Leak Localisation in Urban Water Supply System: A Literature Synopsis on Model-Based Methodologies

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***Abstract*—In water supply systems (WSS), water loss is inexorable, nevertheless, the volume of these losses differ from one WSS to the other. Because of its association with financial losses, environmental concern and most importantly saving of the water resource, advanced computing tools and methodologies have been developed for sustainable management of water resource through leak localisation. Over the years, several research studies have been conducted proposing different methodologies for leak localisation in WSS. Amongst the previous methodology used, a model-based approach is cost-effective. Thus, this paper presents a literature synopsis on the model-based approach to localising leaks in WSS. We categorise the model-based approach under orifice discharge modelling, pressure measurement and leak sensitivity analysis, water audit and minimum night flow analysis, leak signature analysis, and optimisation approach. Numerous research studies in this category are discussed therein. Also, technical challenges and research gaps for further studies are introduced.**

***Keywords*—Leak localisation, leak sensitivity analysis, model-based approach, optimisation, water supply systems.**

Fig. 1. Freshwater stress in Africa by 2025 [1].

I. Introduction

Water is a valuable natural resource needed for mankind survival. Population growth around the globe has caused a drastic increase in water demand. The increasing trend, together with the ageing water supply system (WSS) infrastructure, pose a threat to the supply of water to meet the increasing consumer demand. Even around the world, most especially in the African context, managing water resource is a major concern. A projection of the international population action shown in Fig. 1 revealed that by 2025 about 2.7 billion population in 48 countries will face water shortage [1]. It is, therefore, necessary to manage the available water efficiently.

To have access to safe drinking water, raw water (from lakes, ground well) passes through some process before it could be potable for consumption. This is usually done by water utilities. The raw water is sent to a treatment plant for processing and thereafter, the processed water is sent to the consumer through a complex network of distribution pipes. As water is transported through the network, an appreciable volume of water is lost along the pipe. Consequently, some of the processed water does not reach consumers. The water loss is termed as unaccounted for water (UFW) [2]. The UFW may be expressed using the water balance [3] as

$$UFW = W_l + U_{AC} \quad (1)$$

In equation (1), U_{AC} is the unbilled authorised consumption while W_l denotes the water loss which comprises of real losses from leaking pipes and fittings and apparent losses due to illegal connections and water theft. UFW is a major concern around the world. For example, Fig. 2 showed that there is a high rate of water losses in developing countries. In view of this, water utilities in many countries prioritized minimising the UFW through an active methodology for localising leaks.

In the past, several research studies have been conducted proposing different methodologies for leak localisation in WSS with different level of implementation cost [5–8]. In recent years, due to the improvement in computing power, several model-based approaches have been developed and deployed to localising leaks in WSS [11–22]. Amongst these, methodologies, the model-based approach is cost-effective. Thus, this paper presents a literature synopsis on the model-based approach for localising leaks in water supply systems. In this study, the reviewed work was categorised under orifice discharge modelling, pressure measurement and leak sensitivity

The authors wish to acknowledge University of Johannesburg, South Africa for the support.

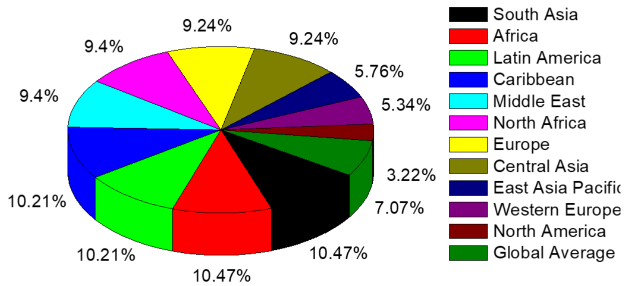

Fig. 2. Population weighted estimate of UFW [4].

analysis, water audit and minimum night flow (MNF) analysis, leak signature analysis, and optimisation approach. Numerous research studies in this category were discussed. Technical challenges and open research areas are also highlighted. The paper is arranged as follows. Section II discusses a short outline of a model-based methodology for leak localisation. Section III presents some selected studies on the model-based leak localisation methodologies and their challenges. In Section IV, a brief summary and challenges of these methods are presented while Section V concludes the paper.

