Water Resour Manage (2018) 32:3247–3269
https://doi.org/10.1007/s11269-018-1985-6

A Selective Literature Review on Leak Management Techniques for Water Distribution System

Aditya Gupta[1] · **K. D. Kulat**[1]

Received: 26 January 2018 / Accepted: 5 April 2018 /
Published online: 26 May 2018

Abstract Water Distribution System suffers from leakages causing social and economic costs. There is need of platform to manage water distribution system more efficiently by detecting, localizing and controlling the leakages even before or as soon as they occur, ensuring quality water services to the consumers. Since last two decades, high efforts have been made by researchers for the development of efficient leakage management techniques for reduction of water losses in distribution system. This paper provides a comprehensive analysis on leakage management techniques covering three aspects: leakage assessment, leakage detection and leakage control, with an objective to identify present challenges and future scope in their respected field. Role of smart water technologies for efficient leakages management in pipeline network is also examined and discussed. Conclusion is drawn regarding current leakage management techniques and proposals for future work and existing challenges are also outlined.

Keywords Leakage assessment · Leakage detection · Transient analysis · Smart water system · Leakage control techniques

1 Introduction

Due to increase in social changes such as urbanization, population and economic growth, etc. water demand is expected to be increased by 40% by 2030 (Endo et al. 2017). According to World Bank nearly 48 billion m^3 of water gets lost annually from water distribution system (WDS), costing US $14 billion to water utilities (Mutikanga et al. 2013). Leakages are the

✉ Aditya Gupta
adityagupta2590@gmail.com

K. D. Kulat
kdkulat@ece.vnit.ac.in

[1] Department of Electronics and Communication, Visvesvaraya National Institute of Technology, Nagpur, India

main source of water losses in Water Distribution System (WDS). It comes under the category of physical losses in non-revenue water (NRW). According to report by water distribution network (WDN) bulletin, leakages in WDS vary from 5% (European countries) to 50% (developing countries)., even developed countries such as Mexico is also facing higher leakage rate of 30% (Plath et al. 2014). Because of these leakages, extra water has to be pumped out, which increases energy consumption also causing economic losses (Colombo and Karney 2005; Gupta et al. 2016). This also increases the water rate charged by companies on consumers (Beal and Flynn 2014). Leakages also cause contamination in water pipeline, causing adverse effect on human health (Kouchi et al. 2017). They also affects public infrastructure such as damaging of roads, etc. Leakages are classified as follows: a) Reported leakages: These are visible and easy to find. b) Unreported leakages: These are mainly underground leakages having moderate flow and are hard to find. These are the major sources of water losses (Farley and Trow 2007). c) Background leakages occur in joints due to poor fitting.

Water leakage is a serious issue since mid of 1980's. Current methods for detecting and locating leaks are labour intensive and often time consuming. Many communities such as American Water Works Association (AWWA), International Water Association (IWA), Environmental protection Agency (EPA), etc., works for water management. Several reports on leakage management (Pilcher et al. 2007; AWWA 2009) have been published by these authorities in the past. Goodwin (1980); Liou et al. (2003); Doug and Scott (2015); Adedeji et al. (2017) & Colombo et al. (2009) have presented a review on leakage management for water distribution systems (WDS). Above mentioned research articles discusses only on single issue i.e. either on leakage detection, leakage assessment or on leakage control. Whereas Puust et al. (2010) have discussed traditional leakage management techniques. Many past technology used for leakage management have under gone significant evolution. With advancement in science and technology has led to emergence of innovative technique for better leakage management. For example sensor based smart water technology has revolutionized the field of leakage management. It is also important to identify the future role of smart water technology for leakage management. To obtain better understanding regarding current trends in leakage management, analysis on specialized literature in the field of leakage assessment, leakage detection, leakage control and smart water technology is carried out during this research. The purpose of this review article is to obtain better analysis and to identify their direction required future work in their above mentioned respected field.

2 Leakage Assessment

It is desire to have a leakage free water supply system. Leakage assessments were performed on district metering area (DMA) introduced in 1980 by UK water authorities, to calculate the amount of water losses in WDS (Savić and Ferrari 2014). Leakage assessment is performed in two steps a) top-down approach and b) bottom-up approach (Puust et al. 2010).

2.1 Top-Down

Top-down approach is a faster way for leak assessment at lower cost. IWA has developed an international standard water balance (EPA 2013) which has gained acceptance from many international organizations such as American Water Works Association (AWWA), US Environmental Protection Agency (EPA), etc. Non-revenue water (NRW) is calculated by subtracting total system input volume from billed authorized consumption (such as meter and unmetered bill). These water losses are further divided into apparent losses (unauthorized consumption and metering errors) and real losses (losses from service reservoirs, mains and services). Annual volume of apparent and real losses is calculated in terms of million cubic meters (Mm^3).

Water loss assessment is performed in six areas of Ar-Riyadh, using top-down approach. Result shows variable leakage rate (5–50%) for different areas in WDS, costing around $ 50 million annually (Khadam et al. 1991). Liemberger and McKenzie (2003) have come up with water balancing software to calculate leakages. It is observed that using the top-down approach, confidence limit of less than ±15% is hard to achieve, during calculation of real losses, even in well-managed WDS (Lambert 2003). Hmiltom (2011) has suggested including more number of variables in water balance table for further improvement in accuracy of Top-Down approach. Lambert et al. (2014) has presented revised standard water Balance by performing minor modifications as shown in Fig. 1.

Development of sensor technology can help in improving the accuracy of Top-down approach. A smart water system is proposed for leakage assessment and its detection using water balance table in University of Lille (Farah and Shahrour 2017). Real time data were collected using hydrological sensors placed in university campus. Analysis of real-time data with the help of water balance helps in estimation of water losses in the network. This applied methodology is able to detect the pipe bursts quickly. There is detection of 25 unreported leaks. Hence causing decrease in the NRW losses by 36%.

Top-Down technique neither involve any extensive-field-work nor is this pressure-dependent method which makes this technique easy to apply in any WDS. But, it focuses on real losses more than apparent losses, thus this methodology overestimates real losses. Their assumption of apparent losses isn't appropriate. There is scope of improvement in methodology used for estimating unauthorized consumption, which is a major limitation of water balance technique. Research needs to be performed on estimation of unauthorized consumption and meters inaccuracies for increasing the efficiency of top-down approach.

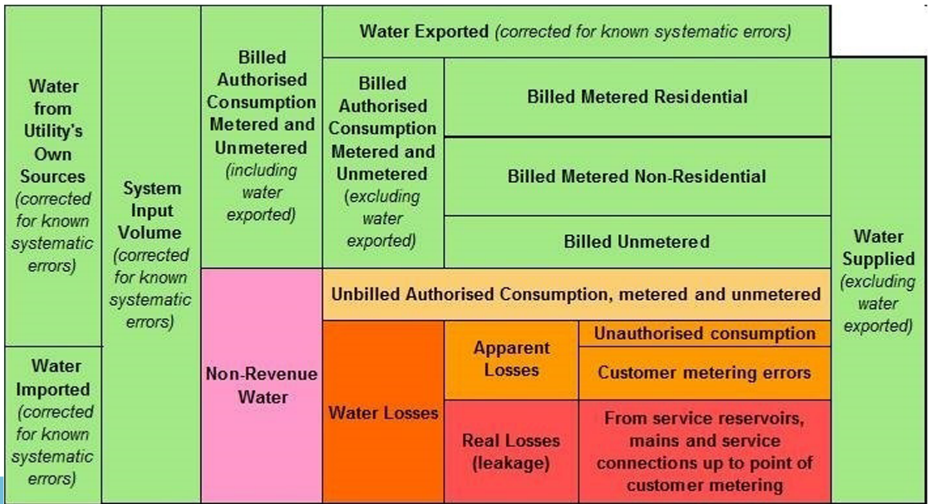

Fig. 1 Water balancing table (Lambert and Hirner 2000)

2.2 Bottom-Up Approach

Bottom-up approach is followed after top-down approach for further leakage assessment of selected DMA. Minimum night flow (MNF) is the most common approach being used for leakage assessment. A MNF analysis is performed on DMA which is a discrete zone having permanent boundary defined by flow meters and closed valves (Farley and Trow 2007). This analysis is performed in DMA having service connections between 500 and 3000 with measured supply input flow. Total water losses can be calculated by subtracting minimum night flow (MNF) from legitimate night flow (LNF). LNF are calculated based on an assumption that only 6% of the populations are active. Calculated Water losses show losses during MNF only rather than for the whole day. Estimating the total volume of real losses for whole day using these MNF losses would result in overestimation of the daily leakage, because of the lower average pressure during the day time due to higher flow rate. Thus leakage rate changes throughout the day depend upon the pressure.

Lambert (2001) comes with the concept of Fixed and Variable Area Discharges (FAVAD) which defines relation between leak discharge and pressure. Losses rates vary with pressure to a power that varies between 0.5 and 1.5. Simplest version of FAVAD concept suitable for most practical predictions is defined as

$$Q = C_d\sqrt{2g}\left(A_0h^{0.5} + mh^{1.5}\right) \tag{1}$$

where A_0 is area; m is head-area slope; C_d is discharge coefficient; and g is acceleration due to gravity. Here mh/A_0 is leak number (L_N).

