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A CRITICAL REVIEW OF LEAKAGE DETECTION STRATEGIES INCLUDING PRESSURE AND WATER QUALITY SENSOR PLACEMENT IN WATER DISTRIBUTION SYSTEMS – SOLE AND INTEGRATED APPROACHES FOR LEAKAGE AND CONTAMINATION INTRUSION

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Abstract

Water leakages in water distribution networks not only affects on natural water resources but also cause problems to nearby infrastructure or environment and makes water distribution networks more prone to contamination. Complexity in water distribution systems makes leakage detection and its monitoring a difficult task. Leakages in water distribution systems are caused due to damages in pipes, lack of maintenance of pressure due to uncertain demand and various operating conditions. Therefore, to manage the pressure in the water distribution systems it is necessary to identify appropriate leak location. Various studies on pressure management focused on optimal sensor placement for leak localization considering various constraints cost of sensors, demand uncertainty, damages and burst in pipes and few focused on valve location and optimization for control of pressure. The main aim of the paper is mainly to provide a comprehensive review of various studies related to leak detection, location and monitoring strategies. Also, it mainly focuses on pressure and water quality sensor placement in water distribution systems with sole and integrated approaches for leakage minimization and contamination intrusion in water distribution systems. A critical review of available methodologies for leakage detection, location, monitoring including existing simulation tools, solution approaches, and available methodologies for pressure sensor placement, technical challenges, and future research direction is presented. Till now no reviews are presented for pressure and water quality sensor placement in water distribution systems along with burst detection.

Keywords
Pressure sensor, Review, Water Distribution System, Water Quality Sensor, and Water Security.

1 INTRODUCTION

The primary aim of water distribution system is to supply adequate and safe water, efficiently and effectively at an affordable cost to all the consumers. However, due to growing challenges such as expanding populations and urbanization, climate and demographic change, infrastructure deficits and aging, inadequate maintenance of water systems, water scarcity, adverse health effects and rehabilitation costs etc. which effects on water quantity and quality in water supply systems. Further, available water sources throughout the world are becoming depleted due to industrialization and this problem is increased with rate of population are increasing specially in developing countries like India. Current issues and challenges of urban water supply systems are highlighted in Table 1. A water distribution network (WDN) is an important and major component of urban water supply systems. Water loss due to leak in pipelines is one of the major challenges in efficient

Table 1. Issues and Challenges of urban water supply including water distribution systems in developing countries like India

Issues or Challenges	Descriptions
Water Quantity	- Inconsistent and intermittent supply - High NRW/UFW - Low coverage of metering - Irrational Tariff - Low billing and collection efficiency - Demand supply gap - Water stress
Water Quality	- Lack of safe drinking water - Pollution and Contamination of drinking water - Accidental and intentional contamination - Lack of proper water treatment and distribution facilities
Technology and Management Issues	- Redundancy and Robustness in the system - Lack of technical innovations - System operation Intelligence - Adoption of innovative design and equipment - Inadequate operation, maintenance, management and monitoring of water distribution systems - Operational optimization of water distribution systems through optimal pump and valve operation – Energy efficiency in the network (Miller et al. 2013, Wakeel et. al. 2016) - Prolonger service of infrastructure like wells, pipes, tanks, pump and fitting
Structural, Institutional, Governance and Social Issues	- Data availability, reliability and transparency in the systems - Lack of existence of water policies, regulations and strategies - Shortage of skilled man power - Disconnected Agencies / lack of Coordination - Inadequate funding - Lack of monitoring - Low capacity of operational & maintenance - Lack of water conservation measures, policies and by-laws - Water efficiency devices /fixtures - Social Awareness and lack of sustainable practises

water distribution networks. Looking to the major issue of water resources availability, scarcity of water resources, high Non-Revenue Water (NRW) which is the difference between system input volume and billed authorized consumptions, may be as high as 40 to 45% in some of the cities of developing countries, of which water loss is one of its most significant parts [1, 2]. Therefore it is utmost important to manage the available resources in an efficient way as well as to minimize the leakage losses in the water distribution systems. Leakages in WDNs are due to increase in pressure and lack of operation and maintenance. Reducing leakages providing benefits in many ways as reduced operation costs and increased revenues in view of expanded existing water supply as compared to new facility of supply, better water resources efficiency, reduces pipe rehabilitation cost, minimizing infrastructure damage, preventing damage to surrounding environment and preventing adverse affect on the human health [3, 4] and ultimately helps in reducing overall operation, maintenance, management and monitoring cost.

