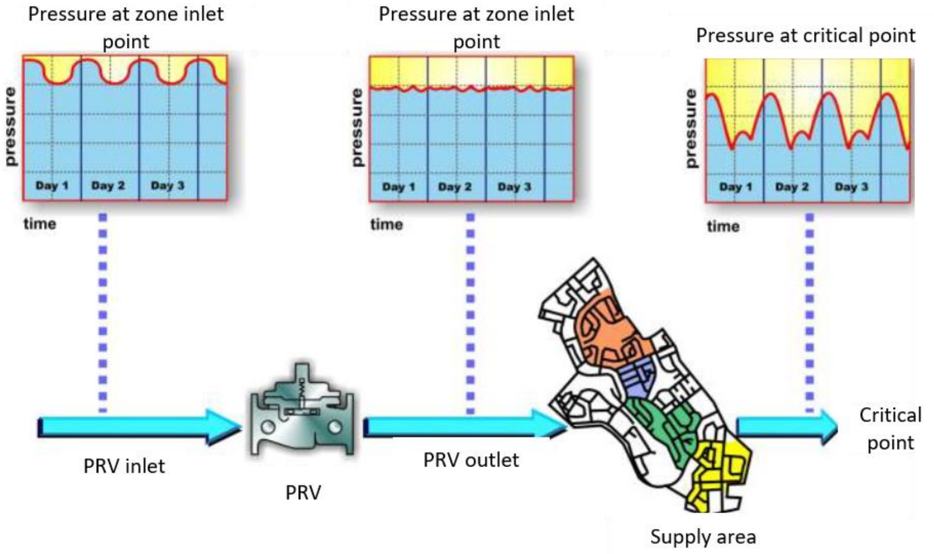


Figure 7: Fixed outlet pressure control [26].

Time-modulated pressure control approach (TMPC): This approach operates in a similar manner to the fixed outlet pressure control approach. In addition to the installed PRVs, an additional device with a controller is added to the network to provide a further pressure reduction during the periods of off-peak demand as shown in Fig. 8 [26]. The TMPC approach offers a greater flexibility of pressure adjustments at specific times of the day, achieved with the help of the controller. The controller is a low cost type and relatively easy to set up. The time-modulated pressure control approach is mainly employed during the period of nightly use when the end users are asleep. A notable limitation of the time-modulated pressure control approach is that of its poor response to water demand requirements, such as the demand for firefighting [26-28]. During the fire fighting demand period, full pressure is usually required to tackle fire outbreak. In addition to the previously mentioned limitation, a higher level of expertise is required to operate and maintain the installations of the devices used in this approach compared to the fixed outlet pressure control approach.

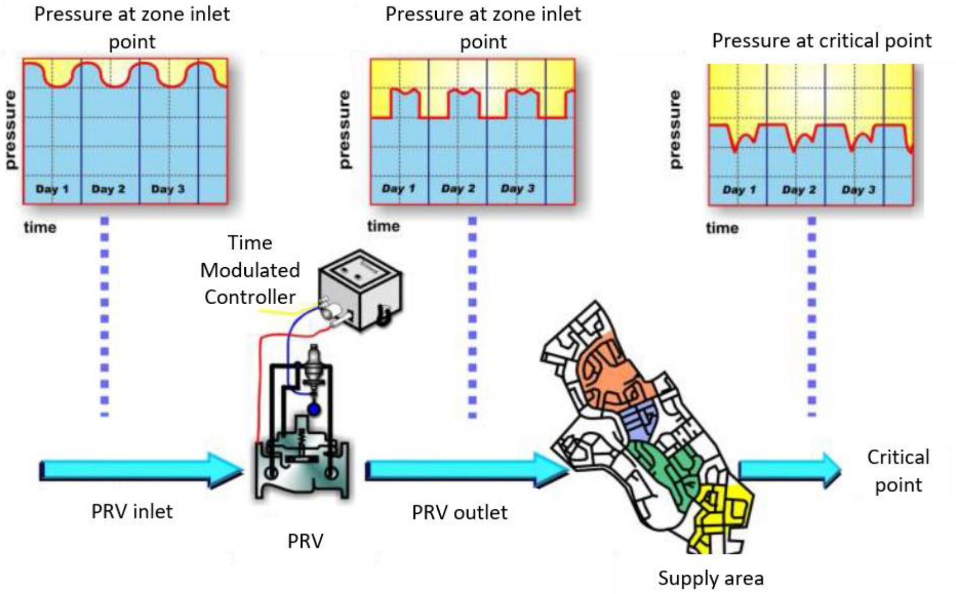


Figure 8: Time modulated pressure control [26].

Flow modulated pressure control (FMPC): In this approach, an electronic controller is used in conjunction with the PRVs and installed at the inlet of the pressure zones in the network as shown in Fig. 9. The flow-modulated pressure control approach provides a greater control and flexibility than the time-modulated pressure control approach, though at the expense of the implementation cost. The approach is not cost effective.

