LEAKAGE DETECTION ALGORITHM INTEGRATING WATER DISTRIBUTION NETWORKS HYDRAULIC MODEL

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KEY WORDS

Hydraulic model, pipe leakage, leakage detection, water distribution systems, water loss.

ABSTRACT

Water loss through leaking pipes is inexorable in water distribution networks (WDNs) and has been recognized as a major challenge facing the operation of municipal water services. This is strongly linked with financial costs due to economic loss, environmental issues, and water resource savings. Water distribution systems are complex in nature with a large number of pipes. Therefore, monitoring long-range pipelines for leaks is a challenging task. This problem is aggravated when there are simultaneous leakages at various points in more than one pipe in the networks. Consequently, there is an urgent industrial need for a reliable approach to provide the capabilities for loss reduction through the detection of leaking pipes in WDNs. Nevertheless, a large number of techniques for detecting leakages have been proposed in the literature. These methods include the use of acoustic correlation techniques, measurements and statistical analysis of the abrupt changes in pressure at the leak points, and the transient based approach to mention but a few. However, their performance in detecting background leakage is quite low. In WDNs, background leakage is often hidden, small, and continuous, posing the biggest threat to water utilities. Therefore, its detection and estimation is vital for effective water service. For effective detection of background leakages, a hydraulic analysis of flow characteristics in water piping networks is indispensable for appraising such type of leakage. A leakage detection algorithm incorporating the hydraulic model of flow in water piping networks should prove worthwhile in detecting and estimating background type leakages.

In this work, a leakage detection algorithm integrating the hydraulic model of the flow in water piping networks is proposed. The hydraulic model takes into account some important parameters of pipes such as pipe deterioration due to ageing, which was not considered in previous leakage detection studies. The deterioration in pipe materials and changes in its diameters over time can lead to unsatisfactory results. Furthermore, in large-scale networks, most leakage detection algorithms only cover a specific area such as the district meter areas (DMAs) of the network. The authors are optimistic that the proposed algorithm for solving network leakage outflow will help improve the leakage detection accuracy while providing the capability to cover a wide area in the large-scale water piping networks.

1. INTRODUCTION

Water loss through leaking pipes is a major problem facing water utilities and has been a major area of research in the past years. Over time, pipes deteriorate leading to breaks and leaks, which may result in a reduction in the water-carrying capacity of pipes. The financial effect of leaking pipes includes the substantial repair costs and loss of the precious natural resource. In many countries, USA for example, almost 20% of the US water supply is lost through leaking pipes [1]. Likewise, in South Africa, a water-scarce country, high water losses through leaking pipes has threaten the operation of its water service with an estimated loss of more than R7 billion annually [2]. Besides the financial cost associated with pipe leakages, it can also pose

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potential dangers by temporarily reducing fire-fighting capabilities and contaminating the water in distribution systems [3]. These factors made leakage detection a very important topic in the research community.

A large number of algorithm, techniques and devices are available in the literature, developed for detection leakages in water piping networks [4-12,13]. Moreover, various techniques and algorithms have been developed to reduce the water loss in the water distribution networks through the real-time pressure control and the real-time control of variable speed pumps [14-18]. Real-time flow monitoring via smart meters is another simple approach that can be used to identify problematic areas [19]. In most cases, the developed approaches are mostly used for detecting leakages characterised by sudden pressure drop (burst type leakage). In water distribution networks (WDNs), two major types of leakages have been reported to include the burst and background type leakage. The burst type leakages are often reported and are caused by physical or structural pipe failure. The later are outflows running from small cracks, holes, deteriorated joints or fittings occurring along the pipes. This leakage do not result into evident and quick pressure drops through the network, thus, are not reported and often run for longer time. As a result, produces relevant impact on WDN water lost volume

In water piping network, background leakage are continuous and are not characterised by sudden pressure drop compared to pipe burst. Therefore, the detection and estimation of such leakage will be a major break-through as 90% of water loss is caused by such leaks [20]. In other to capture such leaks effectively, there is need to understand leakage flow characteristics in water network. A hydraulic model of flow in water network [21,22] is sufficient and should be used in estimating such leakages. A leakage detection algorithm incorporating a hydraulic model of flow in piping network should prove valuable and offer an improve detection accuracy. Hydraulic modelling of flow in individual pipes can provide strong inferences about pipe flow condition if sufficient data about the pipes are available.

