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Systematic Review on Research Trends on Sensor-Based Leak Detection Methods in Water Distribution Systems

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ABSTRACT

A substantial amount of treated water is lost every year due to leakages in water distribution systems. Leakages can be identified and reduced using leakage detection methods, which can be broadly split into computer-based and sensor-based methods. This systematic review focuses on trends in sensor-based leakage detection methods published between 2000 and 2019, following the methodology proposed by PRISMA 2009 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). We conducted a database search using Scopus, obtaining a total of 78 relevant article papers. We categorized the articles based on the primary leakage detection methods discussed, yielding 33 article papers on acoustic methods, 31 article papers on non-acoustic methods, and the remaining article papers on wireless sensor networks (WSN). The highest number of article papers were published in the "Journal of Sound and Vibration". Between 2000 and 2007 we observed that acoustic leak detection methods were the most widely researched methods within the published literature. After 2008, non-acoustic leak detection methods became more prominent, subsequently followed by an increase in research focusing on WSNs. During the transition period between acoustic methods and WSNs, non-acoustic leak detection methods started to emerge, showing promising results in detecting leakages. Research interest in WSNs substantially increased in 2016. The application of WSN methods for leakage detection shows a promising advancement in sensor-based leakage detection methods and opportunities for improvement in the future.

Keywords: acoustic method, non-acoustic method, wireless sensor network, leakage detection, sensor-based, systematic review, water distribution system

INTRODUCTION

Water scarcity is one of the most pressing global issues (Vörösmarty et al. 2000; Oki and Kanae 2006; Kummu et al. 2016). This issue is crucial given the limited availability of raw water resources and increasing domestic, commercial and industrial demands due to population and economic growth. In general, the main causes of water scarcity are insufficient and poor water resources and inadequate infrastructure management. The use of suitable technology can help resolve issues related to water scarcity and contribute to achieving sustainable water resources.

Recent research estimates that leakages cause the loss of approximately 32 billion m^3 of clean water from water distribution networks (WDN) globally each year (Kingdom et al. 2006). Leakages may occur due to several factors, for example, poor installation of pipes at joints and fittings, presence of large and sharp objects (e.g., stones), changes in temperature and uncertainties in water network pressure levels (al Qahtani et al. 2020). Furthermore, leakages can vary in magnitude from small background leakages, which are often not visible and do not get reported, to major pipe bursts, which are typically easily identified and generally receive urgent attention. Regardless of the magnitude of a leakage, they can negatively impact the WDN, water company and consumers. Small background leaks that are not reported will increase the non-revenue water (NRW) of the WDN until they are repaired. Conversely, pipe bursts are usually repaired quickly, but the quantity of water loss can substantially impact the value of NRW. Additionally, repair works due to pipe bursts often lead to unscheduled water disruptions that can cause an inconvenience to the consumers.

The early detection of leakages is likely to benefit water companies, facilitating the repair of faulty pipes prior to the formation of substantial leakages (i.e., pipe bursts). WDNs typically use a variety of different pipe materials and diameters, including transmission mains, distribution pipes, and connection pipes. Over the past few decades, a number of researchers have proposed leakage detection methods for different WDN conditions. Leakage detection methods can be broadly categorized into hardware-based and software-based methods (Li et al. 2015). For clarity, we define hardware-based leak detection methods as sensor-based leak detection methods.

Within this paper we provide a systematic review of recent research on sensor-based leak detection methods published between 2000 and 2019. Our review focuses on three aspects of sensor-based leak detection methods. First, the trend of academic journals that have published article papers related to sensor-based leak detection methods. Second, the research trends over the past two-decades, and lastly, the recent trend in the relationship between leakage detection methods and pipe diameter. The purpose of this review is to emphasize and analyse the research trends of water leakage reduction strategies, providing a holistic view to help determine future research directions and knowledge gaps in leakage reduction studies.

METHODOLOGY

DATABASE SEARCH

To conduct the database search for this systematic review we followed the methodology proposed by *Preferred Reporting Items for Systematic Reviews and Meta-Analyses*, herein referred to as PRISMA 2009 (Moher et al. 2009). PRISMA 2009 consists of 4 phases, namely identification of documents (article papers), document screening, document eligibility, and the final documents included within the results. A more detailed description of the methodology is provided below and summarized in Figure 1.

