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

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ABSTRACT

Water is a precious natural resource; human survival and nearly all modes of economic production depends on water. The efficient use of water resources is a subject of major concern for water utilities around the world. Within the last years, there has been a growing recognition of increasing water demands due to human population growth and urbanization. This poses a threat to the available water resource prompting for the efficient use of this resource. Nonetheless, one of the major challenges in improving the efficiency of drinking water supply networks is the minimization of water losses due to leaking pipes. In water distribution piping networks, water losses are unavoidable and are estimated to account up to 30% to 40% of the total amount of water supplied (input volume into the system) in many countries. Therefore, to satisfy the steadily growing water demand, this very important issue requires urgent attention.

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 agreements 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; human survival and nearly all modes of economic production depends on water. 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 the statistics done by Wu *et al*. [1], shown in Fig. 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, drilling, pumping and treating in a water plant for storage and distribution, among others has to be carried out perhaps 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. More so, in order to meet this demand and for effective water supply to the end users, the water is

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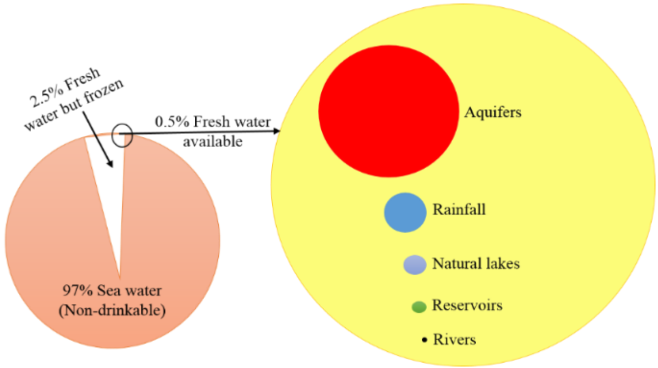

Figure 1: Illustration of water availability [1].

usually transported through a large network of pipes as transmission mains and distribution system. Owing to this, a water distribution network is an essential infrastructure meant to supply autochthonous fresh water across cities. Its purpose is to deliver to the users, sufficient amount of water demanded under adequate pressure for various demand conditions in a large-scale network, as well as to generate revenue for the water utility companies and the government. 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 reach the end users and generate revenue for water industries and the government. Instead, a significant portion of this water does not generate revenue for water industries, termed as, non-revenue water (*NRW*) [1] expressed as

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

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

where *UAC* denotes the unbilled authorized consumption and W_{losses} represents the water loss. By substituting (2) into (1), a major component of the *NRW* is the real losses as a result of leakages from pipes, joints and fittings. The apparent losses are due to customer's meter's inaccuracies and illegal consumption [1]. In most water utilities, reduction of the *NRW* is a major priority. For instance, in South Africa, the *NRW* threatens its financial viability of the municipal water services with an estimated loss of around R7 billion annually [3]. However, traditional approaches of solving water loss problems are not enough to make a significant improvement; for this, new approaches involving increased automation and monitoring are needed [4]. 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 customers [1].

Water losses through leaking pipes are inevitable in water distribution systems, therefore, water utility companies have to continuously make efforts in order to reduce losses in the system. In the past, leakage detection techniques have been developed. Unfortunately, most of these techniques are only effective for some type of leakage flow [5]. For leakage flow, such as flow through creeping joints, detection is a major issue. More so, background leakages are hidden and difficult to detect and posed the largest threat to water utility companies; 90% of water loss are caused by *small, hidden leaks* [6]. Considering the hydraulic model for leakage detection and estimation is one of the promising approaches for detecting small, continuous background and burst leakages in WDNs [7]. Nevertheless, pressure control approaches have been proposed as an effective means of reducing such type of leakages in large-scale water distribution networks.

In this manuscript, we present an overview of the pressure management scheme adopted for leakage control in WDNs. Some past and recent research efforts in this domain were also discussed. The importance and operational capabilities of these techniques are highlighted. The rest of the paper is organized 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 is briefly discussed while Section 4 concludes the paper.