In most hydraulic models for leakage detection, leakage flow is usually treated as being uniformly distributed along the pipe. However, in reality, this assumption can lead to large error in leakage outflows. This is because the pipe diameter is not constant throughout the entire service life of the pipe. The diameter reduces due to aging which increases the pipe roughness coefficient [23-26]. Therefore, in this paper, these very important parameters were taken care-off in the leakage detection algorithm in solving the network leakage outflows. The algorithm starts from the paradigm introduced by [27,28]; the global gradient based methodology for solving the system of equations derived from the WDN topology.

2. THE PROPOSED LEAKAGE DETECTION ALGORITHM

The flow chart of the proposed leakage detection algorithm is illustrated in Fig. 1. As discussed earlier, the algorithm uses the framework of the global gradient algorithm [28] to estimate the network leakage flow at the node as well as the pipe level. A reliable algorithm for detecting background leakage in water piping networks requires a hydraulic leakage modelling of flow in WDNs. As a result, a deep knowledge of the hydraulic characteristics of flow in water piping networks is vital. The proposed leakage detection algorithm uses the framework of the Todini’s hydraulic simulation model [28]; the global gradient algorithm to offer a more realistic representation.

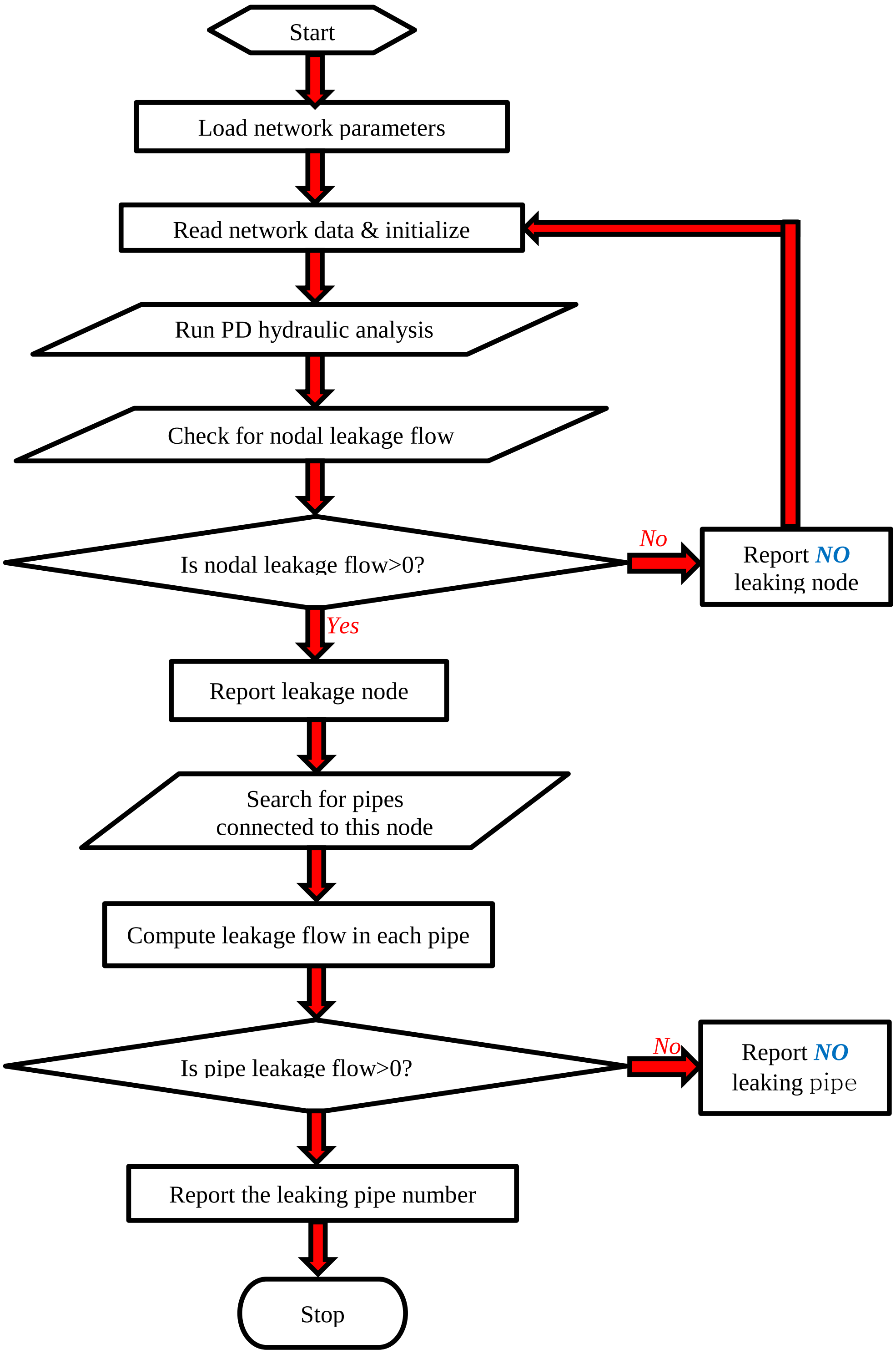

Figure 1: Schematics of the proposed leakage detection algorithm.