For the first phase of PRISMA 2009, i.e., identification of documents, we used Scopus as our database source. Scopus was chosen because the documents listed in the database have gone through a thorough review process, and the database is well-established. The database search in Scopus was performed using keywords, where the choice of keywords was crucial to obtaining the desired results. We used two main keywords to search for leakage detection methods for the WDN: "leakage detection" and "water distribution network". We extended our keyword search for "leakage detection" to incorporate words that have a similar meaning, including "leak detection" and "burst detection". We also extended our keyword search for "water distribution system" to include "WDS" and "WDN". We searched for these keywords under the Title-Abstract-Keywords search category in Scopus.

For the second phase of document screening, we limited the search to article papers written in English with a publication date between 2000 and 2019. For the third phase, the eligibility of the documents, each of the article papers that had been short listed from phase 2 were manually reviewed based on their abstract and keywords. For the final phase of the process we selected article papers which included the type of leakage detection method and information on pipe diameter.

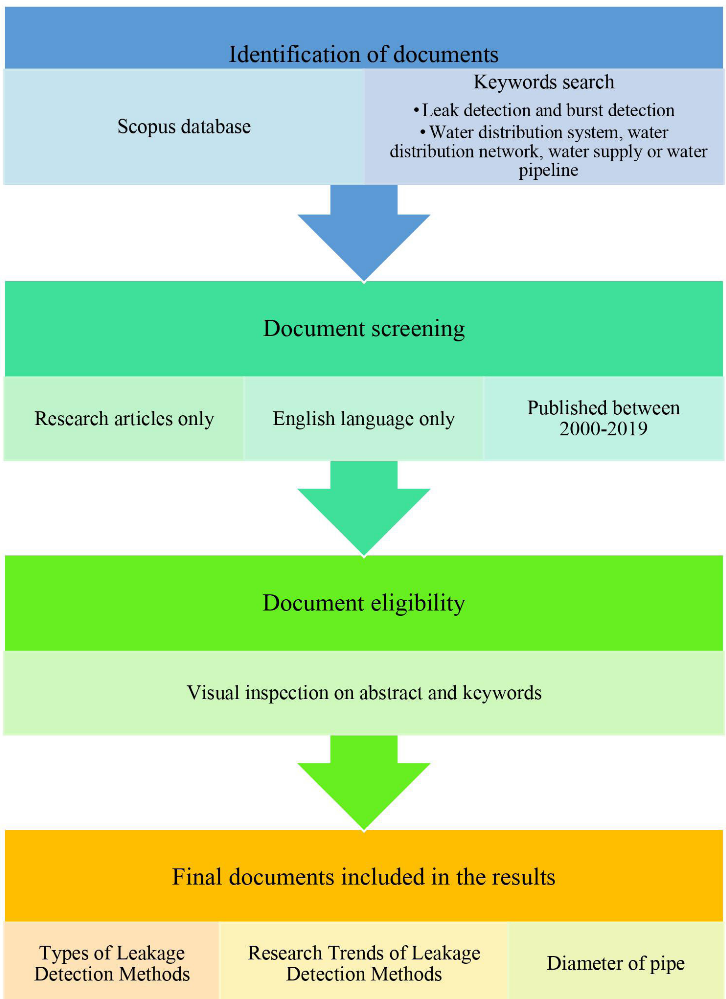

FIGURE 1. Flow chart of the methodology for the database search used to identify the relevant literature, following the PRISMA 2009 methodology

Souce: Moher et al. (2009)

RESULTS AND DISCUSSION

Within this systematic review we focused on the leakage detection methods used by researchers over the past two decades. The results of the database screening and types of leakage detection methods are presented in the following subsections. The results of this systematic review on leakage detection methods presented here include: (1) the list of academic journals that published papers related to sensor-based leak detection methods, (2) research trends in terms of the types of leakage detection methods for the past two-decades and (3) the leakage detection methods used in relation to pipe diameter.

DATABASE SCREENING RESULTS

Although our database search focused on sensor-based methods, we extended our search to include all leakage detection methods, i.e., both sensor-based and non-sensor based methods. During the identification phase, Scopus identified 340 related article papers based on the keywords used (see methods). All the article papers where screened manually based on the Title-Abstract-Keywords search category, resulting in 252 article papers related to leakage detection methods in WDNs. We observed that the majority of the screened article papers included discussions on computation-based leak detection algorithms, involving the use of complex modelling, advanced algorithms and machine learning to detect leakages in WDNs. To remove article papers that focused primarily on computer-based leak detection methods, we conducted an additional screening protocol that omitted these papers. After this additional filtering process 78 article papers were retained. Lastly, none of the 78 article papers were rejected during the eligibility process, yielding a total of 78 article papers for this review.