2. WATER DISTRIBUTION NETWORK

A water distribution network such as the one shown in Fig. 2 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. A WDN can also have a fixed grade node such as a reservoir or storage tank, where the head or pressure is known. The pump is used to deliver sufficient pressure to meet customer's demand at the junction nodes. Hydraulic model plays a critical role in the designing and planning of the WDN as well as in the management and controlling of the WDN. A steady-state hydraulic model [8] assessment will provide insight and understanding of the pipe network and its associated components to address potential adverse incidents. Dynamic hydraulic model [4] use the real-time sensed data from sensor node attached to WDN component such as water meter [9] 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.

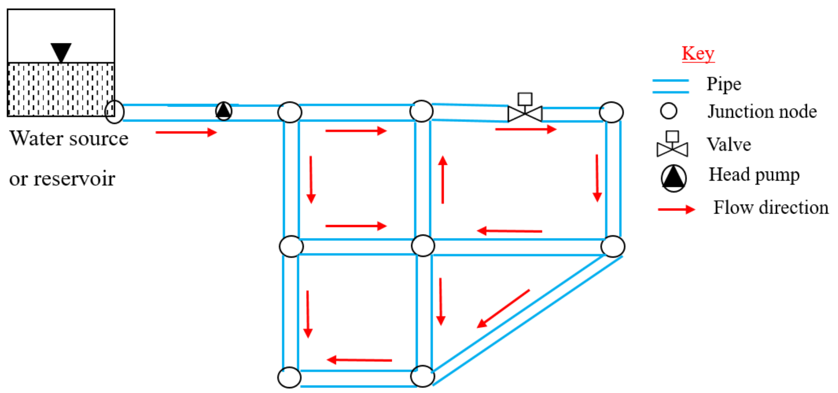

Figure 2: Schematics of a water distribution network.

In WDNs, losses are unpredictable and can occur through leakages at the junction nodes as well as along the pipes. As a result, in order to reduce network leakages, several leakage management strategies illustrated in Fig. 3 have been proposed for use by the water utilities.

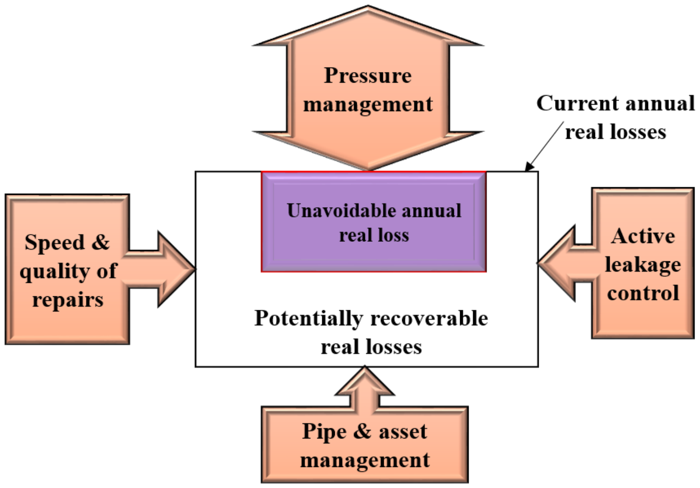

Figure 3: The basic leakage management strategy [1].

Observing Fig. 3, one can see 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 [10-13]. By representing leakages as a flow through an opening in the pipe, the leakage—pressure relationship is expressed as [11-13]:

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

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 exponents. The value of n range from 0.5 to 2.5 depending on the type of leaks [11,13]. 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 was based on the use of fixed area and variable area discharge (FAVAD) concept proposed by May [10]. This concept is based on the fact that leak openings varies along the pipe length. Therefore, the expression for the leakage—pressure relationship proposed by May [10] is given 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 (2 and 3), one can see that reducing the network pressure will greatly reduce leakage flow rate. Therefore, in WDNs, pressure management strategy is recognized as one of the most efficient and cost effective policy to reduce leakages [14]. Apart from minimizing leakages in WDNs, the water utility companies can also benefit from pressure management by reducing the risks of pipe burst and consequently extends the pipe's lifetime [15,16]. This will in no small measure, reduce the cost of maintenance and repairs dedicated to pipelines.

