Review of Water Leak Detection and Localization Methods through Hydrophone Technology

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Abstract

Acoustic technologies are popular for detection of leak detriments in water pipelines. However, problems of false alarms, detection of weak or difficult leaks, accurate leak pinpointing, and the high cost of long-term monitoring remain prevalent. These issues demand a more sophisticated testing approach suitable for real-world application. In particular, hydrophone technology has strong promise for long-range leak detection in high attenuation conditions. However, existing review studies only cover the methods of leak detection holistically with limited insight into the practical implementation of sensing technologies for water leak detection. In particular, the problem of detecting and localizing leaks using hydro-acoustic data has not been yet extensively studied. The current study, therefore, presents a state-of-the-art review of the extant literature on water leak detection and localization taking hydrophones as a good example of hydro-acoustic water leak detection. The study compares hydrophones with other popular sensing technologies like accelerometers and guides on its better application for detecting water leaks. Current research directions, gaps, and future work foci are also identified to enable further development of a hydrophone-based water leak detection system. Review shows that existing experiments are limited to controlled conditions where impacts of surrounding strata, ambient noise, and difficult pipe geometries cannot be studied. Future studies can apply the technology to real-life cases, developing faster analytical methods and hybrid solutions using a multi-sensing approach. This can help water leak experts enormously in cost-effective, efficient detection of leaks.

Keywords: Hydrophones, Water leaks, Detection, Localization, WDN

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1 Introduction

Water leakage is a plaguing issue in the current throes of global water crises. It is the biggest constituent of the 126 billion cubic meters volume per year of non-revenue water (NRW) estimates (Liemberger and Wyatt 2019). Discontinued water supply for an extended time during leak rectifications can cause a further nuisance to users. Additionally, false alarms and wrong assessment of leak location can cause huge repair costs. Thus, early and accurate identification of leaks and timely rectifications can significantly improve water distribution and supply efficiency. In this regard, acoustic techniques have the potential for both short and long-term leak monitoring and control (Hunaidi and Chu 1999; Khulief et al. 2013; Xu et al. 2019). Among these techniques, hydrophones have invoked interest for their capability of capturing the in-pipe acoustic signature of leak signals (Khulief et al. 2012). This is significantly different from out-of-pipe technologies like accelerometers (Marmarokopos et al. 2018).

Generally, pipe leaks can generate high-frequency noise if there is unsteady flow separation at the leak location, or low-frequency noise if hydrodynamic cavitation occurs at the leak location (Gao et al. 2004). During cavitation, pressure drop below the vapor pressure can generate shock waves which upon falling on the pipe wall create sound (Khulief et al. 2013; Khulief et al. 2012). In this situation, leak orifices act as high-pass sound filters, expelling high-frequency sound energy outside the pipe system and reflecting low-frequency sound signals into the pipe (Brennan et al. 2019). The high-frequency sound wave is attenuated significantly inside the pipe, leaving low-frequency sound signals to be the primary source of data for leak diagnostic studies. As hydrophones are efficient in detecting low-frequency noise signals, they can be the most suitable instrument for leak detection in such conditions (Hamilton and Charalambous 2020). Plastic pipes and large diameter having high attenuation of sound waves making hydrophones successful in producing high-resolution correlation in this case as compared to other technologies (Gao et al. 2017; Hunaidi and Chu 1999). Various experimental studies demonstrate hydrophones to produce similar or higher accuracy results as compared to accelerometers, pressure sensors, or ground microphones (Gao et al. 2005). Furthermore, Cody et al. (2020) suggest that acoustic methods deliver high-resolution data for the detection of small leaks. However, coverage of the entire network through hydrophones is argued to be time-consuming, costly, and non-effective as compared to other hardware technologies (Li et al. 2015).

This implies a lack of clarity in the effective implementation of hydrophone sensor technology for leak detection and localization/pinpointing. A detailed knowledge base seems to be missing in this regard to provide practical guidance. Generally, the review studies available in this domain of knowledge mostly aim to compare all available techniques for water leak detection. For example, Puust et al. (2010) discussed the leakage assessment methods, the major technologies in-use for leak detection and pinpointing, and the hydraulic transient models for managing leaks. Li et al. (2015) categorized the leak detection methods into hardware and software-based methods. Furthermore, Datta and Sarkar (2016) presented a detailed taxonomy for fault detection methods, distinguishing between blockage and leakage detection methods. Zaman et al. (2020). Similarly, El-Zahab and Zayed (2019) overviewed all popular leak detection methods. These studies only use a broad scope to advance the taxonomical and epistemological construct for water leak detection methods. Generic discussion on all methods, however, does not help practitioners gain a working insight of any hardware-based acoustic methods like hydrophones for practical implementation in the field. In this regard, some of the relevant empirical studies have revealed its merit to be used for real-time monitoring for leak detection (Lechgar et al. 2016; Xu et al. 2019). However, practical implementation requires the identification of constraints for its use for efficient leak detection, accurate localization, and long-term monitoring of real networks. The current study addresses this knowledge gap by a systematic review to explore the analytical methods applicable to hydro-acoustic data.