TYPES OF LEAKAGE DETECTION METHODS

Based on the 78 article papers obtained in the database search, we categorized the sensor-based leak detection methods into three classifications: acoustics, non-acoustics, and wireless sensor network (WSN) methods. Out of the 78 article papers, 33 were related to acoustic methods, 31 to non-acoustic methods and the remaining article papers were related to WSNs. Examples of acoustic based leak detection methods identified within the literature reviewed include leak noise correlators, acoustic emissions and hydrophone sensors (Yazdekhasti et al. 2018). Examples of non-acoustic leak detection methods include ground penetrating radar (GPR) (Lai et al. 2016), infrared thermography (Bach and Kodikara, 2017), remote sensing (Agapiou et al. 2016) and fibre optic pressure sensors (Gong et al. 2018). Lastly, article papers that discussed WSNs primarily focused on sensors or nodes that record and analyse water leakage data and transfer the output to a central computer to detect leaks in WDNs. The source of energy for nodes used in WSN systems can be from energy harvesting devices or batteries (Almazyad et al. 2014).

RESEARCH TRENDS OF LEAKAGE DETECTION METHODS

A total of 45 academic journals have published research that focus on sensor-based leakage detection in WDNs, yielding 78 article papers (see methods). Here, we limit our discussion to academic journals that have only published at least 3 related article papers between 2000 and 2019, summarized in Table 1. The academic journals were sorted by the number of article papers published and the journal impact factor (JIF) was based on the Web of Science (WoS) index. The journal with the highest JIF was the "Journal of Sound and Vibration", with a JIF score of 3.429, publishing 11 relevant article papers between 2000 and 2019. All the article papers published in this journal were related to acoustic leak detection methods, where the authors have studied fundamental or conceptual parts of the leak noise correlators. The second ranking journal was "Sensors (Switzerland)", with a JIF score of 3.275 and 6 published article papers in the specified time interval. Two of the article papers published by this journal were related to non-acoustic leakage detection methods, focusing on using vibration sensors and pressure sensors. This journal also included a further 2 article papers related to WSNs, which focused on a scalable design for the simulation of WSNs and leakage detection utilising machine learning. The third ranking journal was "Measurement", which published 2 article papers related to acoustic methods and 2 papers related to non-acoustic methods. Lastly, our database search identified three journals with three published article papers within the specified time interval (Table 1). These journals included the "Journal of Pipeline Systems Engineering and Practice", which published 3 article papers related to acoustic methods, the "Journal of Applied Geophysics" which published 2 article papers on the topics of ground penetrating radar (GPR) and a paper related to acoustic-based leak detection methods, and lastly, "Measurement Science and Technology" which published 2 article papers on non-acoustic based leak detection and 1 article paper related to WSNs.

TABLE 1. Journals that have published at least 3 papers related to leakage detection methods using acoustics, non-acoustics and WSN

No.	Academic Journals	Total published papers	Number of Published Papers			Journal Impact Factors
			Acoustics	Non-acoustics	WSN	
1.	Journal of Sound and Vibration	11	11	0	0	3.429
2.	Sensors (Switzerland)	6	2	2	2	3.275
3.	Measurement	4	2	2	0	3.364
4.	Journal of Pipeline Systems Engineering and Practice	3	3	0	0	1.500
5.	Journal of Applied Geophysics	3	1	2	0	1.975
6.	Measurement Science and Technology	3	0	2	1	1.857

We compared the research trends among acoustic, non-acoustic and WSN methods for leakage detection in WDN, splitting the research trends into three time intervals: Period 1 (2000 to 2007), Period 2 (2008 to 2014) and Period 3 (2015 to 2019) (Figure 2). During Period 1, a total of 10 papers were published; however, these publications only focused on acoustic (8 papers) and non-acoustic (2 papers) methods. This is not surprising considering these methods are the oldest and most established methods for leakage detection in WDSs.