II. Model-based Methodologies

In a model-based methodology for localising leaks in water supply networks (WSNs), the operation of a WSN is represented by mathematical formulations. The mathematical formulation uses the principle of momentum, mass and energy conservation to estimate discharge and pressure in the water network. In such a system, a leak threshold is usually defined based on the practical experience of leak scenario in water supply networks. Then, if the discharge estimate is above the threshold, a leak alarm will be raised. Usually, the model-based approach is used to locate leaks within the water pipe network or a monitored network section such as the district meter area (DMA).

III. Selected Studies on Model-Based Leak Localisation Methodologies

In this section, an appraisal of some selected research studies focusing on model-based methods for localising leaks in water supply systems is presented. As previously stated, we categorised these research studies under orifice discharge modelling, pressure measurement and leak sensitivity analysis, water audit and analysis of minimum night flow, leak signature analysis, and optimisation approach.

A. Orifice discharge modelling

Previous research studies [9–11] have shown that leak discharge increases with pressure. In this methodology, leak discharge is considered as a flow through an orifice along the pipe and thus modelled as a pressure-dependent at selected points in the network. The orifice flow equation [9] may be expressed as

$$Q_l = CA(2gh)^n \qquad h > 0 \tag{2}$$

where Q_l is used to define leak flow rate, C is a coefficient relating to leak discharge, h signifies the pressure head, A is the orifice area, and n represents the pressure-to-leakage exponent. The n depends on the type of leak. In the case of pipe burst, the value of n of 0.5 has been reported [9]. Another leakage model is proposed in [12, 13]. In these works, Q_l is defined as a function of the orifice area as shown in equation (3).

$$Q_l = C\sqrt{2g}\left(A_0 h^{0.5} + m h^{1.5}\right) \tag{3}$$

In equation (3), A_0 denotes the initial area of the orifice at zero pressure and m is the pressure-area slope constant. Values of m depends on the shape of the leak the openings in pipes. For instance, when a round shape orifice is considered, the value of m is considered to be very small [13]. In many research studies [14–16], the expression in equations (2) and (3) is adopted to model network leakage flow with some technical challenges reported. The research attempt in [14, 23] has shown that, given certain specific pipe conditions, inaccurate results may be produced by the orifice flow model. For example, [14] revealed that if the considered pipe is of flexible materials, the orifice flow equation may inaccurate results.

In Wu *et al.* [24], a pressure-dependent leak localisation model in water supply networks using a genetic optimisation approach was developed. At selected nodes of the networks, the leak localisation is formulated using orifice flow equation and converted into an optimisation problem. The results show that leak localisation is achieved with this method. In this case, a burst type leak could be localised. However, for other leak types such as background leaks, adapting such methodology is a major concern. Elsewhere, Hunaidi [25] proposed an empirical model for background leakage evaluation during the night period. Such a model is expressed as

$$BL_n = \left(\frac{AL_m + BN_c + C}{15 L_p N_c}\right) \times \left(\frac{P_{av}}{71}\right)^{N_i} \tag{4}$$

where BL_n is the night background leakage discharge (l/h), P_{av} denotes the average pressure in the pipe, N_i is an exponent with values from 0.5 to 1.5 depending on the pipe material. Also, L_m represents the total length of the distribution mains, N_c depicts the number of service connections while L_p denotes the average length of service connections pipes. Likewise in (4), A, B, and C are constants whose values are 24 $lit/km/hr$, 1.5 $lit/connection/hr$ and 0.4 $lit/connection/hr$ respectively. The expression was used to model background leaks during night hours. However, due to demand variations during the day, a multi-period analysis is essential.