Advancement in the application is explored through the identification of current research directions, gaps in knowledge, and possible future directions for the use of hydrophones for water leak detection.

2 Research Methodology

The study conducts a review on leak detection in water distribution systems using hydrophones based on scientometric techniques and qualitative content analysis. The research themes are first identified by analyzing the citation data of articles. The identified themes of research are then discussed in-depth to highlight the current practices, research gaps and future directions of work. The search design for articles involved both database search from Web of Science (WoS) and backward snowballing. At first, the literary works were first identified through a focused search on the WoS database. The WoS search was designed using relevant keywords: ‘hydrophones’, ‘leak detection’, ‘pinpointing’, ‘localization’, ‘burst detection’, and ‘water leaks’. In total, 39 relevant literary sources were identified using the process highlighted in Fig. 1. To find more relevant articles, the method of backward snowballing was utilized (Mourão et al. 2020). For the backward snowballing, cited references from the initially identified 39 works were included in the search. Through this hybrid approach, a total of 252 more relevant articles were identified. In total, 291 articles were collected and screened for duplicates and irrelevant articles based on Title-Abstract-Keyword search. After screening, 80 articles were found eligible for further analysis. Full-text analysis of these 80 articles was then conducted to finalize 72 articles for review. The PRISMA flow diagram showing the detailed shortlisting process and exclusion criteria are presented in Fig. 1. The shortlisted studies are first classified based on study type, hydrophone type, and leak detection phases. Furthermore, bibliographic coupling using VOSviewer version 1.6.9 was used to identify prominent research directions and research topics. Bibliographic coupling is a similarity-based network analysis method forming a network of publications based on the number of citations common between them

(Patrício and Ferreira 2020). It does this by forming clusters using two measures: the number of citations and the total link strength (TLS). The number of citations shows the individual influence of the publication itself and the TLS indicates the strength of correlation between publications. After categorizing the dominant research themes, detailed content analysis was carried out to identify the topics of interest, after which particular research gaps and future directions in the research were suggested using qualitative full-text analyses of the articles.

3 Research trends

The year-wise analysis of the shortlisted studies is presented in Fig. 2. Results reveal very limited studies on the subject till the year 2000 with more than 50% of articles published in the last five years. A growing interest implies promise for use of hydrophone devices for leak detection. Therefore, the current study presents a timely review examining the scholarly space to identify useful and pragmatic outlooks for its diverse application in different aspects of the water leak detection problem.

4 Classification of scholarly works

4.1 Types of research studies

The type of studies conducted till now in the domain is presented in Fig. 3. The research in the domain of leak detection is generally guided by empirical evidence. This is supported by the high number of experimental studies on the application of hydrophones for leak detection (63% of total). There are 23% of studies in the data which are marked both theoretical and experimental. Such studies offer a conceptual construct as the basis of their experimental work. For example, Gao and Liu (2017) developed a theoretical model for the relationship between internal pressure and wall displacements and validated the model using lab experiments. Moreover, only scattered efforts are made towards studying the physical concepts and mechanisms of wave propagation inside the pipe. Only 7% of real-life cases and theoretical studies could be found on the topic which implies a big gap in research. For example, Lechgar et al. (2016) explored hydrophone implementation for leak detection in Casablanca. Overall, theoretical studies including a review of previous work on the current research area are also negligible. Findings overall, reveal three-scale experimentation using hydrophones: lab, test-bed, and real pipe network. Most studies for leak detection are based on lab or test-bed experimentation as shown in Fig. 3 (Gao et al. 2009; Hunaidi and Chu 1999). Although effective for understanding fundamental physical principles, controlled conditions are difficult to replicate in the field. This is due to the presence of various uncertainties, attenuation effects, and high background noise in real conditions. Thus, extending the lab experiments to real networks is an important step for demonstrating the feasibility of the technique (Guo et al. 2019).