An interesting progression is seen during Period 2, where there is a clear increase in the number of publications related to non-acoustic methods compared to traditional methods (i.e., acoustic methods). In addition, this time interval included the first publication on WSN methods (Allen et al. 2012). Although acoustic and non-acoustic methods are among the earliest reported methods, improvements are still reported within Period 2 because these methods are effective. There were 18 and 50 article published during Period 2 and Period 3, respectively. During Period 3 the study of WSN for leak detection and localization became more prominent in the published literature (Figure 2).

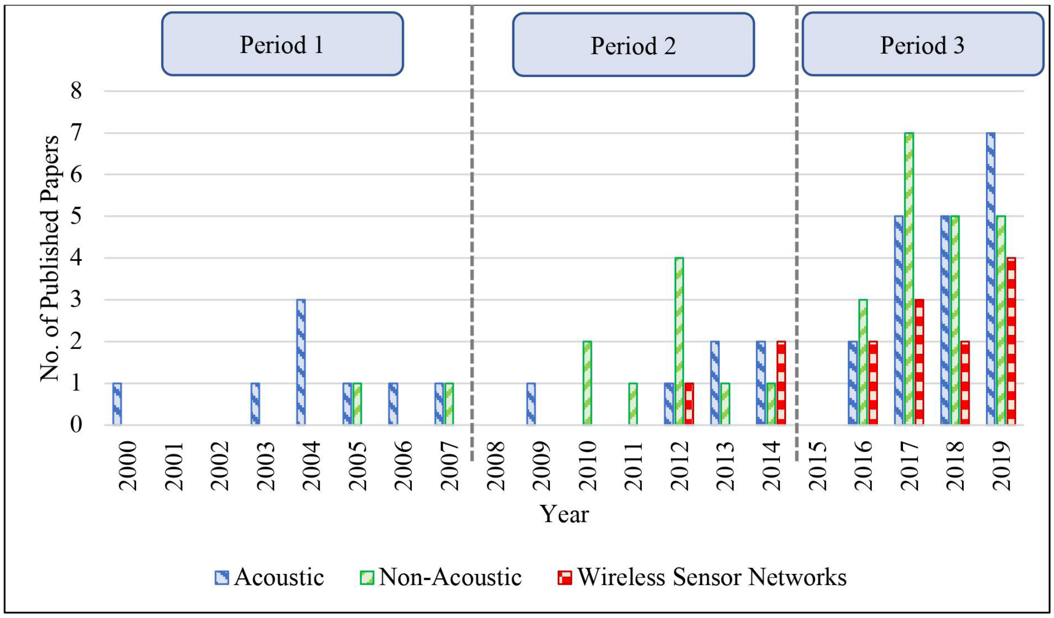

FIGURE 2. Comparison of trends among acoustic, non-acoustic and WSNs for leakage detection in water distribution systems.

RECENT TRENDS OF LEAKAGE DETECTION METHODS IN RELATION TO PIPE DIAMETER

Due to the lack of available data on pipe diameters used within Periods 1 and 2, we limit our discussion on the relationship between research trends of leakage detection methods and pipe diameter to Period 3 only (Table 2). We focused on three main categories of pipe diameter: connection pipes (25 mm to 90 mm), distribution pipes (50 mm to 400 mm) and transmission mains (250 mm to 1600 mm). Each category of pipe has its own function and importance in a WDN. For example, transmission mains are important as they deliver substantial volumes of water. As a result, transmission mains are often equipped with pressure sensors and flow meters to detect leakages. Leakages in transmissions mains are usually easily detected, located and quickly reported due to the volume and public visibility of leakages. Distribution and connection pipes are smaller in diameter but occur in higher quantities relative to transmission mains. These pipes are usually buried under ground and leaks are difficult to identify visually. Flow meters and pressure sensors are difficult to install directly in distribution and connection pipes, and usually require a hydrant or pipe fittings for the installation process. In older pipes, it may be difficult to locate functioning hydrant or pipe fittings due to damage related to corrosion, theft and lack of maintenance. Leakages in distribution and connection pipes are typically smaller in volume but can be widespread.

To assess the relationship between leakage detection methods and pipe diameter we divided leakage detection methods into three classes based on the methods used to collect the data: experimental, case study and modelling (simulation) (Table 2). Pipe diameter was further subdivided into six different diameter ranges: range 1 (less than 50mm), range 2 (50mm to 90mm), range 3 (90mm to 150mm), range 4 (150mm to 250mm), range 5 (250mm to 400mm) and range 6 (larger than 400mm). Pipe diameters that fall within range 1 and range 2 typically represent connection pipes, range 2 through to range 5 represent distribution pipes and range 5 and 6 typically represent transmission mains (Table 2). Due to the lack of information about the pipe diameter in 7 of the 50 published article papers in Period 3, our analysis was limited to data sourced from the remaining 43 article papers.