The most generalize equations used for analysis of pressure-leakage relationships (Lambert 2001), is define as

$$\frac{L1}{L0} = \left(\frac{P1}{P0}\right)\beta \tag{2}$$

where L1, L0 are leakage rates and P1, P0 are pressure heads at respective area; and β is pressure exponential varies from 0.5 to 2.5.

Thornton and Lambert (2005) have verified the value of β for different countries. Australia has β values of 1.33, while for USA it varies from 0.7 to 1.33. He also concluded that the values of β will be in range of 0.5 to 1.0 for smaller leakages in PVC pipeline. Gomes et al. (2013) discusses how variation in value of β may affect the cost benefit of pressure management. The benefits of pressure management will be high for place having higher value of β. De Marchis et al. (2013) have studied small longitudinal cracks on plastic pipeline (63 mm, diameter) network, under head variations of 10 m to 60 m. It is observed that effective leak area varies linearly with head. Power equation (Eq. 1) best reproduces the head-effective area relationship. Test under larger diameter pipeline can be taken as future work.

Tabesh et al. (2009) used MNF and showed its usefulness in determining water losses. Leak assessment is performed on Iranian town, having 5772 connections. The WDS is having annual real loss of 1.28 Mm^3 by volume. Evolvement of sensor technology has increased the data reliability with removal of human error, makes leakage assessment faster and more efficient. Bottom-up approach (Savić and Ferrari 2014) is used for leakage assessment in DMA of Lisbon water supply system. Leak localization operation has been carried out using acoustic sensors. Reduction in water losses by 40% is observed, causing total annual saving of

63,500 €. Bottom-Up approach results in better accuracy of leakage assessment when compared to top-down technique. Actual field measurements were taken during MNF, thus it can be seen as both leakage assessment and reduction process if followed by leakage detection process (Taha et al. 2016). Network zoning, requirement of costly equipment, data reliability, intense field work, requirement of trained manpower, pressure-dependent can be seen as some of the limitations of MNF. 24 Hour Zone Measurement (HZM) (Liemberger and Farley 2004) is another method for leakage assessment. HZM suffers from limitation that, it can only be used in WDS having maximum of two inflow points.

2.2.1 Burst and Background Estimates (BABE)

(Lambert 1994) is the methodology to model leakage components objectively. Background losses are continuous can be classified as reported and unreported bursts having variable durations which depend upon (1) awareness time; (2) location time: (3) repair time. BABE approach use data such as standard components (pressure, average burst flow rates), pipeline related data (e.g. length of mains and frequency of bursts); and data from company policies in terms of their influence on the duration time a burst runs (Lambert 1994). Utilizing the above data, leakage can be calculated by:

$$V = N*Q*T*P \tag{3}$$

Where V is volume of leakage; N is the number of leaks; Q is leak flow rate and T is the average leak durations.

It is considered that all the pipeline bursts ≥500 l/h has been repaired. Such factors were generated to simplify the leakage volume calculation. This is one of the earlier methods that also breaks down real losses into sub-components and also considers the pipeline infrastructure condition. Pressure-dependability, large assumptions, intensive reliable data such as number of connections, pipeline mains length etc. and having capability that it can only be applied for utilities which having regular Active leakage Control can be seen as some of the limitations of this techniques.

The BABE model uses intensive assumptions from specific cases that are not sufficiently for various international networks which may lead to underestimating the amount of real losses, thus affecting its accuracy. Thus, it is not recommended to use BABE factors for water loss assessment unless there is no other option available. It should be used as a supplementary tools to breakdown the real losses into its sub-components.

The general leakage equation adopted by researchers, to describes the flow rate (*Q)* through the orifice in the form of a power equation is define as (Lambert 2001)

$$Q = Ch^{N1} \tag{4}$$

where C is leakage coefficient; N1 is the leakage exponent; and h is pressure head.

Van Zyl and Cassa (2013) has studied the relation between power equation (Eq. 1) and FAVAD (Eq. 2) for leakage modeling with respect to change in pressure. It is observed that leakage exponential is different for same leak at different pressure. It varies from 0.5 to 1.5, when pressure varies from 0 to ∞. Relation between leak exponential (N1) and leak number (L_N) is also derived for longitudinal and spiral crack. The value of N1 is 0.5 and 1.5 for Ln < 0.01 and 100, respectively. Plotting leakage exponential against leak number always result in same line, irrespective of pressure value.

2.2.2 Infrastructure Leakage Index (ILI)

is an efficient tool for determining, how effectively a utility is managing real losses in WDS and is also adopted by IWA (Michael 2007). ILI is given by:

$$\mathrm{ILI} = \mathrm{CARL}/\mathrm{UARL} \tag{5}$$

where CARL is current annual real losses obtained from IWA balance standard sheet; and UARL is unavoidable current annual real losses, is defined as

$$\mathrm{UARL} = \left(5.5\mathrm{L_m} + .15\,\mathrm{N_c} + 7.5\mathrm{L_p}\right)*\mathrm{P} \tag{6}$$

where P is average pressure; L_p is length of private pipe; L_m is length mains; and N_c is number of service connections (Michael 2007).

It is observed that low income countries have more ILI than high income countries. ILI has shown promising and efficient results. ILI is not recommended to use in the area having less than 5000 customers and having pressure below 35 psi (Michael 2007). While calculating ILI, one does not consider social, economical, environmental and institutional factors, also known as four dimensions of sustainability. Pires et al. (2017) has tried to identify the key indicators based on these four dimensions of sustainability, in order to identify the effectiveness of urban water leakage management tool. The study concludes by citing 24 key indicators among 170 key factors such as water quality, protection of natural resources i.e. soil water, etc. for identifying the effectiveness of leakage management tool.

Tucciarelli et al. (1999) has performed leakage assessment, by calculating the difference between predicted and measured values of flow and head from sensors. Prediction of flow and head of WDS is performed using maximization of likelihood functions. Thus analysis on collected hydraulic parameters using sensor technology can be seen as one of the future approaches for leakage assessment.

3 Leak Detection and Localization Techniques

Leak assessment techniques prove to be efficient in finding out the water losses in WDS. But there is need to detect and localize leakages in WDS. This makes pipeline repairing faster and easier. Leakages can be determined using acoustic and non-acoustic techniques.

3.1 Acoustic Techniques

In early 1900's, listening sticks where the only acoustic instruments available for detecting and pinpointing leakage. Now a day, acoustic devices such as data loggers and leak noise corelaters are available. These devices picks up the sound generated due to water leaking in pipeline thus making leakage localization possible. Water research Centre, UK has come up with hand held digital noise correlation device (Ozevin and Harding 2012). It is more immune to noise but suffers from the drawbacks of limited operating range of 150 m and also do not perform well for plastic pipes. Other acoustic devices such as ground microphone also suffer from limited surveying range of 1.3 - 3 m (Puust et al. 2010). Outer environmental noise may affect the performance of these acoustic devices. Sometimes it is possible that noise may not travel across the boundary of pipeline (mainly PVC), thus reduces its leakage detection efficiency.

These acoustic devices can be unreliable for leaks in non-metallic pipes and large-diameter pipes. Their effectiveness also depends on the experience of the user. These techniques are also time consuming.

Advancements in science and technology have led to more efficient modern acoustic equipment. Use of technologies such as microphones, acoustic sensors and smart balls has made leakage detection and its localization easier and efficient, even in large-diameter pipes. Tang et al. (2009) have used acoustic sensors based smart network for the detection and localization of burst event in simple pipeline network. Wavelet transform have been used for the denoising of received acoustic signal. Cross correlation of acoustic signals is performed to calculate the difference in time of arrival of two acoustic signals, which is utilized for the successful localization of burst event. Frequency content of noise depends upon size of the leak, pipe material and pressure. It works best for small and clean metallic pipelines. Multiple leakages in single pipeline may lead towards misleading results (Tang et al. 2009). Flow of water in leaked pipeline causing generation of acoustic emission (AE). Monitoring of this AE is used for identifying water leaks in small-diameter polyethylene (PE) pipeline (Martini et al. 2016). Water leaks were artificially induced at different distances from the transducer measuring location. Measurements of AE are carried out, in case of leakage the AE amplitude crosses predefined threshold. However, in underground pipeline reliable leak detection could not be achieved due to presence of soil causing attenuation of AE signals.

Small devices (Fletcher 2008) having ball like structure also known as smart balls is introduced in the pipeline system, mainly used for plastic pipes, which travel along the flow. It catches the noise coming from leak position. It is used in 1990 by Sahara system for small leakage detection (Pilcher et al. 2007). Pipe-pig mounting devices come under this class. Khulief et al. (2011) have developed leakage detection techniques, using swimming hydrophone, which travel inside the pipeline. Leak signal can be easily identified, when hydrophone passes from position of leak. The strength of leakage signal increases, with increase in pressure. Frequency band of acoustic signal depends upon the leak size. Hydrophones are physically inserted into pipeline, which may also affect the water quality. Pipeline should be made free from blockage before using these devices. Therefore usages of such devices in ageing pipeline are difficult, as they suffer from corrosion, blockage, etc.