Water losses, as part of NRW, are classified into real and apparent losses. Apparent losses are to be reported in between 1% and 9% of the total water supplied in different countries around the world. Real losses are further expressed as Infrastructure leakage index (ILI) which is the ratio between current annual real losses (CARL) and unavoidable annual real losses (UARL) [1].

The amount of leakage depends upon several factors as pipe material and age, pipe depth, pipe corrosion, pressure surges, improper handling and storage during construction, poor workmanship, operating pressure etc. In general three leakage indicators are noted as an increase of head loss and decrease of peak factor and reservoir volume [5].

Recently numbers of reviews have been provided by various studies: Puust et al. [6] provided a comprehensive of leakage management methods consisting of leakage assessment, leakage detection and leakage control methods which has been further extended by considering both real and apparent losses [7]. Other reviews assessment of water losses (Gupta and Kulat [8], Al-washali [9]), leakage detection (Li et al. [10], Datta and Sarkar[11]), condition assessment of water pipes [12]. Other focuses on transient-based methods (Colombo et al. [13]), various pipeline fault detection methods (Datta & Sarkar[11]), pressure-based methods (Abdulshaheed et al. [14]), externally and internally-based methods (Adedeji et al. [15]), data-driven methods (Wu & Liu [16]), and current and proposed intelligent methods (Chan et al. [17]), Critical Review of Steady-state leak detection and localization methods (Zaman et al. [18]), Model-based and data-driven approaches (Hu et al. [19]).

The main aim of the paper is mainly to provide a comprehensive review of various studies related to leak detection, location and monitoring strategies. It also focuses on pressure and water quality sensor placement in water distribution systems with sole and integrated approaches for leakage minimization and contamination intrusion in water distribution systems. A critical review of available methodologies for leakage detection, location, monitoring including existing simulation tools, solution approaches, and available methodologies for pressure sensor placement, technical challenges, and future research direction is presented. Till now no reviews are presented for pressure and water quality sensor placement in water distribution systems along with burst detection.

This classified is done based on Mutikanga et al. [7]. 1) Leakage assessment i.e quantifying the amount of water lost, 2) Methodology based on leakage detection and location by survey/observation or by performing signal analysis i.e. detection of leakage hotspots and leakage control methods and 3) Methodology based on leakage detection and location using modelling, calibration and optimization, and 4) Leakage monitoring and controlling methods which includes those methods which measures flows into discrete zones or DMAs, and to continuously and regularly monitor and control the flow into the DMAs, and manage the pressure in the DMAs and Night flow analysis 5) Online monitoring, leak locations and detections using pressure sensors and burst identifications. It covers methods based on water audit, District Metered Areas (DMAs), Minimum Night Flow (MNF) analysis, leakage hydraulic analysis, flow statistical analysis, acoustics, transients, pressure management, network asset management, optimization techniques, online monitoring and detection. Literature is further updated till 2022. It also covers pressure and water quality sensor placement in water distribution systems sole and integrated approaches for leakage and contamination intrusion and burst detection. This review is in progress.

2 OVERVIEW OF LEAK DETECTION METHODS

2.1 Methodology based on leakage assessment

A number of studies have been conducted previously for water audit for analysing water loss components i.e real losses in distribution systems [20]. However, this method does not focus on the apparent losses which are mainly due to meter inaccuracies, data handling errors and unauthorised consumptions. Various other techniques which are used for estimation of leakage are minimum night flow analysis (MNF analysis) and Burst and Background Estimates (BABE) [21]. BABE is a component-based approach for estimating annual losses [22]. It was observed that majority of losses are reported due to pipe-joint failure, relatively older age pipes, poor repairing and maintenance of water taps, pipe joints and shower taps, negligence of the consumer and unreliable water supply [21].