The basic hydraulic equations describing the flow in a water distribution system are govern by two basic principles; namely the principle of mass and energy conservation. For any water piping networks such as the one shown in Fig. 2 comprising of n_p, pipes, n_n junction nodes, n_0 fixed-grade nodes (nodes with known heads/elevation), the mass continuity equation can be written for each node, and the energy conservation equation can be written for any loop.

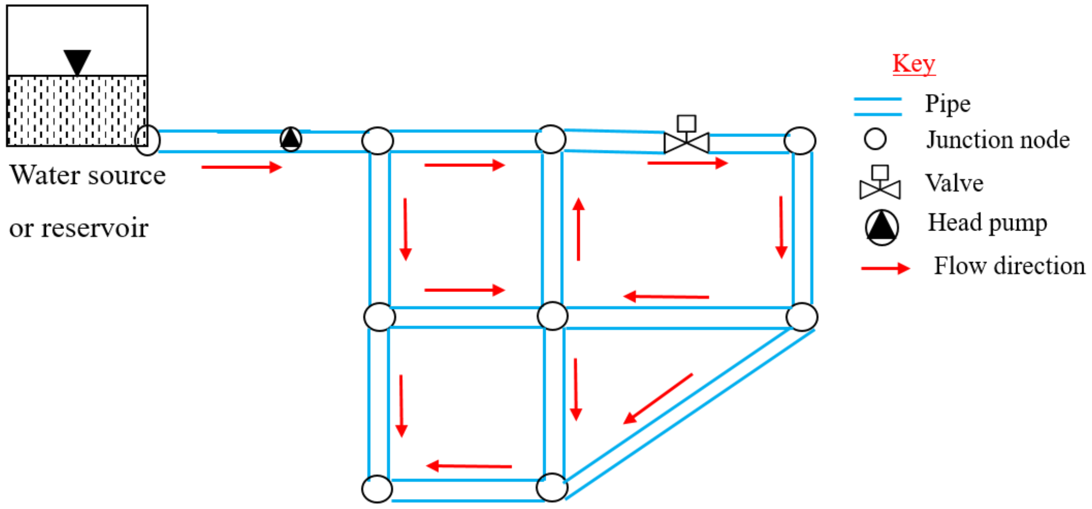

Figure 2: Schematics of a water distribution network.

The flow in the water piping network can be described by the following system of equations based on energy and mass balance conservation using the formulation of the GGA by Pilati and Todini [27] and Todini [28,29] for looped water distribution networks as

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & 0 \end{bmatrix} \begin{bmatrix} Q \\ H \end{bmatrix} = \begin{bmatrix} -A_{10}H_0 \\ -q \end{bmatrix} \tag{1}$$

where,

$Q \in \mathbb{R}^{1\times n_p}$ represents the column vector of unknown pipe discharge.

$H \in \mathbb{R}^{1\times n_n}$ represents column vector of unknown nodal heads.

$H_0 \in \mathbb{R}^{1\times (n_t - n_n)}$ represents column vector of known nodal heads.

$q \in \mathbb{R}^{1\times n_n}$ represents column vector of known nodal demands.

n_p: the number of pipes in the network.

n_n: the number of nodes.

n_t: the total number of nodes in the network.

n_{t-nn}: the number of nodes with known nodal heads (n_0).