3.2 Non Acoustic Techniques

Trace gas techniques are used for leakage detection in non-metallic pipes under low pressure (Haniffa and Hashim 2011). Non-reactive gasses such as helium are ejected along with water in pipeline. During the burst event, these gases come out of the pipeline causing pinpointing of location. Even though this system is quite accurate and has fast response, high cost of device acts as a barrier in its usage. Infrared thermography (Fan et al. 2005) uses thermal image for finding an area with less temperature with respect to the surrounding. This detected area can be probable leakage location. This proved to be useful for underground pipeline leakage detection. Ground penetrating Radars (GPR) (Farley 2008) detects any irregularity present in the pipeline such as breakage, this irregularities is reflected into the record of pipeline. Even, if there is any metal present between pipeline and GPR, then also the device will detect it as irregularities, thus it suffers from false detection (Pilcher et al. 2007). It is not useful for pipeline surveying having more than 2 m deep in ground. GPR is still into the development phase.

Non-acoustic sensors such as GPR and infrared thermography are still in development phase, and suffer from limited surveying range and false detection. Moreover there implementation results in real complex WDS still need to be verified. Whereas Trace gases are more efficient technique for leakage detection when compared to other non-acoustic techniques, but have high implementation cost.

3.3 Leakage Detection Using Transient Analysis

Transient analysis for leakage detection has become an important research area in past 20–25 years. Transient analysis is more immune to outer environmental noise. Some of the well-known transient techniques being used for leakage detection are as follows.

3.3.1 Inverse Transient Analysis (ITA)

ITA (Liggett and Chen 1994) of pressure signal has grabbed attention of researchers in the recent past for leakage detection in pipeline system. Since its arrival many modifications have been tried in terms of mathematical modeling. For experimental verification of ITA, Vítkovský et al. (2001) has implemented ITA in laboratory. Shuffled complex evolution (SCE) has been introduced for optimization. Proposed algorithm performs better than Levenberg–Marquardt (LM). Although it performs better for larger leakages, but may fails for smaller leakages. Kapelan et al. (2003) presented a hybrid genetic algorithm (HGA) transient model for leakage detection. LM and genetic algorithm (GA) are used for optimization process. Results shows HGA also performs better then LM method. Haghighi and Covas (2012) have introduced Backward ITA for leakage identification. Leak is assumed to be Gaussi distributed in pipeline. Leak function is optimized step by step and leak is added until objective function becomes nearly zero. Sequential quadratic programming (SQP) is applied for optimization of search space. This proposed system is applied on WDS of Dundee, UK. The system correctly identifies the burst of 7.7 l/s. Modeling error is one of the limiting factors involve during the field implementation of ITA. In real time complex system, unless hydraulic characteristics of system are known, ITA is difficult to apply, as system have multiple random fluctuations hence another conformation is required (probably acoustic techniques) after detection of burst using ITA (Covas and Ramos 2010). Vítkovský et al. (2001) highlighted that data errors (while measuring and calibrating), unsteady friction and model structure errors are the common errors presents during field implementation of ITA.

Earlier transient-analysis based leakage detection techniques have presented numerical case studies, laboratory experiments under controlled environment and limited field testing which is not able to achieve the level of validation required in complex systems under a wide range of conditions. Even in these simple networks, interpretation of measured data is not trivial. Therefore validation of transient analysis under real complex systems considering typical operating conditions can be seen as essential future work.

Damping of transient pressure signal is exponential during leakages; whereas under normal condition transient pressure signal doesn't show such property (Wang et al. 2002). Thus leakage can be detected using transient damping method (TDM). Damping may also occur due to other elements of WDS such as fire hydrate, joints in pipeline, which may be misclassified as burst event. Kim (2005) has analyzed impulse response analysis (IRA) of pressure signal for leak detection in pipeline network. GA is used along with impulse response for finding burst location in pipeline system. Measurement needs to be made for leakage and non-leakage pipeline keeping all other parameters same, this makes it difficult for field implementation. Further research in field of TDM and IRA is required before applying this technique to real complex network containing numerous loops, branches and demands which produces complex waveforms not amenable to straightforward scrutiny.

3.3.2 Frequency Domain Analysis

Frequency analysis of pressure transient signal changes at time of leakage, when compared to regular condition. This irregularity in frequency domain depends upon the size of leak and location. Fourier and Laplace are commonly used transforms for this purpose (Zecchin et al. 2006). Covas et al. (2005) has introduced standing wave difference method (SWDM) for leakage detection. Leakages in pipeline system create an equidistant resonance peak in the pressure signal with a secondary superimposed standing wave. Frequency analysis (using FFT) of this pressure amplitude at the excitation site allows identifying the leak frequencies and depending upon the resonance effect the probable leak location can be estimated. However the method shows only simulated results and hence proposed methodology requires validation with laboratory or field implementation.

Ferrante and Brunone (2003) has shown use of pressure transient analysis for pipeline leakage detection. Spectrum of pressure signal is analyzed at downstream end of single pipeline structure. Equation for transient pressure signal is solved in frequency domain. It is observed that spectrum depends upon system characteristics. Hence leakage can be identified by analyzing the spectrum of transient pressure signal. This experiment is limited to single pipeline structure; hence its testing under complex network can be seen as future work.

Burst in pipeline creates negative reflecting waves as shown in Fig. 2, causing discontinuity in observed signal. Wavelet can identify discontinuity easily, thus wavelet can be a perfect tool for identification and localization of burst event. Ferrante et al. (2007) has performed analysis of continuous and discrete wavelet transform on transient pressure for leakage detection. Wavelet can identify small variation in signal, even under presence of white noise, thus can also identify smaller leaks. It is observed that scaling of mother wavelet can identifies discontinuity more efficiently. Among different wavelet analyzed (db2, db8, db4, gaus1, gaus2), db1 performs best due to its step wise variation, which is same as that of pressure variation, this enhances the correlation between them. DWT performs better than CWT for signal reconstruction during de-noising process. Haar wavelet is not considered into account during comparison process which can be seen as one of the drawbacks. Wavelet transform is used for detecting discontinuities in a pressure

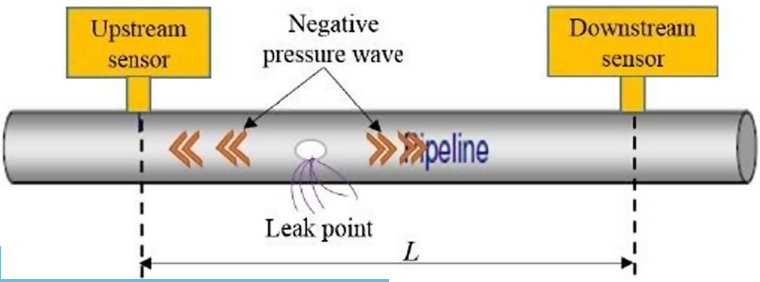

Fig. 2 Generation of negative pressure waves due to pipeline burst (Adedeji et al. 2017)

transient signal for leakage detection and therefore improper shape of injected transient signal makes detection of leak reflection difficult (Fig. 3).

Transient wave (Ramos et al. 2009) of high pressure followed by low pressure may cause ruptures in pipeline system. Shamloo and Haghighi (2009) suggested that, the effect of friction and water hammering can be reduced by increasing the closing time of valve. Skulovich et al. (2014) introduced Quasi-Newton and GA algorithm to minimize the transient developed from closing of valve. Valve closing curve parameter is optimized to reduce the effect of transient in system. Ferrante et al. (2014) has performed analysis on leakage detection under steady and unsteady condition, in university of Perugia. It is observed that in steady state analysis, the detectability of leakage increase with enhancement in system pressure, whereas in transient analysis constant high pressure tends to decrease the leakage detectability.

3.4 Prediction Modeling

Ye and Fenner (2010) have used Kalman filter for prediction of hydraulic parameters (flow and pressure) from past acquired data. Depending upon the difference between the predicted and measured field data, leakages get detected. This process is applied in WDS of north England. The proposed methodology is computationally less complex and requires less data when compared to other techniques such as Artificial Neural Networks (ANN). This technique is useful for detecting small leakages and small abrupt changes. Wu et al. (2009) presented model for leakage detection of WDS. Leakages are assumed to be pressure dependent. Leakages in WDS are detected by calibrating the difference between simulated and measured hydraulic parameters. Three objective functions have been used in this study for simulation purpose using GA. Proposed algorithm is applied on district water system in UK. Twenty-two leaky