MNF analysis requires zoning and intensive field work and trained manpower. BABE is applicable only in case of regular active leakage control (ALC). The details of these methods are presented in [23]. Apart from these water and waste water balance method is also suggested by [24]. Considering the uncertainty in water distribution systems such as water demand and fluctuations, it was observed that the average of the two methods would be preferred for estimating water loss components in intermittent water supply systems. MNF methods are more suitable for the DMA scale rather than system-wide scale. Assessing the WL components by using at least two methods should improve the prioritisation, economic modelling, monitoring.

2.2 Methodology based on leakage detection and location by survey/observation/field studies or experimental studies by performing signal analysis

A leakage detection and location method includes finding location of leaks using acoustic equipments like listening devices, leak noise loggers, infrared thermography, smart-balls etc. in static and dynamic environment or using survey work or by observing pressure and flow data or by analyzing leakage-pressure relationship. Static leak detection provides early detection with minimal human interference and a dynamic leak detection system provides localization and pinpointing. Various leak detection technologies and their advantages and disadvantages are highlighted by [25]. Also, video cameras, microphones, acoustic sensors, are also helpful in finding the leaks in large-diameter pipes [26 -28]. Al-Ghamdi [29] has performed the field survey to identify the relationship between leakage rate and pressure in the selected areas of city of Makkhan, Saudi Arabia. The value of leakage exponent is identified based on network age and pipe materials.

2.3 Methodology based on leakage detection and location by theoretical/numerical method using modelling, calibration and optimization

It includes the methods based on leakage-pressure relationship to analyse the impact of pressure on leakage, modelling and optimization techniques, calibration of leakage model coefficients, infrastructure asset management, pressure management etc. considering benchmark problems and real life networks.

2.3.1 Leakage-Pressure Relationship to analyse the impact of pressure on leakage

Almandoz et al. [30] used a modelling approach for evaluation of water losses based on the physical losses in mains and service connections and the volume of water consumed but not measured by meters.

Numerous studies have worked on leakage-pressure relationship. Van Zyl [31] focused on four factors which influence leakage-pressure relationship: Leak hydraulics, pipe material behaviour and soil hydraulics and water demand. Maskit and Maskit and Ostfeld [32] proposed the methodology for calibrating leakage model coefficients for the group of pipes based on pipe age and material. The problem is solved using genetic algorithm (GA). Zyl [33] observed 4 factors for high sensitivity of leakage to pressure as pipe material behaviour, leak hydraulics, soil hydraulics and water demand along with the way of individual leak combines in a pressure management zone. Kiziloz [34] development of leakage rate prediction model using artificial neural networks (ANN) where network pressure and age is considered as a reference. Nourhan Samir et al. [35] modelled leakage as a function of pipe length, calibrating leakage coefficient to develop pressure fluctuation using PRVs. Method is applied to DMA wise.

2.3.2 Methodology based on pressure and asset management

Previous literatures have classified the leakages into three categories in WDSs as reported, unreported and background leakages. Reported leakages are emerging and visible leakages. Unreported leakages are non-surface leakages that are detectable by acoustic devices and background leakages are considered as non-surface leakages which are unreported and acoustically undetectable. Pressure control and Asset management is an effective way for minimizing leaks in WDSs, particularly helps in reducing background leakages. Several studies used for pressure management are fixed and variable area discharges [36-37]. Pressure in WDN can be controlled using varying types of control system such as fixed outlet pressure control, time-modulated pressure control Awad et al. [38] and flow modulated pressure control. Leakages could further be optimized using number of valves and their locations. Araujo et al. [39] optimised the number of valves and its location as well as valves opening adjustments for simulation in an extended period to minimise pressures and consequently leakage levels. Adedejia et al. [37] provided a critical review on pressure management strategies.