In most hydraulic simulation model and software packages [30], nodal demand is usually treated as being uniformly distributed. However, in the practical sense, demand is not uniformly distributed and thus must be treated as pressure driven [28]. Likewise, leakage is dependent on pressure [31,32] and its model should be treated as pressure driven demand in the global gradient formulations. Therefore, in the GGA formulation, leakage and pressure driven model can be included as

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} Q \\ H \end{bmatrix} = \begin{bmatrix} -A_{10}H_0 \\ \tilde{q} \end{bmatrix} \tag{2}$$

Considering (1), only the matrix A_{22} and $\vec{q}$ was added to the GGA formulation. $A_{22} \in \mathbb{R}^{n_n \times n_n}$ is a diagonal matrix whose element can be derived from the pressure/head driven demand relation [33]:

$$A_{22}(i) = q_i \begin{cases} 1 & if \quad P_i \geq P_i^{des} \\ \left(\dfrac{P_i - P_i^{\min}}{P_i^{des} - P_i^{\min}} \right)^n & if \quad P_i^{\min} < P_i \leq P_i^{des} \\ 0 & if \quad P_i \leq P_i^{\min} \end{cases} \tag{3}$$

where,
q_i^{avl}: available flow/demand at node *i*.
q_i^{req}: Required flow/demand at node *i*.
P_i^{des}: design/service pressure necessary to fully satisfy the required nodal demand.
P_i^{min}: Minimum nodal pressure below which no water can be supplied to node *i*.
P_i: current pressure at node *i*.
n: exponent of the pressure demand relationships (typically 0.5) [33].

The matrix $A_{11} \in \mathbb{R}^{n_p \times n_p}$ is a diagonal matrix whose elements is derived from the relation

$$A_{11} = r_k \left| Q_k \right|^{n-1} \quad k = 1,........n_p \tag{4}$$

In (4), r_k is the resistance factor for the k^{th} pipe while *n* represents the pressure exponent whose value depends on the headloss model used (Hazem William, Diacy Weisbach or Manning head loss model) [34].

Previous research works conducted are based on the assumption of uniformly distributed demand at the pipe level as well as constant pipe diameter throughout the service life of the pipe. In the practical sense, this assumption is not valid [23-26]. Pipe diameter reduces as the pipe material deteriorate due to aging. While the assumption of uniformly distributed demands along the pipes is often used when there is poor knowledge about the actual connections and demands [25]. The pioneer work of the authors in [25] revealed that a large errors in energy balance conservation can be generated when uniform demand is lumped into the two end nodes of a pipe in order to exclusively conserve mass balance.

It should be noted that aging of pipes reduces its diameter as well as increases its roughness. A pipe resistance correction factor developed in [25], can be introduced into the head loss model and as a result, the diagonal matrix A_{11} can be rewritten as

$$A_{11} = \varepsilon_k r_k \left| Q \right|^{n-1} \quad k = 1,........n_p \tag{5}$$

where,
ε_k represents the pipe resistance correction factor derived in [25]. Also,

$$A_{12} = A_{21}^T \tag{6}$$

Likewise in (2),

$\vec{q} \in \mathbb{R}^{1 \times n_n}$ represents the column vector of nodal demands which comprises of the actual nodal demand and the nodal leakage flow. That is,

$$q(i,\mathrm{i}) = q_{act}(i) + q_{leak}(i) \tag{7}$$

where,
$q_{act} \in \mathbb{R}^{1\times n_n}$ represents the column vector of the actual pressure driven nodal demand;
$q_{leak} \in \mathbb{R}^{1\times n_n}$ represents the column vector of the unknown nodal leakage flow.

Traditionally, in most leakage model, leakage is usually allocated to the pipe ends nodes. Although, in the present study, the leakage flow rate at the pipe level is also determined. In water distribution networks, background leakage is small, hidden and run continuously along the length L of the k^{th} pipe in the network, then such leakage flow can be treated as pressure dependent and expressed as

$$q^{backgrond}{}_{leak(\mathrm{i,k})} = \begin{cases} C_k L_{i,k}\left(P_{(\mathrm{i,k})}\right)^{\delta} if \quad P_i > 0 \\ 0 \qquad if \quad P_i \le 0 \end{cases} \quad \forall i \in (1,2,......n_n) \tag{8}$$

where,
C_k represents the background leakage discharge coefficient which need to be determined. For background leakage, the pressure exponent δ of 1.18 has been reported [35-37].