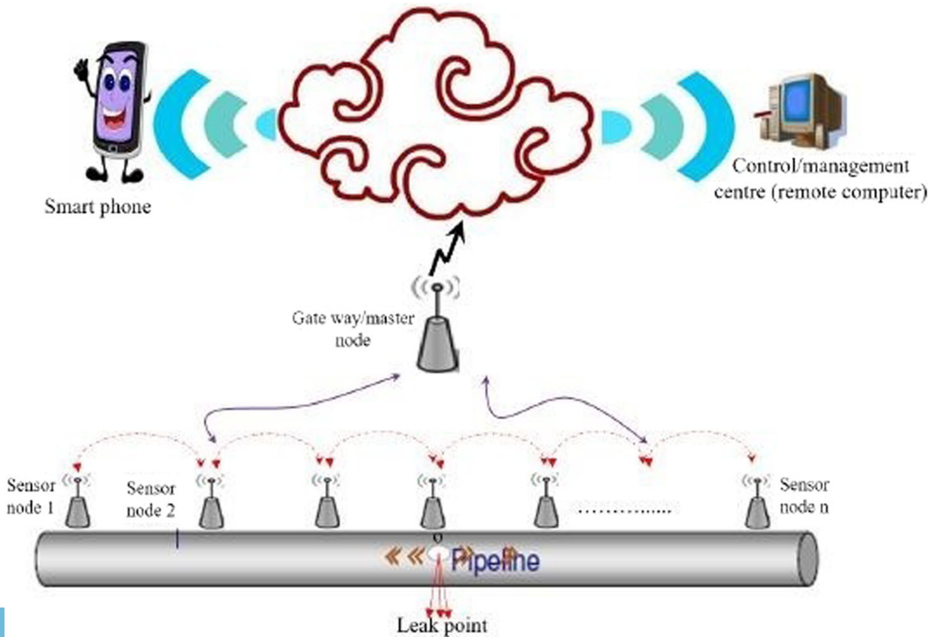

Fig. 3 Water sensor network for monitoring of pipeline leakages (Adedeji et al. 2016)

pipes have been detected in the given WDS. Inaccuracy in prediction modeling may lead towards misleading results thus efficient prediction modeling having high accuracy is desired. Other efficient algorithm such as pattern sequences based forecasting (PSF) (Bokde et al. 2017) and ARIMA. Other method for leak assessment can also be found in Farley (2008) and Mounce et al. (2007).

Efficient leakage detection can reduces water losses and increase the water available to end consumers earlier deprived form it thereby reducing water scarcity worldwide. More precise identification of the location of burst events also reduces the man power and cost required for reinstate pipelines. However the reliability, privacy and synchronization of sensor data are a challenging task, when it comes to field implementation.

4 Leakage Control Management

Leak assessment techniques also have its own drawback of data limitation, accuracy and it's a costlier affair too. Researchers now started to focus on controlling the leakages (Mutikanga et al. 2013). Active leak control, pressure management, online monitoring of DMA using supervisory control and data acquisition (SCADA), etc. comes under leakage control techniques (Girard and Stewart 2007). Most of the countries still prefer passive method which is simple but not effective. Active Leakage control still suffers from false alarm. Following are the leading techniques being used for leakage control.

4.1 Pressure Management

Asset and pressure management are the two important tools to reduce background leakages. Performing assets management is a costlier affair (Covelli et al. 2016). In actual scenario leakage is expressed as an emitter flow in terms of operating pressure. Change in leakage (L0 to L1) can be analyzed by $L1/L0 = (P1/P0)^{N1}$ (Lambert and Fantozzi 2010). N1 is pressure exponential varies from 0.5 to 2.3. Thus leakages can also be controlled by reducing excess pressures in water distribution systems. Pressure reduction also reduces the possibility of pipe burst or crack (Adedeji et al. 2018). Sensor technology performs online monitoring of hydraulic parameter which helps in identifying and reducing the excess pressure using isolated valves, pump scheduling and pressure reducing valve (PRV).This avoids bursting of pipeline and thus also reduces background losses.

4.1.1 Pump Scheduling and Demand Prediction

Walski et al. (2006) have proposed a computer model to demonstrate how pressure reduction affects leakage. It is observed that variable speed pump can play an important role in reducing pressure and flow. Conclusion is drawn that, reducing the pressure during the peak hour, might not be feasible solution for leakage control, as that may cause pressure deficiency in the water network. Nazif et al. (2010) have used GA for optimization of water storage level in tank for pressure reduction in WDS of Tehran, Iran. This pressure management strategy has reduced leakages from 11% to 5%.

An advanced pump scheduling system controlled by OPIR software has been installed in Poznan (Bakker et al. 2014). OPIR software learns from past readings, the pressure and flow demand is forecasted for next 48 h. Nine pressure measuring points were equipped with a local logger and GSM modem. The five identical variable speed pumps and nine Pressure reducing valves (PRVs) (NGE9001) have been installed at different locations to vary the water pressure in the system depending on the optimal predicted flow and pressure. Dynamic pressure control techniques causing 29% reduction of the pump pressure resulted in reduction of the background leakage by 20%, causing an annual energy reduction of 337,000 kWh, causing saving of € 21,500.

Colombo and Karney (2009) highlighted that reduction in demand will play a huge role for energy consumption reduction. Authors also concluded that pressure management for leakage detection will be more effective in newly constructed WDS having smoother pipeline. Spiliotis and Tsakiris (2012) has shown robustness of fuzzy linear programming for efficient calculation of demand pattern for controlling pressure in WDS.

4.1.2 Pressure Reducing Valve

Pressure management using valves has proved to be a promising technique for leakage reduction in recent past. Araujo et al. (2006) have suggested the use of pressure reducing valve (PRV) for reducing pressure in water infrastructure. It has been observed that there is high reduction in leakage (18%) is achieved after using 4–6 PRV in Benchmark WDS. Nicolini and Zovatto (2009) have used multiobjective GA (NSGA-II) for PRV localization and control. There is 19% reduction in leakage rate is observed after installation of five PRV in benchmark WDS proposed by Araujo et al. (2006). Nicolini et al. (2010) have used GA for localization and optimized control of PRV, to be installed in WDS of Buja, Italy. Installation of 4 number of PRV, leads to water saving and average pressure reduction of 115,650 cm/yr. and 18.7 m (15.76%), respectively. Gupta et al. (2017) have proposed modified reference pressure algorithm proposed by Nicolini and Zovatto (2009) for improvement of PRV localization. NSGA-II is utilized for optimum setting of PRV. The proposed algorithm leads to minimization leakage rate by 20.64% when compared to 17% by Nicolini and Zovatto (2009). Application of proposed method for larger WDS can be seen as future work.

Creaco and Pezzinga (2014) proposed a hybrid objective algorithm (GA and linear programing (LP)) for valve installations and pipe replacements for optimizing the WDS. GA is used for optimized placement of valves and LP is used to search for an optimal setting of the control valve. In addition, their study explored a trade-off between the number of PRV and leakage volume. The proposed algorithm is quiet efficient when compared to GA. De Paola et al. (2016) presented a harmony search (HS) model to determine the optimum control setting across the valves. More favorable results are observed with HS algorithm than the GA for pressure reduction in the WDS. Dai and Li (2014) have modified mixed-integrated nonlinear program (MINLP) for localization of PRV. The system is applied to larger scale network contain 2643 pipeline and 1890 nodes. High reduction in excessive pressure is observed after pressure management. Gupta et al. (2017) have proposed a hybrid tank storage water level and PRV optimization for pressure management in Anytown WDS. Three PRVs have been installed for reducing pressure in WDS. Optimized pressure values across PRVs are calculated using NSGA-II. The system shows leakage reduction of 26.08%. The proposed hybrid algorithm can be used only for WDS which uses water storage tanks for water distribution.

PRV optimization algorithm uses population based algorithm for efficient localization and control setting of valves. Larger size of search space while applying evolutionary population based algorithm such as NSGA-II may sometime get difficult in finding out the solution closer to global optimum solution (Gupta et al. 2018). Maier et al. (2014) has presented a study on current status, challenges and future work required on evolutionary algorithm (EA) for solving water management issues. Future EA required fundamental shift of focus towards improving problem formulations, computational efficiency and decision making in complex network. He concluded that, till 2025, there will be high success in solving high impact real world problem to see considerable industry engagement and uptake of EA. A novel water network sectorization methodology based on social network community detection algorithm is proposed for WDS sectorization of Managua city (Campbell et al. 2016). The sectorization leads to reduction in pipeline burst, background leakage reduction, etc. Monte Carlo simulation is used to calculate the benefits achieved due to decrease in burst requncy, etc. The proposed sectorization algorithm leades to a net benefit of 25,572 $/year. The authors also concluded that, there is a lack of mathematical formulations to compute the relation among sectorization and its mentioned benefits hence need to be developed in future.

Ramos et al. (2009) has explored performance variation of pressure management on different pipeline material, and it is observed that PVC pipes handle the transient better than cast iron pipes. Avoiding pressure deficiency at any node, especially during emergency condition such as fire flow, etc., can be seen as challenging task during optimization of WDS using PRV.

Despite having various benefits, pressure management is used rarely as a leakage control tool in developing countries. One of the reasons is the due to unviability of decision support tools for identify the benefits of pressure management to justify decisions of pressure management (Mutikanga et al. 2011). Early study should be performed before going for pressure management projects to understand the economic and social benefits of such project. Efficient network zoning algorithm, that works effectively in complex networks also need to be developed which will make applicability of PRV more efficiently for leakage control.