The majority of the research on acoustic and non-acoustic methods of leakage detection examined within this review focused on connection and distribution pipes. Research on leakage detection using noise correlators included pipe diameters from range 1 to range 6. Bakhti et al. (2019) investigated the hybrid empirical mode decomposition (EMD)-correlation acoustic digital leaks detector in WDSs. This experimental set-up included an acoustic signal sensor and amplifier. The materials used for this experiment comprised steel pipes and soft polyvinyl chloride (PVC) pipes with a diameter of 40mm and 15mm, respectively (range 1, see Table 2). Almeida et al. (2018) and Brennan et al. (2019) studied the correlation between leakage detection using high performance polyethylene (HPPE) and PVC pipes, respectively. Both studies used pipes with a diameter of 150mm (range 3, see Table 2). Adaptive noise cancellation based on EMD in leak detection of WDSs has been studied using pipelines with diameter 100mm, 200mm and 700mm (range 3 through to range 6, see Table 2) (Guo et al. 2016). Although our review highlights many studies that focus on noise correlators, these studies are limited in scope and there is still room for improvement using this method.

Within our review we identified several studies that focused on using sensors to detect leakage detection based on vibrations. Ismail et al. (2018) and Okosun et al. (2019) researched leakage detection based on three-axis accelerometer sensors and output-only piezoelectric sensors. Ismail et al. (2018) used three-axis accelerometer sensors with an experimental setup of a 10 m acrylonitrile butadiene styrene (ABS) pipe with a diameter 25mm. Okosun et al. (2019) used output-only piezoelectric sensors with an experimental setup of 1 m galvanized steel (GS) pipe with an outer diameter of 40mm. Yazdekhasti et al. (2017; 2018) also used vibration based leak detection methods. Their experimental setup consisted of a pump, reservoir, accelerometer, leak simulator and PVC pipes with a diameter of 76mm and 102mm. Lastly, Guo et al. (2019) conducted an experiment using a 102 m section of ductile cast iron pipe with an inner diameter of 300mm in conjunction with two fiber optic hydrophones to observe the signal of vibration when leakage was simulated. Taken together these studies suggest that vibration sensors are an important non-acoustic leak detection method that can cover a range of pipe diameters (range 1 through to range 3 and range 5, see Table 2).

Our results for pipe diameter for acoustic and non-acoustic methods were predominately obtained from experimental research papers. To simulate real-life cases, the diameter of pipes used for experimental research should reflect the pipe diameters typically used for distribution pipes. Thus, most of the published literature on acoustic and non-acoustic methods tended to focus on pipes with a diameter within range 3 (i.e., distribution pipes). For non-acoustic methods, only a few researchers considered pipe diameters within range 1, equivalent to diameters typical of connection pipes. Although the research that focused on WSN also focused on pipe diameters within range 3, the data for these studies were obtained from simulation rather than experimental works.

WSN methods were usually applied to distribution pipes and transmission mains, providing a contrast to the pipe diameters typically focused on in research published on acoustic and non-acoustic leakage detection methods. WSNs are typically used for water networks that contain different types and diameters of pipes. The results of our review indicate that research on WSNs has focused on a smaller range of pipe diameters compared to the acoustic and non-acoustics methods. This indicates that there is still scope for further research in leakage detection based on WSNs.

TABLE 2. The trends in relationships between types of leak detection methods and ranges of pipe diameters. Researchers that considered more than one range of pipe diameter are highlighted using blue for acoustics, green for non-acoustics and red for WSN