The cost of the electronic controller used is higher as it requires a properly sized meter in addition to the PRVs [26-30].

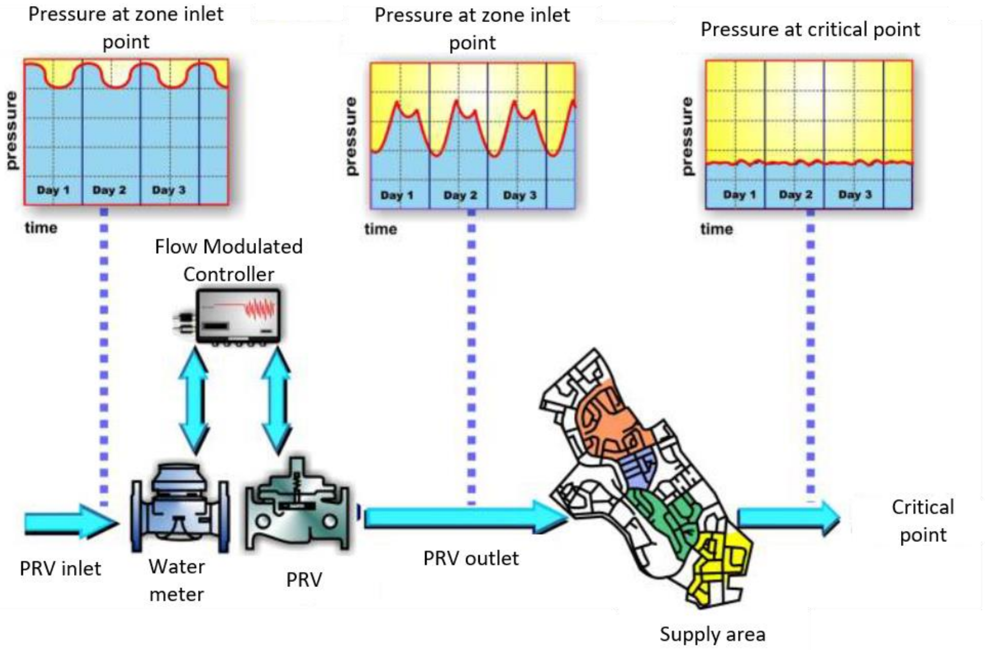


Figure 9: Flow modulated pressure control [26].

A significant advantage of the flow modulated pressure control is its capability to automatically respond to fire service demand requirements [31].

Closed loop pressure control (CLPC): This type of pressure control technique is achieved by adjusting the settings of the PRVs based on the pressure at critical point(s) in the PMAs. In this technique as shown in Fig. 10, a pressure sensor placed at the critical point(s) of the network is used to provide live data to the pressure controller at the inlet of the PMAs. While this pressure control technique is more complex and expensive, its potential for maximising the benefit of the pressure management cannot be overlooked. It provides the ultimate level of control. A major disadvantage is that there is a greater opportunity for equipment to fail using this technique [26, 31].

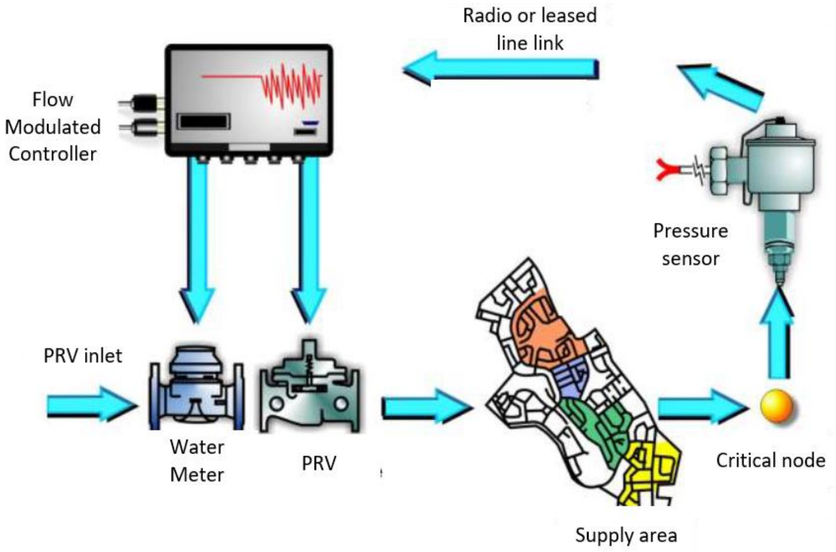


Figure 10: Closed loop pressure control [26].

Parameter-less P-controller is another efficient controller to adjust the pressure, which is based on the flow in a pressure control valve (PCV) and is argued to be easy to implement. The authors of [32] investigate the robustness of the parameter-less remote real-time pressure control in water distribution systems to control a PCV [33,34] and the variable speed pumps [35]. This has the advantages over the fixed outlet and time modulated pressure control approach in that the controller used is easy to set up and has the capability to respond to changing water demand conditions.