B. Water audit and MNF analysis

A water audit is based on the fact that the discharge at the entrance of a system must be equal to that at the outlet in a leak-free situation. In this method, the quantity of water lost is usually determined in a DMA during a specific time period. During this period, measurement of water flow rate is conducted during a MNF hour (between 2 am and 4 am). Water demand is generally low in the MNF hours, the pressure and the leaks hit their highest values [26]. The discrete meter area is formed by sectorizing the water supply distribution network into zones by the closure of valves. Thus, the water volume at the entrance and exit of the zone can be metered [27]. With this, necessary data related to the water entering the zone (input volume) and those consumed by users can be collected. Consequently, the water loss is estimated by subtracting the water consumed by users from the system input volume.

Farah & Shahrour [28] proposed a leak localisation method using water balance and automated MNF analysis. The proposed method is applied to one water network at the University of Lille. The network is equipped with a set of sensors for recording and transmitting flow measurements in the network. Thus, real-time data analysis allows the water balance to be verified and the water loss level evaluated in the network. Many case studies [29, 30] reported the efficient use of the minimum night flow analysis approach. In most of these cases, the minimum night flow methodology is often done manually and at uneven intervals. Consequently, data from an MNF analysis depends on user's examination to generate alarm about possible leaks.

C. Pressure measurement and leak sensitivity analysis

This leak localisation methodology is based on pressure measurement sensitivity analysis. Like the one shown in Fig. 3, localising potential leaky pipes in water distribution networks using this methodology works by contrasting the measured pressure at the entrance of a DMA with the estimates derived from a hydraulic simulation model. Thereafter, a set of the difference between those pressure values is evaluated. This difference is known as a residual vector $\check{R} \in \Re^{(n_s \times 1)}$ computed as

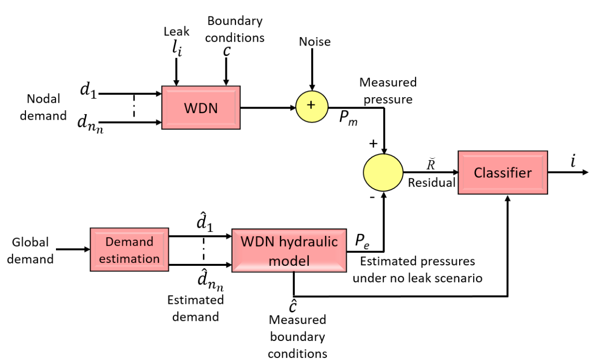

Fig. 3. A methodology for leak sensitivity analysis of pressure measurements [19].

$$\check{R} = P_m - P_e \tag{5}$$

where P_m $(n_s \times 1)$ is used to represents the pressure measured at the interior nodes of the DMA and P_e $(n_s \times 1)$ is its equivalent pressure estimate. The estimated pressure is computed using a hydraulic model under no leak situation. Also, n_s represents the number of pressure sensors positioned at interior nodes of the DMA. $\check{R}$ may be estimated at any time t as [17, 18]

$$R(t) = \begin{bmatrix} P_{m,1}(t) - P_{e,1}(t) \\ \vdots \\ P_{m,n_s}(t) - P_{e,n_s}(t) \end{bmatrix} \tag{6}$$

After computing $\check{R}$, a leak sensitivity analysis is conducted. Thus, the deviation in each pressure measurement at time t report the occurrence of possible leaks which is captured in the leak sensitivity matrix (LSM). The LSM may be expressed as [19, 36]

$$LSM = \begin{bmatrix} PS_{11} & \cdots & PS_{1N} \\ \vdots & \ddots & \vdots \\ PS_{M1} & \cdots & PS_{MN} \end{bmatrix} \tag{7}$$

In which

$$PS_{ij} = \frac{\hat{P}_{e(ij)} - \hat{P}_{e(i)}}{f_j}, \quad (i = 1, ..., M; j = 1, ...N) \tag{8}$$

Considering (8), $\hat{P}_{e(i)}$ is used to denote the pressure estimate in node i in no leak situation while $\hat{P}_{e(ij)}$ is that due to leak f_j occurrence at node j. In addition, N and M signify the total number of demand nodes and nodes with pressure sensors. Thus, the element of the LSM reports the impact of possible leaks on the pressure measurements at the node where the sensors are installed.