4.2 WDS Optimization

It is required to identify the pipeline which needed to be replaced for reducing background water losses and for improving water quality services. Battle for background leak assessment for water network (BBLAWN) completion is held in WDSA conference in Italy (2014), aiming to optimize WDS by reducing leakages and energy consumption (Giustolisi et al. 2015). 14 research teams have presented solutions for optimization of Town-c WDS having 5 DMA. Pump optimization along with PRV installation and pipe replacement is suggested by researchers, resulted in reduction of leakage and energy consumption by 28.5% and 12%, respectively. Roshani and Filion (2014) have attempted to optimize C-Town WDS (BBLAWN) through pipe replacement and installation of 19 PRV. NSGA-II is used for optimization of WDS along with EPANET solver for hydraulic simulations. It is observed that the leakage has been reduced down to 15 L/s when compared to 60 L/s earlier. Eck et al. (2014) proposes optimization techniques to suggest the pipeline need to be replaced in WDS for controlling leakages, in near future. The proposed algorithm is applied to B-Town test bench (BBLAWN). Author has suggested replacing 42 pipelines, along with installation of 22 PRV for optimized leakage reduction.

Shafiee et al. (2015) presented an algorithm to minimize the cost of new infrastructure and repairing operations like pipeline replacement. NSGA-II is used to select the tank size, pump and PRV placement. This algorithm is having higher computational complexity and can consume up to 1500 min. 10,800 EPANET simulations are also required during optimization process which makes it difficult to implement in real systems. Lin et al. (2015)

has utilized cluster identification method (CIM) for detection of defective pipeline in water network. Overlapping lower case proportion (OLCP) is the CIM used for proposed algorithm. This is generally used to identify the diseases in human beings. CIM evaluates the difference between the measure and predicted data to detect the existing failure in pipeline of WDS. Initially OLCP calculates the probability of pipeline failure utilizing minimum number of resources such as age, material and size of pipeline installed. The records obtained from proposed algorithm are compared with actual records to determine the significance of algorithm in WDS of Taiwan. The failure pipeline observed in actual WDS is within the pipeline cluster determined by proposed algorithm. Unreliable data may lead towards false prediction, which can make WDS inefficient for providing efficient services. WDS optimization techniques are still in an early development phase. From the theoretical results the algorithm seems to be worked perfectly for the planned DMA of WDS. Developing countries have peculiar technical characteristics such as unreliable and incomplete data, poorly zoned networks and irregular water supply. Applicability of such WDS optimization algorithm in such WDS still remained questioned and can be seen as future work for the researchers.

5 Smart Water System

Wireless sensor technology has advanced to the point that can provide real-time online monitoring of water infrastructure. Data acquired from these sensors, when combines with efficient data processing techniques enables automatic detection and localization of irregularities such as burst event.

Tool for Integrated Leak Detection (TILDE), a research project funded by the European Commission is applied in Cyprus and Norway for leakage control (Pretner et al. 2008). The TILDE data management system allows the integrated management of all data coming from flow and pressure sensor and based on the analysis of gathered data, the system identifies the pipeline location, where the repairing is required due to leakage. The Leakage Check-Up is performed by IWA's water balance allows the user to calculate the components of Non-Revenue Water and leakage performance indicators. The system also maintains specific record for each leakage. This is useful to identify the pipes with the highest number of leaks (number of leaks/km) and their leakage frequency (no. leaks/km/year). Smart meters are installed in New York City by Bolton Point Water System (Raleigh 2013). The flow meter reading is continuously monitored on Sensus smart water technology. It is observed that one home went from using no water to running 100 gal per hour for 3 days in the absence of house owner. Thus internal pipe burst or leakage is identified easily with the help of smart meter network.

Mounce et al. 2007 describe a supervisory control and data acquisition (SCADA) system which has been installed in the water distribution system for North Yorkshire in the UK. This system analyses the data collected from smart meters. An alarm system has been also developed for identification of abnormal flow in pipeline. It has been found that 40% of the alarms correspond to burst events. Data reliability and false alarming are current challenges during the implementation of this method. Stoianov et al. (2007) and Mounce et al. (2015) have also shown the usage of wireless pressure, smart meter and flow sensors network for leakage detection by monitoring abrupt changes. Table 1 discusses regarding available burst detection and localization techniques along with real world case studies and their drawbacks.

Table 1 Smart water techniques for burst event detection in WDS

References	Techniques	Utilized place	Result	Remarks
Lee et al. (2015)	Cumulative sum (CUMSUM) and Haar wavelet analysis is performed on pressure transient signal for online burst event detection in WDS. 2.577 km is the total pipeline area covered under the test.	Boston, USA	System can identify multiple burst events having leakage rate of 3–8.33 l/s. Proposed algorithm shows false alarming of 0%	The proposed algorithm has average localization error of 22 m.There is vast improvement in localization error is observed as compared to Zan et al. (2014).
Zan et al. (2014, 2011)	JTFA algorithm is applied on observed pressure transient for detection of burst event in WDS. A novel methodology for localization of burst event on the basis of magnitude or intensity of spectrogram of frequency range lies between 18 and 22 Hz is proposed. The proposed algorithm has shown nine successful detection of bust in WDS, which are manually created during testing phase.	Singapore	The system can correctly identify the burst of 3–7 l/s.	The effectiveness of proposed algorithm during actual bust event is not mentioned in the literature. These systems are inefficient for smaller leaks and have burst localization error of 50 m.
Covas and Ramos (2010)	ITA is utilized for leak localization using eight pressure sensors (range from 0 to 10 bar) in two polyethylene pipeline in test bed at Imperial college and then applied at Thames water utilities of London.	London	The proposed algorithm is successfully able to detect leak having flow rate of 0.35–2.7 l/s	Success of leakage detection depends on noise observed. As pipeline gets divided in smaller section the localization accuracy of burst gets increases (±24 m) but leak size error also gets increase. No tests were carried out for underground pipeline system.

5.1 Recent Laboratory Experiments

Worldwide many researchers in the institutes with the help of laboratory experimental setup are trying to develop more efficient leakage detection techniques using smart sensor network. A smart WDS is proposed for real-time leakage detection using pressure sensors are placed in pipeline of WDS (Adedeji et al. 2016). Real time pressure data is transmitted at monitoring center. Bursting of pipeline causing generation of transient signal reflected back into sensor. In order to detect leakages, a pattern matching algorithm is utilized to differentiate the pattern of the slope curve of a normal leak and that regular transient operation regularly occurring at the pipeline. The experiment is performed for single pipeline, hence its verification under complex WDS is required. A wireless sensor network is designed for detection and localization of multiple leakages in 80 m pipeline network using multilable learning methods (Kayaalp et al. 2017). Three pressure sensors are installed and data is collected in real time. Multi-label classification methods such as RAkELd, BRkNN, and BR are applied on observed data, leak is labeled as 1 whereas non-leak is labeled as 0. Depending upon data labeling, SVM performs the classification of leakages. RAkELd method performs best having detection rate of 98%. A non-invasive leak detection algorithm is proposed for detection of smaller leakages in pipeline by observing the changes in the correlation between surface acceleration of pipeline. (Yazdekhasti et al. 2017). Test is performed on a 76 mm diameter polyvinyl chloride pipeline test system considering varying leak. Acceleration data is collected using five accelerometer sensors placed in pipeline. When compared with no leak condition presence of a leakage in pipeline changes the Cross-correlation function of the acceleration. The system is able to detect leaks as small as 3/8th inches (or 9.525 mm) in diameter. Further validation of above discussed experiments on complex real pipeline network is required to determine the true extent of the merits and limitations of the proposed techniques.

5.2 Smart Water System, Singapore

In Singapore (Allen et al. 2012; Allen et al. 2011) smart water grid network is installed, which aims to monitor water flow, pressure along with water quality check and detection of burst event. Pressure, water flow, pH and ORP sensor has been installed. WaterWise uses decision support tools module (DSTM) for pump optimization and demand prediction through online monitoring. Wavelet has been used for detection of burst events by monitoring the pressure heads at different nodes (Srirangarajan et al. 2013). The system shows successful detection of burst event having variable leak size of 7 l/s to 3 l/s. Classifying burst event from other hydraulic operations is still challenging and can be taken as future work. The system is also not able to reduce apparent losses thus smart metering can be seen as one of the solutions to deal with reduction of apparent losses.

5.3 Smart Water Metering, Australia

smart meter (Beal and Stewart 2013) is installed in Australia to improve the quality of water services. The smart meter reading is collected at central location. It is required to know the peak demand for building required future water network. Analysis of peak hour and peak day is examined for 18 months. Peak day demand have peak factor between 1 and 1.5. It is observed that peak factors were lower, than the values assumed for residential water supply. South-east- Queensland residency end user study (SEQREUS) is performed in winter 2010 (Beal et al. 2011), with aim to analyze demand pattern and end use event. This has increased awareness among people regarding water consumption. As a result many users have started using water efficient washing machine, resulted in reduction of water consumption. It is also observed that lower income homes have higher per capita water consumption. Beal and Flynn (2015) has summarized the survey performed in 2013 and 2014 regarding smart meter and intelligent water network. During this survey, it is observed that a variety of smart meter and communication network is installed in WDS of Australia, to know about water consumption pattern along with its uses and operational expenditure. This have increases the revenue of smart meter industry. Reduction in water losses is observed in WDS after smart meter installation. There is also increase in customer satisfaction. It is observed that there is lack of knowledge and expertise in designing and implementation of smart water network. It can conclude that smart meter helps in provides additional information of post meter leakage detection and reduces apparent losses by reducing data handling errors.