Optimisation approach: The optimisation approach is used for controlling the operational settings of the PRVs or the PCVs. The use of optimisation for controlling the water pressure in piping networks has been studied in the past and in recent times. Optimisation is a powerful tool used to achieve optimal opening adjustment and settings of the pressure control valves or pressure reducing valves. The optimal location as well as the opening adjustment of these valves is vital for effective pressure regulation. To achieve this, numerous research efforts dealing with this problem have been published. The pioneer works of Jowitt and Xu [36], Hindi and Hamam [37-41] gave the first insight into the problem. In these research works, an optimal location of control valves in water networks was introduced using optimisation approach. Other notable research works are those published by [23,24,42,43]. The results of these research works revealed that the optimisation methods may be used for determining the optimal location of PRVs [37,42] as well as its opening adjustments and settings [23,24,36,38-41]. Araujo *et al*. [23] developed a model to support decision system for the location and opening adjustment of control valves in a WDN. The developed model uses genetic optimisation method to achieve pressure control. More so, Nazif *et al*. [43] developed a model for reducing pressure in urban WDNs using genetic algorithm based optimisation method and artificial neural networks. The results of the developed model reveal that the network leakage can be reduced by more than 30% as a result of the pressure regulation.

3.2 Compared performance analysis of pressure control approach

Table 1 shows the various pressure management approaches considered in this manuscript. As it may be seen in Table 1, the FOPC is relatively simple to use and easy to set up. However, in practical situations where there are pressure variations, the approach fails to capture and adjust to compensate for these variations. The limitation of the FOPC method is overcome in the TMPC approach.

Method	Remarks	Cost	Limitation	Application
Fixed outlet pressure control (FOPC) [26-30]	Simple	Not expensive	Unable to adapt to pressure variation during peak and off-peak demands	Used in small scale water piping networks.
Time modulated pressure control (TMPC)[26-28]	The controller used is easy to set up	A little bit expensive	Low response to water demand variations	Majorly used during the minimum night flow hours (MNFHs).
Flow modulated pressure control (FMPC) [26-30]	Complex	Expensive	Low response to water demand variations	Can be used during both MNFHs and high demand period
Closed loop pressure control (CLPC) [26, 31]	It provides the ultimate level of control	Expensive	There is a greater tendency for equipment failure	Can be used during both MNFHs and high demand period in real-time.
Parameter-less P-controller [32-36]	The controller is easy to setup and has the ability to respond to water demand variations.	Not expensive	Practical application in large-scale water piping networks required.	Can be used during both MNFHs and high demand period in real-time.
Optimisation approach (OA) [23,24,34-43]	For optimal location and opening adjustment of the pressure reducing valves	Not expensive	Practical application in large-scale water piping networks is required.	Can be used during both MNFHs and high demand period.

Table1: Pressure management approach

The TMPC approach offers better flexibility to pressure variations and can be used during the minimum night flow period. However, during water demand variations such as those beyond the MNF hours, the approach has poor response to such variation. Although, the FMPC offers a greater control and flexibility to water demand and pressure variations than the FOPC and TMPC pressure management approaches, the cost of installation is quite expensive. The CLPC has the potential to provide the ultimate level of control. However, such technique is quite complex and there is tendency of equipment failure. In the optimisation approach, optimal location and opening adjustment of PRVs using optimisation technique is the major research areas in the past years. While such an approach is better in this regards, practical application in large-scale water piping network is a major concern. The parameter-less P-controller has the ability to adapt to water demand variations and can be particularly used during both peak demand and MNF hours. Like the optimisation approach, practical application in large-scale water piping network is required.

As shown in Table 1, it is evident that each of the pressure control technique has one or more advantages and disadvantages. The key issue is to select the most appropriate form of pressure control or a combination of the above pressure control for a specific application. However, the choice of selection will strongly depend on the conditions within the supply area of the network. For instance, the volume of water loss at critical point(s) of the network, the available budget and the implementation cost, among others, must be taken into consideration in selecting one or a combination of the pressure control techniques.

4. CONCLUSION

Water loss through leaking pipes have been a major threat to water utilities around the world rendering it as a major area of attention in the research community. It is a general agreement that reducing pressure will reduce the leakage flow rate as well as the possibility of pipe burst. Frequent variations in pressure are associated with higher frequency of new leaks. There is no doubt that pressure management is a fundamental tool in any leakage management strategies. Several pressure management strategies have been proposed for leakage reduction in water distribution systems. The operational performance of the parameter-less controller as well as the optimisation approach gives them an edge above other pressure control strategies discussed in this chapter. With recent advancements in technology which led to the development of electronic and hydraulic controllers coupled with the PRVs, an improvement and a probable combination of both approaches, that is, the optimisation and parameter-less controller could be best suited for pressure reduction in smart water networks.

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