This methodology also employs a leak classifier as illustrated in Fig. 3, which is applied to $\check{R}$ for leak classification. The classifier is trained under various leak scenarios with the data from a hydraulic simulator. Several cases of leaks are generated employing orifice flow along the pipes. In order to localise potential leaking pipes in the network, $\check{R}$ is compared to the elements of the LSM. Thereafter, a correlation method is applied to $\check{R}$ and the columns of the LSM. The elements of $\check{R}$ having a good association with that of LSM spot the most possible leaking node [18]. The research efforts in [20, 31–33] provide studies on model-based leak localisation under this category. In Candelieri *et al.* [20], a methodology for localising leaks in water piping networks is proposed. The methodology employs a hydraulic model of water networks such as EPANET software and machine learning for leak localisation. The later utilises spectral clustering and support vector. In the former, leak scenarios were created utilising orifice discharge. Thus, the data from this model is used to train the system. In [31], pressure measurements were analysed utilising a cumulative integral. With the help of statistical estimation, leak localisation was achieved. When applied to water networks, less false alarms was obtained even though burst type leakage was localised. In [32], a methodology to localise leaks in WSS examining flow measurements was proposed. This method also employs a hydraulic method (for flow estimate) and fuzzy analysis. A residual was estimated as the difference between the measured and flow estimate. Thus, a fuzzy-based analysis was then applied to this deviation to report potential leaks. Just like the previous research studies, a burst type leak was localised. Furthermore, Misiunas *et al.* [33] developed an algorithm for leak localisation by applying a cumulative sum to the sudden change in pressures as a result of leaks. The sudden changes are represented as a peak and in a situation where the peak is exceeded, a leak is reported. The strength of these methods strongly relies on the accuracy of the model and measurements.

A model-based methodology which involves the estimation of the leak sensitivity matrix is a concern. The LSM was considered to be strenuous to estimate as a result of WSS complexity and demand uncertainty [34]. An improvement using graph theory and sparse storage has been presented by [35].

D. Optimisation approach

The optimisation approach for leak localisation in water supply networks is formulated as a minimisation problem. In this approach, the aim is to minimise the difference between the measured and estimated pressures. In [21], a leak localisation methodology shown in Fig. 4 utilising optimisation approach is proposed.

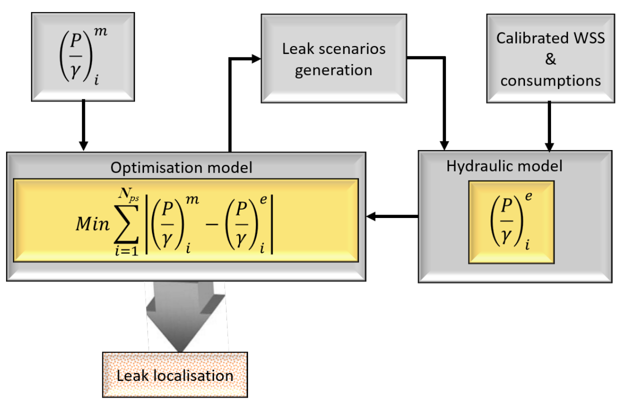

Fig. 4. An optimisation approach for leak localisation in WSS [21].