The study of leakage flow hydraulics is vital for more realistic representation of the leakage flow. In most representation, leakage is usually distributed uniformly along the length of the pipe. However, this assumption might lead to some erroneous results. In accordance with the research work of the authors in [23-26], an integral part of a leakage detection algorithm should take note of the pipe deterioration and the corresponding decrease in diameter due to aging. In reality, the pipe diameter is not constant thorough out the service life of the pipe. Pipe materials deteriorate and its diameters reduces due to aging. Therefore, a leakage detection model showing the relationship between pipe diameter and age is vital in developing an effective leakage detection model. To this end, the discharge coefficients can be treated as a function of the pipe diameter, leakage shape and the pipe age expressed mathematically as

$$C_{i,k} \in \left(D_{i,k}, a_{i,k}, \tau_{i,k}\right) \tag{9}$$

Therefore, a further expression of leakage flow is introduced as

$$q_{leak(\mathrm{i,k})} = \begin{cases} C_k L_{i,k} D_{i,k}^{d} e^{a\tau}\left(P_{(\mathrm{i,k})}\right)^{1.18} if \quad P_i > 0 \\ 0 \qquad if \quad P_i \le 0 \end{cases} \tag{10}$$

where,
$D_{i,k}$: diameter of the k^{th} pipe connected to node i.
$\tau_{i,k}$: age of the k^{th} pipe connected to node i.
$a_{i,k}$: leakage shape parameter on the k^{th} pipe connected to node i (difficult to determine).

$$d = \begin{cases} 1 \qquad for \quad D < 125mm \\ -1 \qquad for \quad D > 125mm \end{cases} \tag{11}$$

The proposed algorithm incorporates these important parameters into the leakage model. The leakage discharge coefficient can be estimated using measurement of discharged during the minimum night flow hours. Once relevant network data is available, the GGA based methodology can be used to run a hydraulic analysis of flows in the network given the network topology and as a result, the leakage flow in the network can be estimated.

The algorithm run a pressure dependent hydraulic analysis of the flow (including leakage flow) in the network using the GGA based methodology, based on the network topology, and check for the nodal leakage flow. Afterwards, the algorithm checks if the nodal leakage discharge is greater than a specified threshold, say 0.001 *l/s*. A leaking node is detected and reported if there exist a nodal leakage discharge above the threshold. Consequently, the algorithm searches for all the pipes connected to such node and computes the leakage flow rates in each pipe. It also check for leakage flow rate above a specified threshold and if found, such pipe is detected and its number reported as a leaking pipe. Owing to this, the estimate of such leakage is determined and given by the algorithm. The process can be repeated more often to capture the variation in the nodal demand.

3. CONCLUSIONS

A more realistic leakage detection algorithm has been a major subject of discussion in the past years and in recent times. Due to the financial and environmental cost of leaking pipes, there is an industrial need for an efficient leakage detection approach. In this paper, we introduced and briefly discussed a leakage detection algorithm using the framework of the global gradient algorithm based methodology for the hydraulic analysis of flow in large scale piping network. Some very important parameters are discussed and included in the present study. The authors are optimistic that the proposed algorithm will improve leakage detection capability in water piping networks.

ACKNOWLEDGEMENTS

This research work was supported by the Tshwane University of Technology, Pretoria and the Council for Scientific and Industrial Research of South Africa.

REFERENCES

[1] Thornton, J., Sturm, R. & Kunkel, G. (2008). Water loss control. 2nd ed. New York: McGraw Hill Professional.

[2] Mckenzie, R., 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.

[3] Shridhar Y., Seth D.Guikema, & Kelly B. (2009).Statistical models for the analysis of water distribution system pipe break data. *Reliability Engineering and System Safety*, **94**, 282-293.

[4] Mpesha, W., Gassman, S.L. & Chaudrhy, M.H. (2001). Leak detection in pipes by frequency response method. *Journal of Hydraulic Engineering*, **125**(7), 761-764.

[5] Kapelan, Z.S., Savic, D.A. & Walters, G.A. (2003). A hybrid inverse transient model for leakage detection and roughness calibration in pipe networks. *Journal of Hydraulic Research*, **41**(5), 481-492.

[6] Buchberger, S.G. & Nadimpalli, G. (2004). Leak estimation in water distribution systems by statistical analysis of flow readings. *Journal of Water Resources Planning and Management*, **130**, 321-329.