2.4 Methodology based on leakage monitoring and controlling

Leakage monitoring and controlling methods includes those methods which measures flows into discrete zones or DMAs and to continuously or regularly monitor and control the flow into the DMAs and manage the pressure using PRV at the inlet of the DMAs or by managing and analyzing the night flow and based on the excess flow determine leakages in the system. These methods are useful for prioritizing high risk zones and not identifying the location of leak.

In view of reducing NRW and reduced operation costs and increasing infrastructure life and reducing pipe bursts, water utility managers often choose to reduce excessive operating pressure or to perform service pressure regulations in WDNs. For managing the pressure in WDSs, optimization of control valves with suitable locations and settings is implemented [40-43].

Several researchers focused on Leakage reduction through Pressure Management using optimal locations of PRV [44-45].

Considering the complexity and uncertainty of water distribution systems makes it difficult for operation, maintenance and monitoring of the systems. Thus, based on the concept of graph theory a partition of WDNs is performed based on structural and connectivity analysis of the network. This partition of the network is known as cluster for topological or connectivity analysis suggested by [46]. This clustering of water distribution facilitates for various purposes as sensor placement, detection of contamination source intrusion and calibration of the model and leakage detection or pressure management studies etc. Further, clustering is one of the ways for DMA formation. Perelman et al. [47] minimizes objective function the number of open boundary valve in the pipe. In addition, pressure management is aided by installing pressure reducing valves (PRVs) at the inlet of each DMAs. The control of pressures in each DMA leads to a reduction in leakage through pipe joints and connections.

Recently several researchers work on the concept of DMAs, consisting of dividing the WDNs into small area for reducing management complexity of WDSs and provide ease in monitoring. Various studies and technical reports reported the guidelines on formation of DMAs [48-50]. Partitioning is carried out using graph theory [51-52] and DMA is established based on several factors as maximum and minimum number of consumer connections (i.e DMA size recommended for a district), the main transmission system should be kept separated from the DMAs in order to ensure a flexible and reliable water supply; the connectedness of each district to the water supply source and be independent, i.e without any connection with other DMAs; and other factors to take into account are pressure constraints at demand nodes, final leakage level target, implementation and maintenance costs [52]. Studies showed that DMAs are the cost-effective technology in case of water loss control and leakage management However, DMAs design required careful formation, in case of failure may reduce reliability, redundancy and water quality of the network. In DMAs, quantity of water leaving and entering the districts is metered. Further in case of large scale water quality contamination in WDSs, DMAs would limit the spread of contamination and minimize the extent of response actions required for the system [53]. Ulanicki et al. [54] installed PRVs at the inlet of DMAs which further helps in reduction of leakage reduction.

In past, a number of methods for formation of DMAs have been previously suggested Manual trial and error approaches (55) to automated tools integrating network analysis (56), graph theory consisting of clustering [57-58, 46]), complex networks (59-60), and heuristic methods [60-62]. The general procedure for DMA design is to identify water mains, partition the network into sub-networks, and isolate interconnecting lines using simulation-based heuristics to minimize the number of connections and dependencies between the sub-networks [46-47].

Haider, H. [63] developed a framework for intermittent water supply in order to conserve limited water resources in arid region of Saudi Arabia. Water losses are evaluated using active leakage control, passive leakage control, infrastructure asset management. Night flow analysis is performed to observe the relationship between pressure and water loss for pressure reduction.

Jadhao and Gupta [64] reduced excess pressure of DMAs during night flow. This work is further extended by Sharma et. al. [65] who considered segment identification using existing valves to identify DMAs in water network and boundary optimization is done using GA. Resilience Index is used as a performance evaluation criterion for optimal DMA configuration. Applications are shown on part of a real life network of Nagpur City.