Failures of smart meter create uncertainties related in WDS, which will eventually reduce water quality services and also increases apparent losses. Hence replacement of these devices at appropriate timing is desired. Algorithm needs to be developed for finding out the efficient replacement time of smart meters. Arregui et al. (2011) have proposed an algorithm which suggests optimum time for the replacement of smart meters. Application this technique under more complex network is required for its validation.

Review on smart technology and their role for efficient detection of leakages is also discussed in Beal and Flynn (2014) and Hope et al. (2011). Smart meter (Nina 2012) faces problems of data privacy, interference with medical and electronic devices, power consumption, job losses and high cost.

6 Conclusion

Water leakage management started in early 1900. Initially ground sticks were used for leakage detection, which is replaced by acoustic and non-acoustic devices. Leakage detection using transient analysis have been applied successfully in many real world WDS, for efficient leakage detection. Leakage control using PRV installation, WDS optimization and pump scheduling have shown efficient results and have become an active research area for reducing background leakages since last decay. With the involvement of ICT, water management can now be seen as interdisciplinary field. Smart water system performs analysis on collected data from sensors for detection and localization of pipeline leakages, pressure management for reduction of background leakages. This has reduced water losses and has increased quality of service in WDS. Leakage management techniques reduce water losses and energy consumption in WDS. This water, which gets lost earlier, can be utilized to serve it to the people deprived form it. This will save millions of people, worldwide, from water scarcity. Rather than increasing water supply better management of water resources decrease stress levels during challenges such as droughts, increased population (Treuer et al. 2017) and transboundary water challenges (Petersen-Perlman et al. 2017). It is finding out by group of scholars that efficient management of transboundary water resource can bring the peace among the communities especially after post wars (Krampe 2017). Thus water management institutions, needs to develop management plans that can properly accomplish the installation of sufficient governing mechanisms. Based upon the literature covered by authors, following are the present challenges that need to be resolved in near future by the researchers.

- Water balance assumptions made for calculating apparent losses aren't true for various water distribution systems of developing countries. The lack of an objective methodology for estimating unauthorized consumption is a major limitation. Data reliability in flow measurements is an issue that need to be solved and still it an active area of research. Universal smart metering can improve the data reliability during leak assessment of WDS. Similarly, the BABE model needs validation in more international, representative especially from the committees of developing countries. For this, further study is required to make BARE model adaptable in developing WDS of countries
- Unauthorized water use is another major contributor in NRW losses, which requires sociocultural approaches along with engineering solutions. Unauthorized use in water user

in WDS can be detected on basis of pressure measurements and algorithms for inverse calculations (Liggett and Chen 1994). In a recent laboratory test is was found that the location of illegal branches representing unauthorized connections can be detected by means of fast transient tests (Meniconi et al. 2011). But their actual field implementation still remains though. More techniques should be developed for reduction and assessment of apparent losses (such as finding illegal users) present in real complex WDS. ILI (Harrison et al. 2013) is still an active research area, having capability to further improve the assessment techniques for water losses.

- The current leakage detection techniques applying signal processing to abrupt changes in pressure within a pipeline for leakage detection are ineffective in detecting background leakage in a WDN (Adedeji et al. 2017). It is concluded that despite the numerous research efforts and advancement in leakage detection technologies, a large scope is still open for further research such as effective detection of background type leakages.
- Pinpointing of exact location is still difficult. Present system is having localization error of 30-50 m, thus there is scope of improvement in the localization techniques. This will avoid further usage of acoustic sensors for pinpointing of exact location. More devices for detection of commercial losses are also need to be developed. Only few researchers have utilized their proposed algorithm for leakage detection in underground pipeline system. Therefore in near future every researcher must apply their proposed algorithm for underground pipeline system.
- Online monitoring and leakage detection equipment and technologies, real-time control is still not yet fully developed and optimized for dynamic water loss reduction. Future work is required for reducing spurious alerts. There is also need of algorithm to detect slow progressive leaks and bursts. Further research is required in finding out optimal placement of multiparameter sensors (flow, pressure, water quality) for efficient leakage management (Mutikanga et al. 2013).
- Real-time simulations using integrated, physically-based hydrological models where data are collected from hydrological sensors in real time are going to become more common in practical leakage management applications such as future burst event, effect of pressure management on water network, etc. (Kurtz et al. 2017). Thus researchers should focus more towards development of real time hydrological models simulators.
- Energy management of sensor nodes, secure communication between sensor nodes in an underground application, network failure, are some of the research challenges. Transmitting the reading of these sensors from an underground sensor node to a remote control/admin centre in a reliable way is still an open research problem. Energy harvesting can be seen as a future scope, so that sensors do not take any energy from outside resources. Lot of work can be done into the MAC layer of networking architecture to improve the data security and its reliability.
- Massive data is collected while using sensor technology. Lot of methodology regarding Knowledge Discovery in Databases (KDD) is present and used worldwide (Karwot et al. 2016). There is need of intelligent system which can detect and can locate the network failure. Support systems for the mentioned purposes are still rare or less noticeable.
- A number of water loss management techniques present in the literature but there actual field implementation is very less. Thus close collaboration between the research institutes and the water service provider is required to close this gap of field implementation of proposed techniques.

- Involvements of private companies increase the development and repairing operation of water infrastructure at faster rates (Fritsch 2017). Constructing smart water infrastructure typically requires a significant investment over many years which can discourage the involvement of private industry. As an example, Water Infrastructure Finance and Innovation Act program managed by the United States Environmental Protection Agency provides loans to private firms at a lower rate of interest and for a longer loan period to facilitate improvements in existing water infrastructure and in new water infrastructure (Copeland 2016).

Decision on implementation of high cost devices for leakage detection also depends upon the economy and the leakage percentage. Before investing in water leakage management, it is important to carefully calculate the effect and benefit of the techniques. Economic level of leakage (ELL) is defined as the leakage rate below which leaks are considered as uneconomical to repair. ELL analysis can be done before opting for leakage management technique (Puust et al. 2010). Leakage level should be well above the ELL. For lower leakage rate (4–5%), implementing costly devices may not a feasible solution (due to unavoidable background losses).

This review provides the work carried out by various researchers related to leakage management, associated problems and their solutions, in the last three decades. Researchers who wanted to work in this area, gets a platform to decide future research and also the challenges that they will have to face.

Compliance with Ethical Standards

Conflict of Interest There is no conflict of interest.

References

Adedeji K, Hamam Y, Abe B, Abu-Mahfouz AM (2016) Wireless sensor network-based improved NPW leakage detection algorithm for real-time application in pipelines

Adedeji KB, Hamam Y, Abe BT, Abu-Mahfouz AM (2017) Towards achieving a reliable leakage detection and localization algorithm for application in water piping networks: an overview. IEEE Access 5:20272–20285

Adedeji KB, Hamam Y, Abe BT, Abu-Mahfouz AM (2018) Pressure management strategies for water loss reduction in large-scale water piping networks: a review. In: Gourbesville P, Cunge J, Caignaert G (eds) Advances in Hydroinformatics. Springer Water, Singapore

Allen M, Preis A, Iqbal M, Srirangarajan S, Lim HB, Girod L, Whittle AJ (2011) Real-time in-network distribution system monitoring to improve operational efficiency. J Am Water Works Assoc 103(7):63–75

Allen M, Preis A, Iqbal M, Whittle AJ (2012) Case study: a smart water grid in Singapore. Water Pract Technol 7(4)

Araujo LS, Ramos H, Coelho ST (2006) Pressure control for leakage minimisation in water distribution systems management. Water Resour Manag 20(1):133–149

Arregui FJ, Cobacho R, Cabrera E Jr, Espert V (2011) Graphical method to calculate the optimum replacement period for water meters. J Water Resour Plan Manag 137(1):143–146

AWWA (2009) Water audits and loss control programs. M-36 Publications, 3rd Edition. Available from: http://www.awwa.org/store/productdetail.aspx?productid=6725. Accessed 9 Oct 16

Bakker M, Rajewicz T, Kien H, Vreeburg JHG, Rietveld LC (2014) Advanced control of a water supply system: a case study. Water Pract Technol 9(2):264–276

Beal C, Flynn J (2014) The 2014 review of smart metering and intelligent water networks in Australia and New Zealand. Report prepared for WSAA by the Smart Water Research Centre, Griffith University