Hypothetically leak cases are created to recognize prospective leaking pipes. The problem is formulated as a minimisation function; thus, the objective function is to minimise the differences between both pressure values for all the monitored nodes as illustrated in equation (9). The constraints of the optimisation model in (9) are the conventional hydraulic parameters, such as energy and continuity equations which are taken care off in the hydraulic model.

$$F(x) = Min \sum_{i=1}^{N_{ps}} \left| \left(\frac{P}{\gamma}\right)_i^m - \left(\frac{P}{\gamma}\right)_i^e \right| \qquad (9)$$

In (9), $\left(\frac{P}{\gamma}\right)_i^m$ is used to depicts measured pressure at node i, while its equivalent estimate is $\left(\frac{P}{\gamma}\right)_i^e$. Also, γ concerns the unit weight of water while the number of nodes with pressure sensors is N_{ps}.

Adopting this method requires the optimal position of the sensors for collecting pressure data at minimal cost. Besides, the performance of this leak localisation methodology relies on the quality and design of sensors collecting the data [36, 37].

E. Leak signature analysis

This approach is somewhat similar to the leak sensitivity analysis of pressure measurements. Some of the developed approaches under this include a real-time transient model (RTTM) and extended real-time transient model (ERTTM) [38]. RTTM utilises a mathematical model governed by the fundamentals of momentum, mass and energy conservation to estimate flow rate within the pipe network. In ERTTM method, a hybrid system is formed using the RTTM and statistical analysis. Just like some of the other methodologies, flow rate and pressure measurements are also a requisite. Then, ERTTM leak localisation method (Fig. 5) utilises RTTM module to observe differences between an estimated and its equivalent flow measured at the entrance and exit of a pipe network. This is referred to as the feature generator which computes the deviation $\breve{x}$ and $\breve{y}$ between both inlet and outlet flows as shown in equation (10).

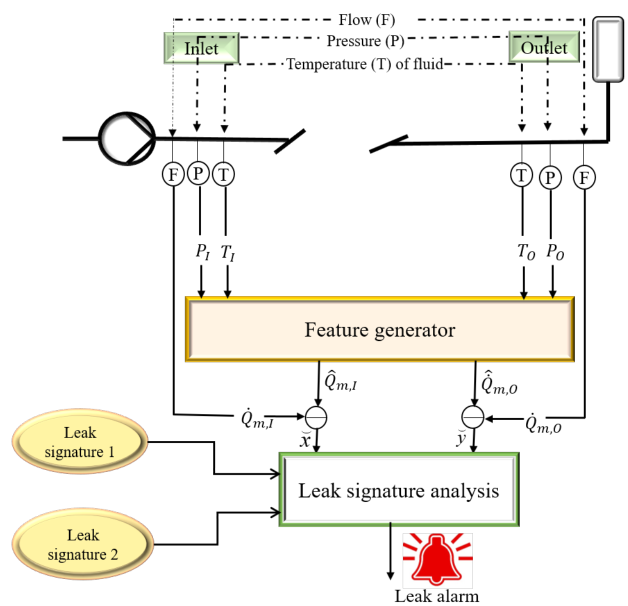

Fig. 5. A schematics of an ERTTM leak localisation methodology [38].

$$\left.\begin{aligned} \breve{x} &= Q_{m,I} - \hat{Q}_{e,I} \\ \breve{y} &= Q_{m,O} - \hat{Q}_{e,O} \end{aligned}\right\} \qquad (10)$$

In equation (10), both $Q_{m,I}$ and $Q_{m,O}$ denote the flow measurements at the entrance and exit of the pipe while $\hat{Q}_{e,I}$ and $\hat{Q}_{e,O}$ are their equivalent flow estimate considering a no-leak situation.

Thereafter a leak signature analysis is performed on the values of $\breve{x}$ and $\breve{y}$. By assigning this deviation to one of

TABLE I

SUMMARY OF THE RESEARCH WORKS ON MODEL-BASED LEAK LOCALISATION METHODOLOGIES.