Traditionally, 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 with k^{th} number of pipes, the probability of a pipe breakage in the network as a result of the system pressure variations is estimated as [17]

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

where Pr_k denotes the probability of breakage in pipe k and D_k represents the diameter of the k^{th} pipe (m). From (5), one can deduce 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 [11]. 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 [18]. To this end, one can conclude 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 has been found 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 minimization through the reduction of excess water pressure is essential [19]. 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 [20] and the use of break pressure tanks [1]. In addition, water pressure in distribution networks is usually regulated by partitioning the complex networks into a smaller sub-networks known as the district meter areas (DMAs) or the pressure management areas (PMAs) [1,15,19,21]. The water pressure in the areas can be regulated by installing network elements such as control valves at the inlet of the zone. Several high level control valves have been developed which can be deployed to the links either to control the water pressure or flow at some specific points in the networks. These 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 specifc zone in 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 options 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 [15]. 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 [22] affirmed that the use of PRVs can adversely reduce the leakage flow rate in WDNs. Observing the results obtained in their work as illustrated in Fig. 4, one can see 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.

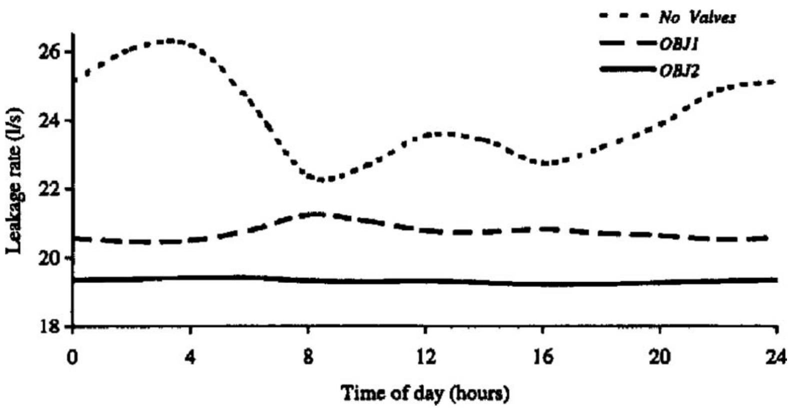

Figure 4: Leakage flow rate comparison with and without pressure regulating valves [22].

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 [16]. For each leakage type illustrated in Fig. 5, one can see that the pressure reduction method is a common intervention tool for leakage flow rate reduction.

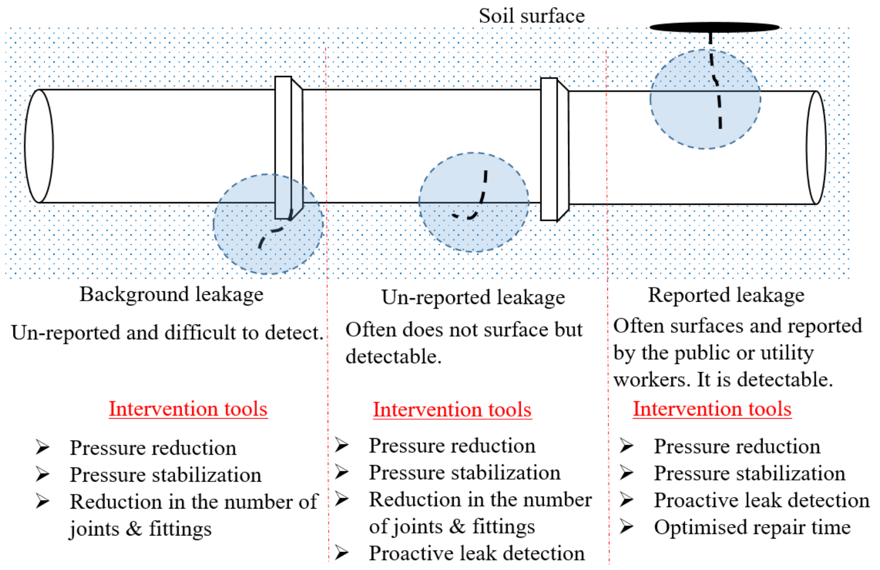

Figure 5: Leakage types and intervention tools [23].