Beal CD, Flynn J (2015) Toward the digital water age: survey and case studies of australian water utility smart-metering programs. Util Policy 32:29–37
Beal CD, Stewart RA (2013) Identifying residential water end uses underpinning peak day and peak hour demand. J Water Resour Plan Manag 140(7):04014008
Beal C, Stewart R, Huang T, Rey E (2011) SEQ residential end use study. J Aust Water Assoc 38(1):80–84
Bokde N, Asencio-Cortés G, Martínez-Álvarez F, Kulat K (2017) PSF: introduction to R package for pattern sequence based forecasting algorithm. R J
Campbell E, Izquierdo J, Montalvo I, Pérez-García R (2016) A novel water supply network sectorization methodology based on a complete economic analysis, including uncertainties. Water 8(5):179
Colombo AF, Karney BW (2005) Impacts of leaks on energy consumption in pumped systems with storage. J Water Resour Plan Manag 131(2):146–155
Colombo AF, Karney BW (2009) Leaks and water use representation in water distribution system models: finding a working equivalence. J Hydraul Eng 135(3):234–239
Colombo AF, Lee P, Karney BW (2009) A selective literature review of transient-based leak detection methods. J Hydro Environ Res 2(4):212–227
Copeland C (2016) Water infrastructure financing: the water infrastructure finance and innovation act (WIFIA) program, United States environmental protect agency (USEPA), USA
Covas D, Ramos H (2010) Case studies of leak detection and location in water pipe systems by inverse transient analysis. J Water Resour Plan Manag 136(2):248–257
Covas D, Ramos H, Almeida AB (2005) Standing wave difference method for leak detection in pipeline systems. J Hydraul Eng ASCE 131(120)
Covelli C, Cimorelli L, Cozzolino L, Della Morte R, Pianese D (2016) Reduction in water losses in water distribution systems using PRVs. Water Sci Technol Water Supply 16(4):1033–1045
Creaco E, Pezzinga G (2014) Multiobjective optimization of pipe replacements and control valve installations for leakage attenuation in water distribution networks. J Water Resour Plan Manag 141(3):04014059
Dai PD, Li P (2014) Optimal localization of pressure reducing valves in water distribution systems by a reformulation approach. Water Resour Manag 28(10):3057–3074
De Marchis M, Fontanazza CM, Freni G, Notaro V, Puleo V (2013) Experimental evidence of leaks in elastic pipes. Water Resour Manag 30(6):2005–2019
De Paola F, Galdiero E, Giugni M (2016) A jazz-based approach for optimal setting of pressure reducing valves in water distribution networks. Eng Optim 48(5):727–739
Doug C, Scott E (2015) Sierra Nevada Snowpack Is Virtually Gone; Water Content Now Is Only 5 Percent of Historic Average, Lowest Since 1950, California Department of Water Resources. Available from: http://www.water.ca.gov/news/newsreleases/2015/040115snowsurvey.pdf. Accessed 29 Oct 15
Eck BJ, Arandia E, Naoum-Sawaya J, Wirth F (2014) A simulation-optimization approach for reducing background leakage in water systems. Procedia Eng 89:59–68
Endo A, Tsurita I, Burnett K, Orencio PM (2017) A review of the current state of research on the water, energy, and food nexus. J Hydrol 11:20–30
Fan C, Sun F, Yang L (2005) Investigation on nondestructive evaluation of pipelines using infrared thermography. In: Infrared and Millimeter Waves and 13th International Conference on Terahertz Electronics, 2005. IRMMW-THz 2005. The Joint 30th International Conference on (Vol. 2, pp. 339–340). IEEE
Farah E, Shahrour I (2017) Leakage detection using smart water system: combination of water balance and automated minimum night flow. Water Resour Manag 31(15):4821–4833
Farley M (2008) Finding 'difficult' leaks. International Water Association Specialist Group – Efficient Operation and Management. Available from: http://www.iwaom.org. Accessed 9 Oct 17
Farley M, Trow S (2007) Losses in water distribution networks; a practitioner's guide to assessment, monitoring, and control, 2nd edn. International Water Association Publishing, UK
Ferrante M, Brunone B (2003) Pipe system diagnosis and leak detection by unsteady-state tests. 1. Harmonic analysis. Adv Water Resour 26(1):95–105
Ferrante M, Brunone B, Meniconi S (2007) Wavelets for the analysis of transient pressure signals for leak detection. J Hydraul Eng 133(11):1274–1282
Ferrante M, Brunone B, Meniconi S, Karney BW, Massari C (2014) Leak Size, Detectability and Test Conditions in Pressurized Pipe Systems: How Leak Size and System Conditions Affect the Effectiveness of Leak Detection Techniques. Water Resources Management 28(13):4583–4598
Fletcher R (2008) SmartBallTM–a new approach in pipeline leak detection. In: Proceedings of the International Pipeline Conference. Calgary, Alberta, Canada
Fritsch O (2017) Integrated and adaptive water resources management: exploring public participation in the UK. Reg Environ Chang 17(7):1933–1944
Girard M, Stewart RA (2007) Implementation of pressure and leakage management strategies on the gold coast, Australia: case study. J Water Resour Plan Manag 133(3):210–217

Giustolisi O, Berardi L, Laucelli D, Savic D, Kapelan Z (2015) Operational and tactical management of water and energy resources in pressurized systems: competition at WDSA 2014. J Water Resour Plan Manag 142(5):C4015002

Gomes R, Sousa J, Sá Marques A (2013) The influence of pressure/leakage relationships from existing leaks in the benefits yielded by pressure management. In: 8th international conference of European Water Resources Association

Goodwin SJ (1980) The results of the experimental programme on leakage and leakage control. Water Research Centre. Technical Report 154

Gupta A, Bokde N, Marathe D, Kulat K (2016) Leakage Reduction in Water Distribution Systems with Efficient Placement and Control of Pressure Reducing Valves Using Soft Computing Techniques. Eng Technol Appl Sci Res 7(2):1528–1534

Gupta A, Bokde N, Marathe D, Kulat KD (2017) Optimization techniques for leakage management in urban water distribution networks. Water Sci Technol Water Supply 17(6):1638–1652

Gupta AD, Bokde N, Kulat KD (2018) Hybrid leakage management for water network using PSF algorithm and soft computing techniques. Water Resour Manag 32(3):1133–1151

Haghighi H, Covas C (2012) Modified inverse transient analysis for leak detection of pressurized pipes. BHR group pressure surges

Haniffa MAM, Hashim FM (2011) Recent developments in in-line inspection tools (ILI) for deepwater pipeline applications. In: National Postgraduate Conference (NPC), 2011 (p 1–6). IEEE Available here: http://sensus.com/web/usca/solutions/smart-water-network. Accessed 15 Oct 16

Harrison B, Gregory W (2013) Managing water utility financial risks through third-party index insurance contracts. Water Resour Res 49(8):4939–4951

Hmiltom S (2011) Water balance-next step. Water Utility Journal, E.W. publications, p 3–11

Hope R, Foster T, Money A, Rouse M, Money N, Thomas M (2011). Smart water systems. Project report to UK DFID, April 2011, Oxford University, Oxford, UK

Kapelan ZS, Savic DA, Walters GA (2003) A hybrid inverse transient model for leakage detection and roughness calibration in pipe networks. J Hydraul Res 41(5):481–492

Karwot J, Kaźmierczak J, Wyczółkowski R, Paszkowski W, Przystałka P (2016) Smart water in smart city: a case study. In: Proceedings of SGEM 16th International Scientific Conference on EARTH&GEOSCIENCES, book (Vol. 3, p 851–858)

Kayaalp F, Zengin A, Kara R, Zavrak S (2017) Leakage detection and localization on water transportation pipelines: a multi-label classification approach. Neural Comput & Applic 28(10):2905–2914

Khadam MA, Shammas NK, Al Y (1991) Water Losses from Municipal Utilities and their impacts. Water International 16(4):254–261

Khulief YA, Khalifa A, Mansour RB, Habib MA (2011) Acoustic detection of leaks in water pipelines using measurements inside pipe. J Pipeline Syst Eng Pract 3(2):47–54

Kim SH (2005) Extensive development of leak detection algorithm by impulse response method. J Hydraul Eng 131:201–208

Kouchi DH, Esmaili K, Faridhosseini A, Sanaeinejad SH, Khalili D, Abbaspour KC (2017) Sensitivity of calibrated parameters and water resource estimates on different objective functions and optimization algorithms. Water 9(6):384

Krampe F (2017) Water for peace? Post-conflict water resource management in Kosovo. Coop Confl 52(2):147–165

Kurtz W, Lapin A, Schilling OS, Tang Q, Schiller E, Braun T, Franssen HJH (2017) Integrating hydrological modelling, data assimilation and cloud computing for real-time management of water resources. Environ Model Softw 93:418–435

Lambert A (1994) Accounting for losses: the bursts and background concept. J IWEM 8, April

Lambert A (2001) What do we know about pressure-leakage relationships in distribution systems. IWA Conf in Systems approach to leakage control and water distribution system management

Lambert AO (2003) Assessing non-revenue water and its components - a practical approach. Water 21 - Magazine of the International Water Association, Vol. August 2003, p 50–51

Lambert AO, Fantozzi M (2010) Recent developments in pressure management. Proc., 6th IWA Water Loss reduction Specialist Conf.,IWA, Hague, The Netherlands

Lambert A, Hirner W 2000 Losses from water supply systems: Standard terminology and recommended performance measures. Available from: www.iwahq.org

Lambert A, Charalambous B, Fantozzi M, Kovac J, Rizzo A, St John SG (2014) 14 years' experience of using IWA best practice water balance and water loss performance indicators in Europe. Proceedings of IWA Specialized Conference: Water Loss 2014, Austria, Vienna, 30 March – 2 April, 2014

Lee SJ, Lee G, Suh JC, Lee JM (2015) Online burst detection and location of water distribution systems and its practical applications. J Water Resour Plan Manag 142(1):04015033