S/N	Research domain	Remarks	References
1	Orifice flow modelling	Leak flow is considered as a flow through an orifice along the pipe and thus modelled as a pressure-dependent at selected points in the network.	[9–16, 23, 24]
2	Water audit and MNF analysis	It is based on the fact that the flow at the entrance of a system must be equal to that at the outlet under no leak situation.	[26–30]
3	Pressure measurements and leak sensitivity analysis	Localises prospective leaky pipes contrasting the measured pressure at the entrance of a DMA with the estimates derived from a hydraulic simulation model.	[17–20, 31–33]
4	Leak signature analysis	The method is somewhat similar to the leak sensitivity analysis of pressure measurements. A deviation between measured and flow estimate at the entrance and exit of a pipe is generated and assigns to class (leak) and (no leak).	[21, 36, 37]
5	Optimisation approach	It is an improvement in some of the model-based approach. The aim is to minimise the difference between the measured and estimated pressures.	[22, 38]

the following categories; *no leak* and *leak*, a leak scenario is reported. A more detailed description of this methodology is reported in [38]. High sensitivity to leakage is achieved with this methodology. Besides, the statistical method used permits the reduction of false alarms. This methodology may also be used to localise small leaks. One limitation of this methodology is that it requires substantial instrumentation for gathering the network operational data which could be used in the mode to generate the deviations.

In Casillas *et al*. [22], a leak signature analysis for leak localisation was introduced. The study, which is referred to as a leak signature space, relates a specified signature with each leak position in space. Pressure measurement variations due to leaks are also determined. The difference between the variations and the reference signature in the space provides an evaluation of the leak localisation. One major challenge is the optimal placement of the sensor (for pressure measurements) and the possible combination of sensors to optimise the differences between the leak signatures in the space. In most of these studies, only a single leak along the pipe could be localised. Thus, an improvement in these methodologies for multiple leak localisation has not been considered.

IV. SUMMARY

Table I presents the summary and the comparison of the model-based leak localisation methodologies. As may be observed, the water audit is based on the fact that the flow rate at the inlet of a system must be equal to that at the outlet in a leak-free scenario. Thus, water loss is estimated by subtracting the water consumed by users from the system input volume. The MNF methodology is often done manually and at uneven intervals. Therefore, data from an MNF analysis depends on user's examination to generate alarm about possible leaks. The optimisation method is conceived as an upgrade to some of these methodologies. However, it requires an optimal position of the sensors for collecting the data at minimal cost.

Also, most of the model-based leak localisation methodologies have the capability to localise leaks in water supply networks and are not affected by changing WSS configurations since they use mathematical models to represents the operations of such system. Thus, model-based methodologies can adjust to the changes in the WSS operational conditions and work well in DMAs of water networks irrespective of the complexity of the DMA. Some model-based methodologies need faultless measurements, sometimes at several locations in the network. For instance, the leak sensitivity analysis of pressure measurements, leak signature analysis and optimisation approach. The accuracy of these measurements depends on the operation of the WSS. In some cases, the measurement can be affected by noisy WSS operations. Also, in most of these methodologies, localisation of potential leaking pipes relating to burst was achieved. Adaptation of these methodologies for background leakage localisation is essential. Generally, most of these studies could only localise a single leak along a pipe. Thus, an improvement in these methodologies for multiple leak localisation is essential.

V. CONCLUSION

An efficient leak localisation methodology plays a key role in reducing water losses in water supply systems. This paper presents a literature synopsis on the leak localisation methodologies with a focus on the model-based approach. Research works in this domain, challenges and research gaps for further studies are presented. The studies show the significance of ongoing work in this domain, so the studies on leak localisation acknowledge some levels of challenges and an efficient method has not been completely accomplished. Nevertheless, this paper has highlighted areas for future research works in model-based approaches. Generally, most of these studies could only localise a single leak along a pipe. Thus, an improvement in these methodologies for multiple leak localisation is essential and has not been considered in previous studies.

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