[7] Lee, P.J., Vitkovsky, J.P., Lambert, M.F., Simpson, A.R. & Liggett, J.A. (2005). Frequency domain analysis for detecting pipeline leaks. *Journal of Hydraulic Engineering*, **131**(7), 596-604.

[8] Beck, S.M, Curren, M.D., Sims, N.D. & Stanway, R. (2005). Pipeline network features and leak detection by cross-correlation analysis of reflected waves. *Journal of Hydraulic Engineering*, **131**(8), 715-723.

[9] Mounce, S.R. & Machell, J. (2006). Burst detection using hydraulic data from water distribution systems with artificial neural networks. *Urban Water Journal*, **3**(1), 21-31.

[10] Turkowski, M., Bratck, A. & Slowikowski, M. (2007). Methods and systems of leak detection in long range pipeline. *Journal of Automation, Mobile Robotics & Intelligent Systems*, **1**(3), 39-46.

[11] Zhang, J., Hoffman, A., Kane, A. & Lewis, J. (2014). Development of pipeline leak detection technologies. *Proceedings of the 10th International Pipeline Conference*, Alberta, Canada, 1-8.

[12] Sadeghioon, A.M., Metje, N., Chapman, D.N. & Anthony, C.J. (2014). Smart pipes: smart wireless sensor networks for leak detection in water pipelines. *Journal of Sensor and Actuator Networks*, **3**, 64-78.

[13] 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.

[14] 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.

[15] 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.

[16] 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.

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

[18] Adedeji, K., Hamam, Y., Abe, B. & Abu-Mahfouz, A.M. (2016). Pressure management strategies for water loss reduction in large-scale water piping networks: a review. *In SimHydro 2017: Choosing the right model in applied hydraulics*, 14th-16th June 2017, Sophia Antipolis.

[19] 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.

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

[21] 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.

[22] 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.

[23] Giustolisi, O. & Todini, E. (2008). On the approximation of distributed demands as nodal demands in WDN analysis. *Proceedings of the XXXI National Hydraulics and Hydraulic Construction Conference*, 9–12 September, Perugia, Italy.

[24] Giustolisi, O. & Todini, E. (2008). The wrong approximation of representing pipe demands as nodal loads in network analysis. *Proceedings of the XXXI National Hydraulics and Hydraulic Construction Conference*, 9–12 September, Perugia, Italy.

[25] Giustolisi, O. & Todini, E. (2009). Pipe hydraulic resistance correction in WDN analysis. *Urban Water Journal*, **6**(1), 39–52.

[26] Ferrante, M., Todini, E., Massari, C., Brunone, C. & Meniconi, S. (2012). Equivalent hydraulic resistance to simulate pipes subject to diffuse outflows. *Journal of Hydroinformatics*, **14**(1), 65-74.

[27] Todini, E. & Pilati, S. (1988). A gradient method for the solution of looped pipe networks. Computer applications in water supply. Vo.1. John Wiley and Sons, 1–20.

[28] Todini, E. (2003). A more realistic approach to the extended period simulation of water distribution networks. Advances in water supply management. Balkema Publishers,173–184.

[29] Todini, E. (2006). On the convergence properties of the different pipe network algorithms. *Proceedings of the 8th Annual Water Distribution Systems Analysis Symposium* (CD-ROM), ASCE, Cincinnati, 1–16.

[30] Bello, O., Piller, O., Abu-Mahfouz, A.M. & Hamam, Y. (2016). Simulation models for management problems in water distribution networks: a review. Submitted for publication.

[31] Thornton, J. (2003). Managing leakage by managing pressure: a practical approach. *Water*, **21**, 43–44

[32] Wu, Z.Y., Sage, P. & Turtle, D. (2010). Pressure-dependent leak detection model and its application to a district water system. *Journal of Water Resources Planning and Management*, **136** (1), 116–128.

[33] 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.

[34] Rossman, L.A. 2000. EPANET 2 user's manual. United States Environmental Protection Agency.

[35] Germanopoulos, G. (1985). A technical note in the inclusion of pressure dependent demand and leakage terms in water supply network models. *Civil Engineering Systems*, **2**(3), 171–179.

[36] Araujo, L. S, Ramos, H. M. & Coelho, S. T. (2003). Estimation of distributed pressure-dependent leakage and consumer demand in water supply networks. *Advance in Water Supply Management*. Imperial College London, UK, 15–17 September.

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