Liemberger R., Farley M (2004) Developing a non-revenue water reduction strategy, part 1: investigating and assessing water losses. In: Paper to IWA Congress

Liemberger R, McKenzie R (2003) Aqualibre: a new innovative water balance software, presented at the IWA/AWWA conference on efficient management of urban water supply, Tenerife

Liggett JA, Chen LC (1994) Inverse transient analysis in pipe networks. ASCE Journal of Hydraulic Engineering 120(8):934–955

Lin HY, Lin BW, Li PH, Kao JJ (2015) The application of the cluster identification method for the detection of leakages in water distribution systems. Int J Environ Sci Technol 12(9):2687–2696

Liou JCP, Hall RJ, McMahon MC (2003) Hazardous liquid leak detection techniques and processes. General Physics Corporation. Report No. DTRS56–02-D-70037-01

Maier HR, Kapelan Z, Kasprzyk J, Kollat J, Matott LS, Cunha MC, Dandy GC, Gibbs MS, Keedwell E, Marchi A (2014) Evolutionary algorithms and other metaheuristics in water resources: current status, research challenges and future directions. Environ Model Softw 62:271–299

Martini A, Troncossi M, Rivola A (2016) Leak detection in water-filled small-diameter polyethylene pipes by means of acoustic emission measurements. Appl Sci 7(1):2

Meniconi S, Brunone B, Ferrante M, Massari C (2011) Transient tests for locating and sizing illegal branches in pipe systems. J Hydroinf 13(3):334–345

Michael D (2007) Report on Infrastructure Leakage Index (ILI) as a Regulatory and ProviderTool

Mounce SR, Boxall JB, Machell J (2007) An artificial neural network/fuzzy logic system for DMA flow meter data analysis providing burst identification and size estimation. Water management challenges in global change, p 313–320

Mounce SR, Pedraza C, Jackson T, Linford P, Boxall JB (2015) Cloud based machine learning approaches for leakage assessment and management in smart water networks. Procedia Eng 119:43–52

Mutikanga HE, Sharma SK, Vairavamoorthy K (2011) Investigating water meter performance in developing countries: a case study of Kampala, Uganda. Water SA 37(4):567–574

Mutikanga HE, Sharma SK, Vairavamoorthy K (2013) Methods and tools for managing losses in water distribution systems. J Water Resour Plan Manag 139(2):166–174

Nazif S, Karamouz M, Tabesh M, Moridi A (2010) Pressure management model for urban water distribution networks. Water Resour Manag 24(3):437–458

Nicolini M, Zovatto L (2009) Optimal location and control of pressure reducing valves in water networks. J Water Resour Plan Manag 135(3):178–187

Nicolini M, Giacomello C, Deb K (2010) Calibration and Optimal Leakage Management for a Real Water Distribution Network. J Water Resour Plan Manag 137(1):4 134–142

Nina B (2012) Analysis: Smart Meter and Smart Grid Problem, Legislative Proposal December 2012, Sebastopol, California, USA. http://www.santepublique-editions.fr/objects/smart-meter-problems-dec-2012-final-voir-p28.pdf. Accessed 17 Oct 16

Ozevin D, Harding J (2012) Novel leak localization in pressurized pipeline networks using acoustic emission and geometric connectivity. Int J Press Vessel Pip 92:63–69

Petersen-Perlman JD, Veilleux JC, Wolf AT (2017) International water conflict and cooperation: challenges and opportunities. Water Int 42(2):105–120

Pilcher R, Hamilton S, Chapman H, Field D, Ristovski B, Stapely S (2007) Leak location and repairs, guideline notes by IWA, version 1. International Water Association, London

Pires A, Morato J, Peixoto H, Botero V, Zuluaga L, Figueroa A (2017) Sustainability assessment of indicators for integrated water resources management. Sci Total Environ 578:139–147

Plath M, Mathias E, Knut W (2014) Energy efficiency and energy saving in the German water industry. Water Pract Technol 9(2):256–263

Pretner A, Belltin A, Saniz L (2008) Application of monitoring and information technologies to optimize asset management. Water Asset Manage Int 4(4):14–19

Puust R, Kapelan Z, Savic DA, Koppel T (2010) A review of methods for leakage management in pipe networks. Urban Water J 7(1):25–45

Raleigh NC (2013) Water 20/20: bringing smart water networks into focus. Sensus. http://sensus.com/documents/10157/1577608/Sensus_Water2020-USweb.pdf/d67d0a75-255a-4a20-86f1-d4548bfcdf78. Accessed 24 April 2016

Ramos H, Tamminen S, Covas D (2009) Water supply system performance for different pipe materials part II: sensitivity analysis to pressure variation. Water Resour Manag 23(2):367–393

Roshani E, Filion Y (2014) WDS leakage management through pressure control and pipes rehabilitation using an optimization approach. Procedia Eng 89:21–28

Savić D, Ferrari G (2014) Design and performance of district metering areas in water distribution systems. Procedia Eng 89:1136–1143

Shafiee ME, Berglund A, Berglund EZ, Brill ED Jr, Mahinthakumar G (2015) Parallel evolutionary algorithm for designing water distribution networks to minimize background leakage. J Water Resour Plan Manag 142(5): C4015007

Shamloo H, Haghighi A (2009) Leak detection in pipelines by inverse backward transient analysis. J Hydraul Res 47(3):311–318

Skulovich O, Perelman L, Ostfeld A (2014) Modeling and optimizing hydraulic transients in water distribution systems. Procedia Eng 70:1558–1565

Spiliotis M, Tsakiris G (2012) Water distribution network analysis under fuzzy demands. Civ Eng Environ Syst 29(2):107–122

Srirangarajan S, Allen M, Preis A, Iqbal M, Lim HB, Whittle AJ (2013) Wavelet-based burst event detection and localization in water distribution systems. J Signal Process Syst 72(1):1–16

Stoianov I, Nachman L, Madden S, Tokmouline T, Csail M (2007) PIPENET: a wireless sensor network for pipeline monitoring. In: Information Processing in Sensor Networks, 2007. IPSN 2007. 6th International Symposium on, p 264–273. IEEE

Tabesh M, Yekta AA, Burrows R (2009) An integrated model to evaluate losses in water distribution systems. Water Resour Manag 23(3):477–492

Taha AW, Sharma S, Kennedy M (2016) Methods of assessment of water losses in water supply systems: a review. Water Resour Manag 30(14):4985–5001

Tang X, Liu Y, Zheng L, Ma C, Wang H (2009) Leak detection of water pipeline using wavelet transform method. In environmental science and information application technology, 2009. ESIAT 2009. International conference on (Vol. 2, p 217–220). IEEE

Thornton J, Lambert A (2005) Progress in practical prediction of pressure: leakage, pressure: burst frequency and pressure: consumption relationships. In: Proceedings of IWA Special Conference'Leakage, p 12–14

Treuer G, Koebele E, Deslatte A, Ernst K, Garcia M, Manago K (2017) A narrative method for analyzing transitions in urban water management: the case of the Miami-Dade water and sewer department. Water Resour Res 53(1):891–908

Tucciarelli T, Criminisi A, Termini D (1999) Leak analysis in pipeline systems by means of optimal valve regulation. J Hydraul Eng 125(3):277–285

United States Environmental Protection Agency (EPA) (2013) Water audits and water loss control for public water systems. Office of Water (4606 M), EPA 816-F-13-002

Van Zyl JE, Cassa AM (2013) Modeling elastically deforming leaks in water distribution pipes. J Hydraul Eng 140(2):182–189

Vítkovský JP, Simpson AR, Lambert MF, Wang XJ (2001) An experimental verification of the inverse transient technique. In: 6th Conference on Hydraulics in Civil Engineering, p 28–30

Walski T, Bezts W, Posluszny ET, Weir M, Whitman BE (2006) Modeling leakage reduction through pressure control. J Am Water Works Assoc 98:147–155

Wang XJ, Lambert MF, Simpson AR, Liggett JA, Vıtkovský JP (2002) Leak detection in pipelines using the damping of fluid transients. J Hydraul Eng 128(7):697–711

Wu ZY, Sage P, Turtle D (2009) Pressure-dependent leak detection model and its application to a district water system. J Water Resour Plan Manag 136(1):116–128

Yazdekhasti S, Piratla KR, Atamturktur S, Khan AA (2017) Novel vibration-based technique for detecting water pipeline leakage. Struct Infrastruct Eng 13(6):731–742

Ye G, Fenner RA (2010) Kalman filtering of hydraulic measurements for burst detection in water distribution systems. J Pipeline Syst Eng Pract 2(1):14–22

Zan TTT, Wong KJ, Lim HB, Whittle AJ (2011) A frequency domain burst detection technique for water distribution systems. In: Sensors, 2011 I.E. (p 1870–1873) IEEE

Zan TTT, Lim HB, Wong KJ, Whittle AJ, Lee BS (2014) Event detection and localization in urban water distribution network. IEEE Sensors J 14(12):4134–4142

Zecchin AC, Lambert MF, Simpson AR, White LB (2006) Laplace-domain comparison of linear modelsof a reservoir-pipe-valve system with a leak. In: Proceedings of the 8th annual water distribution systems analysis symposium. Cincinnati, OH, USA