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 [24-28], the time-modulated pressure control [24-26], the flow modulated pressure control [24-28], parameter-less P-controller [29-32] and the optimisation approach [33-40] to mention but a few.

Fixed outlet pressure control technique: 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, 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 at different times of the day cannot be achieved [24-28].

Time-modulated pressure control approach: 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 [24]. With this approach, a greater flexibility of pressure adjustments at specific times of the day is achieved with the help of the controller. The controller is low cost and relatively easy to set up. The time-modulated pressure control approach is majorly used 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 demand of water, such as the demand for firefighting [24-26]. During this demand period, full pressure is usually required to tackle fire outbreak. In addition to this, 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.

Flow modulated pressure control: 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. The flow-modulated pressure control approach provides a greater control and flexibility than the time-modulated pressure control approach, though at the expense of price. 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 [24-28].

Parameter-less P-controller is another efficient controller to adjust the pressure which is based on the flow in a PCV and is argued to be easy to implement. The authors of [29] investigate the robustness of parameter-less remote real-time pressure control in water distribution systems to control a PCV [30,31] and the variable speed pumps [32]. This has the adavantages over the fixed outlet and time modulated pressure control approach in that the controller used is easy to set up and has the ability to respond to changing water demand conditions.

Optimisation approach: 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 powerfool tool used to acieve 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 [33], Hindi and Hamam [34-38] 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 [21,22,39,40]. The results of these research works revealed that the optimisation methods can be used for determining the optimal location of PRVs [34,39] as well as its opening adjustments and settings [21,22,33,35-38]. Araujo *et al*. [21] 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*. [40] developed a model for reducing pressure in urban WDNs using genetic algorithm based optimisation method and artificial neural networks. The results of the proposed model revealed 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 can be seen in Table 1, the FOPC is relatively simple to use and easy to set up. However, in practical situation when there is pressure variations, the approach fails to capture and adjust itself to compensate for these variations. The limitation of the FOPC method is overcome in the TMPC approach. TMPC approach offers better flexibility to pressure variations and can be used during the minimum night flow period. However, during water demand variation 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. 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 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 varaitions 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.

Method	Remarks	Cost	Limitation	Application
Fixed outlet pressure control (FOPC)[24-28]	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)[24-26]	The controller used is easy to set up	A little bit expensive	Low response to water demands variations	Majorly used during the minimum night flow hours (MNFHs).
Flow modulated pressure control (FMPC)[24-28]	Complex	Expensive	Low response to water demands variations	Can be used during both MNFHs and high demand period
Parameter-less P-controller [29-31]	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) [21,22,31-40]	For optimal location and opening adjustment of the pressure	Not expensive	Practical application in large-scale water piping networks is required.	Can be used during both MNFHs and high demand period.

	reducing valves			

Table1: Pressure management approach

4. CONCLUSION

Leakages have been a major threat to water utilities around the world and has been the major area of attention in the research community. It is a general agreements 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 paper. 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 optimization and parameter-less controller could be best suited for pressure reduction in smart water networks.

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REFERENCES

[1] Wu, Z.Y., Farley, M., Turtle, D., Kapelan, Z., Boxall, J., Mounce, S.R., Dahasahasra, S., Mulay, M. & Kleiner, Y. (2011). Water loss reduction. 1st ed. USA: Bentley Institute Press: 1-68.

[2] Ates, S. (2016). Hydraulic modelling of closed pipes in loop equations of water distribution networks. *Applied Mathematical Modelling*, **40**, 966-983.