However, few studies is carried out on topography-based partitioning method to develop DMAs in WDN. Liu et. al. [66] Compared three methods of partitioning fast greedy, random walk and Merits. Two cases are considered for complex WDN, weighted and non-weighted edges where weights are represented by demands and observed that greedy method is more effective in weighted graph. Recently, Abdulshaheed et al. [67] provided a critical review on pressure based method for monitoring leak both in steady and unsteady conditions. Gupta and Kulat [8] provided a selective review on leak management techniques in WDSs.

2.5 Methodology based on online monitoring, leak locations and detections using pressure sensors and water quality sensors and burst identifications

For better monitoring of pressure and early detection of contamination in WDSs, optimal pressure sensors and water quality sensors are placed in the systems simultaneously so as to provide effective, efficient and safe WDSs in terms of water quality and quality. Pressure sensors are helpful in order to capture abnormal pressure drop so as to locate the leak and burst in WDSs timely. Concerns about the cost of the sensors, both pressure and water quality sensors should be located at some crucial locations in the WDSs. If sufficient number of pressure sensors are placed at crucial locations in WDSs and are evenly installed, continuous pressure trend change would be helpful in location burst. A number of researchers have optimised water quality sensors in WDSs for early detection of contamination (Ostfeld and Salomons [68], Ostfeld et. al. [69], Dorini et al. [70], Weickgenannt et al. [71]. Rathi et al. [72]. Details of the study are given in Table 2. Some studies have considered uncertainty in placement of pressure sensors for leak detection [82-83].

Table 2. Online monitoring, leak locations and detections using pressure sensors and water quality sensors

Reference	Focus on	Remark	Classification
Blesa, J. (2015) [73]	Robustness in the sensor placement methodology is incorporated where only inner pressure sensors in the DMAs are considered	Robust Sensor Placement Methodology	Leak locations using Pressure Sensors
Steffelbauer et al. (2016) [74]	Sensor placement for leak localization considering demand uncertainty which leads to uncertain pressures at measurement points	Uncertainty in demand and measurement locations	Leak locations using Pressure Sensors
Cheng, Li et al. (2017) [75]	Optimal placement of pressure sensors in WDSs based on pressure sensitive matrix	• Sensor placement is optimized based on clustering analysis of pressure sensitive matrix • K-mean algorithm is used to solve optimization problems • Cluster formation to reduce the size and Complexity of the network	Leak locations using Pressure Sensors
Cao et al. (2019) [76]	Simultaneous sensor placement and pressure reduction of WDS	Both pressure sensors and PRVs optimization	Leak locations using Pressure Sensors and pressure reduction using PRV localization
Soroush, F. (2019) [77]	Optimization of no. and location of pressure sensors in WDSs using geospatial tool coupled with GA	Geo-statistical tool is used for pressure monitoring network	Geo-statistical tool coupled with an optimization algorithm
Shao et al. (2019) [78]	Leakage detection based on time series monitoring data using pressure sensor	Correlation coefficient based on time series data is considered for leak detection	Leak detection using pressure sensors
Cheng, W. et al.	Optimizing pressure sensor placement to monitor pipes	Objective is to maximize the	Monitoring of water leakage

(2021) [79]	in which burst event takes place	monitoring network capability to detect leakages with pre-minimum no. of sensors	and quantification of pipe burst
Santos-Ruiz, I. et al. (2022) [80]	Optimal sensor placement for locating leaks in WDNs using information theory.	Multiple leak scenarios are generated and datasets of pressure changed are performed. Heuristic method is applied for ranking of nodes for sensor placement.	Leak locations using Pressure Sensors
Taylor et al. (2018) [81]	Equivalent orifice area to quantify pipe quality	Leakage and intrusion in intermittent water supply	Leakage and contaminant intrusion