Classes of leak detection	Type of data (No. of papers)	Sensors / Approaches	Connection Pipe (25mm – 90mm)		Distributions Pipe (50mm – 400mm)			Transmission Mains (>250mm)
			Range 1 (mm)	Range 2 (mm)	Range 3 (mm)	Range 4 (mm)	Range 5 (mm)	Range 6 (mm)
			< 50	50 to 90	90 to 150	150 to 250	250 to 400	>400
Acoustic	Experimental (13)	Acoustic emission		Martini et al. (2017)	Quy et al. (2019)	Li et al. (2018)		
		Hydrophones sensor			Xu et al. (2019)	Kumar et al. (2017a), Kumar et al. (2017b)		
		Noise correlator	Bakhti et al. (2019)		Brennan et al. (2018), Scussel et al. (2019)			
					Almeida et al. (2018), Brennan et al. (2016)			
					Gao et al. (2017)	Ma et al. (2019)		
	Case Study (2)	Acoustic emissions (AE)			Butterfield et al. (2018)			
					Muntakim et al. (2017)			
	Simulation (3)	Noise correlator			Brennan et al. (2019)			
						Guo et al. (2016)		
		Optimal selection			Yazdekhasti et al. (2018a)			
Non-Acoustic	Experimental (13)	Ground penetrating radar	Lai et al. (2016), de Coster et al. (2019)			Cheung and Lai (2019)		
		Vibration sensor	Ismail et al. (2018), Okosun et al. (2019)	Yazdekhasti et al. (2018b), Yazdekhasti et al. (2017)			Guo et al. (2019)	
		Pressure sensor	Gong et al. (2018)		Wong et al. (2018a), Wong et al. (2018b), Khalifa (2017)			
		Temperature sensor			Jacobsz and Jahnke (2020)			
	Case Study (2)	IR Thermography				Bach and Kodikara (2017)		
		Remote Sensing					Agapiou et al. (2016)	
	Simulation (1)	PVS			us Saqib et al. (2017a)			
Wireless Sensor Network	Experimental (4)	Pressuer sensor	Karray et al. (2018), Kayaalp et al. (2017)					
		Acoustic sensor			Teruhi et al. (2017)			
		ML	Liu et al. (2019)					
	Simulation (6)	MSN			Wu et al. (2016)			
		Hydraulic models	Kosior (2019)		us Saqib et al. (2017b)		Pal and Kant (2019)	
		PVS			Mysorewala (2019)			

Note: IR – Infrared, ML – Machine Learning, MSN - Mobile Sensor Nodes, PVS – Pressure & Vibration Sensors

When leaks occur within transmission mains, leak noise dissipates easily due to the large pipe diameter size, making it difficult for an acoustic sensor to detect any noise from the leakage (Jo and Boon 2012). Therefore, an alternative method for leakage detection in transmission mains is non-acoustic leak detection. In our review we find that the research on non-acoustic leak detection methods in transmission mains (range 5 and range 6) focused on using vibration sensors (Guo et al. 2019), infrared thermography (Bach and Kodikara 2017) and remote sensing (Agapiou et al. 2016). However, the application of WSN methods has also been recently considered for transmission mains (Pal and Kant 2019). WSN can help to reduce the leakage detection time by narrowing down the location of leakages. Thus, the technician does not need to manually search for leakages and can focus their search within a specific area. In summary, we show that for each type of leakage detection method, researchers have focused on a variety of different pipe diameters. Our review highlights several knowledge gaps within the published literature, where further research is required to fully understand the application of leakage detection methods across the full range a pipe diameters.

CONCLUSION

This review paper presents the trends of leakage detection methods over the last two decades (between 2000 to 2019) using the methodology proposed by PRISMA 2009. The results obtained were sorted into three types of leakage detection methods, namely acoustics, non-acoustics and WSNs. We found that acoustic leak detection methods were among the earliest methods established for leakage detection, followed by non-acoustic and WSN methods. The trend of leakage detection method based journals that have published at least 3 articles papers indicate the “Journal of Sound and Vibration” had published the most papers, with all of the published papers related to acoustic methods. Our review indicates that the relationship between leakage detection methods and pipe diameters varies between the different leakage detection methods. The range of pipe diameters considered for acoustic and non-acoustic methods are typically limited (i.e. range 3), while the range of pipe diameters researched for WSN are much wider.

Our review highlights that there is still considerable scope to conduct further research related to leakage detection methods across a broad range of pipe diameters. This research is becoming increasingly important due to the complexity of global WDNs and increasing pipe age. We suggest that future research should focus on the improvement of communication between sensor nodes within networks, improvement of the energy efficiency of networks, and the application of leakage detection based on WSN methods for a wider ranges of pipe diameter. Lastly, we suggest researchers should take the advantage of the vast advancements in wireless sensor technology and focus on developing a more efficient and effective leakage detection method using WSN.

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DECLARATION OF COMPETING INTEREST

None

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