[3] Mckenzie, R.S., Siqalaba, Z.N. & Wegelin, W.A. (2012). The state of non-revenue water in South Africa. Report to the Water Research Commission by WRP Consulting Engineers (Pty) Ltd, WRC Report No. TT 522/12.

[4] Abu-Mahfouz, A.M., Hamam, Y., Page, P.R., Djouani, K. & Kurien, A. (2016). Real-time dynamic hydraulic model for potable water loss reduction. *Procedia Engineering*, **154**(7), 99–106.

[5] Adedeji, K., Hamam, Y., Abe, B. & Abu-Mahfouz, A.M. (2016). Towards achieving a reliable leakage detection and localisation technique for real-time application in pipelines: an overview", Submitted for publication.

[6] Pirsing, A. (2014). Smart water. *In: Seminar Presentation for Water Application, Water Day*, Turkey.

[7] Adedeji, K., Hamam, Y., Abe, B. & Abu-Mahfouz, A.M. (2016). Leakage detection algorithm integrating water distribution networks hydraulic model. *In SimHydro 2017: Choosing the right model in applied hydraulics*, 14th-16th June 2017, Sophia Antipolis.

[8] Osman, M.S., Yoyo, S., Page, P.R. & Abu-Mahfouz, A.M. (2016). Real-time dynamic hydraulic model for water distribution networks: steady state modelling, *In: proceedings of the 6th IASTED International Conference in Environment and Water Resource Management*, September 5th- 7th,Gaborone, Botswana, 142-147.

[9] Mudumbe, M.J. & Abu-Mahfouz, A.M. (2015). Smart water meter system for user-centric consumption measurement. *Proceedings of the IEEE International Conference on Industrial Informatics*, 22nd -24th July, Cambridge, UK, 993-998.

[10] May, J. (1994). Leakage, pressure and control. *BICS International Conference on Leakage Control*, London.

[11] Lambert, A. (2000). What do we know about pressure: leakage relationship in distribution systems? System Approach to Leakage Control and Water Distribution Management, IWA, Brno, Czech Rep.

[12] Thornton, J. (2003). Managing leakage by managing pressure: A practical approach. Water 21, IWA Water Loss Task Force.

[13] Thornton, J. & Lambert, A. (2005). Progress in practical prediction of pressure: leakage, pressure: burst frequency and pressure: consumption relationships. *Proceedings of the IWA Special Conference*, Leakage 05, Nova Scotia, Canada.

[14] Giustolisi, O., Savic, D., & Kapelan, Z. (2008). Pressure-driven demand and leakage simulation for water distribution networks. *Journal of Hydraulic Engineering*, **134**(5), 626-635.

[15] Farley, M., & Trow, S. (2003). Losses in water distribution networks-A practitioner's guide to assessment, monitoring and control, IWA Publishing, London, UK.

[16] Thornton, J. & Lambert, A. (2007). Pressure management extends infrastructure life and reduce unnecessary energy cost. *Proceedings of the IWA Special Conference on Water Loss*, Bucharest, Romania, 511-521.

[17] Swamee, P.K., Tyagi, A., & Shandilya, V.K. (1999). Optimal configuration of a well-field. *Ground Water*, **37**(3), 382-386.

[18] AbdelMeguid, H.S (2011). Pressure, leakage and energy management in water distribution networks. PhD Thesis, Faculty of Technology, De Montfort University, Leicester, UK.

[19] Ulanicki, B., Bounds, P., Rance, J.P. & Reynolds, L. (2000). Open and closed loop pressure control for leakage reduction. *Urban Water*, **2**, 105-114.

[20] Xylem Gould Water Technology. Aquavar e-ABII. Xylem Inc., Rye Brook, New York, USA. [Online]. Available from: http://goulds.com/pump-controllers/aquavar-abii-pump-controller-aqua-boost-residential/ [Accessed: 15/10/2016].

[21] Araujo, L.S., Ramos, H., & Coelho, S.T. (2006). Pressure control for leakage minimisation in water distribution systems management. *Water Resources Management*, **20**, 133-149.