3 SOME OBSERVATIONS AND ISSUES NEED CONSENSUS FOR FUTURE RESEARCH

- Original or Reduced Network: A real life network may involve thousands of pipe and nodes, and numbers of sensors are restricted. Considering the possibility of each and every node of original network as possible location of pressure and water quality sensors may increase computational burden, which can be significantly reduced by suitably eliminating some of the nodes from list of candidate nodes such that sensor placement accuracy is not affected. Any skeletonization method can be used.
- Dynamic water quality simulation and pressure driven approach is lacking. A cluster analysis is performed for easy applications of large and complex network problems. However, which method of cluster analysis used is a question.
- Type of leakage assessment methods: As large number of leakage assessment methods have developed in past however, quantifying the leakage assessment using any one method is inaccurate in case of uncertainties. However, the average of the two methods would be preferred for estimating water loss components in intermittent water supply systems.
- Even though hydraulic model is a valuable tool for leakage hydraulic analysis, however, few studies have used calibrated hydraulic model for DMA selection. A calibrated hydraulic model helps in the selection of the DMAs. Further, after performing DMAs, few studies have recalibrated DMA EPANET model with real data. If recalibrated model could be used it will be minimize the errors between the real and simulated network. It would be helpful for pressure management or helps in identifying crucial locations of pressure and water quality sensors in WDN.
- Installation of smart pressure gauges and automated pressure control valves: Smart pressure gauges installed at average zone points for continuous monitoring of operating pressure in pipe networks. Providing water at high pressure during night period increased water losses. Using automated pressure control valves can reduce the night pressure to some extents. It is recommended to reduce excessive operating pressure to more practical values.
- Past study showed that majority of the percentage of leakages are found to be at property connections or either in service lines or at the junction of the service lines and the property connections. Leakage Identification and repair of service connections and

storage tank in the households can reduce the leakages to some extents. Further, house connections made up of galvanized iron (GI) needs to be replaced with polyvinyl chloride (PVC) or polyethylene (PE) pipes.

- Type of solution methodology: Practical application of leakage detection and identification of appropriate location for large-scale water distribution networks is still a major challenge. Even though large no. of methodologies is developed however, few comparative works exist on leakage detection method to choose the best algorithm for generic case study.
- Even though large no. of solution methodologies are developed and applied for optimal valve location for pressure management in WDSs. However, few comparisons exist and best method in any general case study is lacking.
- As of now large number of partitioning method is suggested. However, the best method for general case is needed. Topography-based partitioning graph theory method would be more useful for establishing DMAs.
- Lacking of work in the area of leakage and contaminant intrusion simultaneously. Lack of relationship between contaminant volume intruded and system pressure, supply duration in intermittent as well as continuous supply since supply duration is important in case of flushing water quality.

4 SUMMARY AND CONCLUSIONS

The issue of water losses and reduction in efficiency of water distribution systems and security concern of water system has motivated several researchers to develop a methodology for optimal placement of both pressure and water quality sensors in WDNs for online monitoring and management of pressure and leakages which would be helpful in resolving the issues of water quantity and quality in WDSs and their adverse impacts. A critical review of available methodologies for leak detection strategies is presented in this paper with a view to raise issues requiring consensus amongst researchers. Several methods for leak localization, detection, monitoring and controlled is suggested in past. Many studies have focused on pressure and asset management. For identifying accurate leak detection, calibrated model is to be considered. Numerous studies have suggested for formation of DMA designs. However, topography-based partitioning methods for establishing DMAs are lacking. Current research work is moving towards better monitoring of pressure and early detection of contamination in WDSs. Therefore, optimal pressure sensors and water quality sensors are placed in the systems simultaneously so as to provide effective, efficient and safe WDSs in terms of water quantity and quality. Pressure sensors are helpful in order to capture abnormal pressure drop so as to locate the leak and burst in WDSs timely. Concerns about the cost of the sensors, both pressure and water quality sensors should be located at some crucial locations in the WDSs. If sufficient number of pressure sensors are placed at crucial locations in WDSs and are evenly installed, continuous pressure trend change would be helpful in location burst. The research work pertaining to these issues are highlighted for developing consensus amongst researchers for future research work on detection problems. This review is further in progress for better classification of methodologies.

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