[22] Kalanithy, V. & Lumbers, J. (1998). Leakage reduction in water distribution systems: optimal valve control. *Journal of Hydraulic Engineering*, **124**(1), 1146-1154.

[23] Tardelli, F.J. (2006). Control of e ReduçãoPerdas. In *Abastecimento de Água*, 3rd ed. São Paulo: Departamento de Engenharia e HidráulicaSanitária, Polytechnic School of the University of São Paulo.

[24] Mckenzie, R.S. & Wegelin, W.A. (2009). Implementation of pressure management in municipal water supply systems. IWA, pres. Paper 0309.

[25] McKenzie, R., Wegelin, W. & Rohner, K. (2000). Leakage reduction through pressure management in the greater Johannesburg area. *American Water Works Association Annual Conference*, Denver, Colorado, 11th-15th June, 2000.

[26] McKenzie, R. (2002). Khayelitsha: leakage reduction through advanced pressure control. *Journal of the Institution of Municipal Engineering of South Africa*, **27**, 8, 43 to 47.

[27] McKenzie, R., Mostert, H & Wegelin, W. (2003). *Leakage Reduction through Pressure Management in Khayelitsha, Western Cape: South Africa*. *Australian Water Association Annual Conference*, Perth, 7th - 10th April, 2003.

[28] Meyer, N, Wright, D. & Engelbrecht, M. (2009). Large scale pressure management implementation in the City of Cape Town, *IWA Water Loss Conference*, April 2009.

[29] Philip R. Page, Adnan M. Abu-Mahfouz, Olivier Piller, Matome M., Muhammad S.O. (2017). Robustness of parameter-less remote real-time pressure control in water distribution systems. *In SimHydro 2017: Choosing the right model in applied hydraulics*, 14th-16th June, Sophia Antipolis.

[30] Page, P.R., Abu-Mahfouz, A.M. & Yoyo, S. (2016). Real-time adjustment of pressure to demand in water distribution systems: Parameter-less P-controller algorithm. *Procedia Engineering*, **154**, 391-397, 2016.

[31] Page, P.R., Abu-Mahfouz, A.M. & Yoyo, S. (2016). Parameter-less remote real-time control for the adjustment of pressure in water distribution systems. Submitted for publication.

[32] P.R. Page, A.M. Abu-Mahfouz, M. Mothetha, "Pressure management of water distribution systems via the remote real-time control of variable speed pumps, "Submitted for publication, 2016.

[33] Jowitt, P. W. & Xu, C. (1990). Optimal valve control in water distribution networks. *Journal of Water Resources Planning and Management*, 455-472.

[34] Hindi, K.S. & Hamam, Y.M. (1991a). Locating pressure control elements for leakage minimization in water supply networks: An optimization model. *Engineering Optimization*, **22**, 281-291.

[35] Hindi, K.S. & Hamam, Y.M. (1991b). Pressure control for leakage minimization in water supply networks part 1. Single period models. *International Journal of System Science*, **22** (9), 1573-1585.

[36] Hindi, K.S. & Hamam, Y.M. (1991c). Pressure control for leakage minimization in water supply networks part 2. Multi-period models. *International Journal of System Science*, **22** (9), 1587-1598.

[37] Hindi, K.S. & Hamam, Y.M. (1991d). An optimisation model for setting pressure controllers to minimise leakage. *IFIP Working Conference on Optimisation based Computer Aided Modelling and Design*, Hague.

[38] Hamam, Y.M., & Hindi, K.S. (1992). Optimised on-line leakage minimisation in water piping networks using neural nets. *IFIP Working Conference*, Dagschul, Germany.

[39] Reis, F.R., Porto, R.M. & Chaudhry, F.H. (1997). Optimal location of control valves in pipe networks by genetic algorithm. *Journal of Water Resources Planning and Management*, 317-326.

[40] Nazif, S., Karamouz, M., Tabesh, M. & Moridi, A. (2010). Pressure management model for urban water distribution networks. *Water Resource Management*, **24**, 437-458.