4.2 Leak detection phases

Generally, the leak detection process can be classified into three phases: Detection, localization, and pinpointing (Hamilton and Charalambous 2020). It can be seen that in almost all situations, a leak is suspected in the system if there is a distinct peak in the sound signal. To determine whether or not the suspected leak is real, pre-processing is required to remove the ambient noise effects as there can be a false alarm in the system. This process to confirm the presence of a leak in the system is known as ‘leak detection’ or ‘leak identification’ (Cody et al. 2020). El-Zahab and Zayed (2019) included differentiating leaks from false alarms as an essential step of leak identification. Once the presence of a leak is confirmed, the location of the leak is determined. This process can be termed as ‘localization’, ‘location’, or pinpointing’ depending upon the accuracy with which we can determine the distance of the leak from the sensor (Sun et al. 2020). Many authors differentiate between these terms for the particular focus of their research or the purpose of brevity. For example, El-Zahab and Zayed (2019) consider narrowing down the location of the leak to a particular segment of the water network or a specific district metered area (DMA) as “leak localization”; determining the location of the leak with an accuracy of 30cm as “leak location” and determining the leak location with an accuracy of 20cm as “pinpointing”. On the contrary, Zaman et al. (2020) define “leak localization” as pinpointing the location of the leak. In practical terms, these three terms refer to the same process of estimating the location of the leak (Datta and Sarkar 2016; El-Zahab and Zayed 2019; Ma et al. 2019). On basis of the generic three-phase leak categorization, it was observed through content analysis that 57 studies discuss leak detection, 41 discuss location/localization, and only 6 studies focus on pinpointing the exact location of leak through hydrophones. Very few articles focus on two or three leak detection phases, simultaneously.

5 Significant Research Directions

Analyzing the past research developments in any field helps in building the theoretical background for more advanced research. The current study does this using the results of bibliographic coupling. The current study uses the metric to track research developments because of its retrospect perspective of analysis (Ferreira 2018). Fig. 5 shows the developments using the network visualization in the VOS viewer. In total, 4 main clusters of research foci are visible in Fig. 5, formed through bibliographic coupling explained in section 2. As 60 out of the 72 shortlisted studies were connected, the network formed was visualized using 60 publications. The resulting clusters have been assigned names following the dominant research direction of the articles in the cluster and discussed in the same order in the sub-sections: **Cluster#1 (Section 5.1): 5.1** Leak detection and localization using hydrophones and comparison with accelerometers; **Cluster#2 (Section 5.2):** Innovation for long-term leak detection and localization; **Cluster#3 (Section 5.3):** Implementation of hydrophones in real networks; and **Cluster#4 (Section 5.4):** Hydrophone measurements and pipe flow dynamics.

5.1 Leak detection and localization using hydrophones and comparison with accelerometers

Cluster#1 has 21 articles including the five most cited works in the field presented in Table 1 and Table 2. Mainly the studies in Cluster#1 involve the comparison of hydrophones with other sensors for selection of suitable acoustic methods (Gao et al. 2005), modeling the acoustic properties for leak noise and efficient time-delay estimation (Hunaidi and Chu 1999), and improving the signal analysis and signal quality of cross-correlation function (Brennan et al. 2019; Gao et al. 2017). Seminal work from Hunaidi and Chu (1999) empirically compared the performance of hydrophones and accelerometers for water leak detection through experimentation. Their results demonstrated the promising use of hydrophones especially for low-frequency leak signal propagation (<50 Hz) in PVC pipes whose material has high signal attenuation properties. In the experimentation of their related work, Hunaidi et al. (2000) further demonstrated that hydrophones can detect small leaks even at 6 L/min (1.6 GPM).

These studies have inspired many researchers to design similar experiments and improve the leak detection process and cross-correlation accuracy. For example, Gao et al. (2004) developed a model for cross-correlation of leak signals in plastic pipes exploring the effect of anti-aliasing filters on the removal of noise from low-frequency noise data. By combing the cross-correlation with the concepts of wave propagation in fluid-filled pipes, a cut-off filter range of 10-50Hz was estimated for leak detection through hydrophones. Gao et al. (2004) and Gao et al. (2005) further compared the findings of hydrophone data with accelerometers. It was found that acoustic pressure data from hydrophones is useful for correlation for leak cases with small signal-to-noise (SNR) ratio. Furthermore, Gao et al. (2006) explains the method of cross-correlation for leak localization in-depth and compares the different time delay estimators used for the purpose.

There are overall two basic methods of cross-correlation: basic cross-correlation (BCC) and generalized cross-correlation (GCC). The difference between both methods is that in the GCC method, the signals are pre-filtered through a pre-whitening process for removing the background noise and sharpening the peak of the cross-correlation function. For the basic cross-correlation, acoustic signals are measured at two different access points at both sides of suspected leaks through hydrophones. These hydrophones can be either attached to the hydrants or inserted in the pipe through valve openings (Gao et al. 2009; Gao et al. 2005; Khulief et al. 2013; Xu et al. 2019). The presence of a leak is confirmed if there is a distinct peak in the cross-correlation of the two measured signals, $s_1(t)$ and $s_2(t)$. The location of the leak can then be calculated concerning any one of the sensor locations, $l_1$or l_2 using the time delay (t_{peak}) between the arrival times of signals to the sensor locations given as: $l_1 = \frac{l-ct_{peak}}{2} \ldots \ldots \ldots \ldots \ldots \ldots \ldots Equation\ (1)$

Where l is the distance between access points and the propagation wave speed c in the buried pipe. For any two random signals, $s_1(t)$ and $s_2(t),$ the theoretical BCC function is given as:

$$R_{s1\,s2}(t_d) = E[s_1(t)s_2(t+t_d)] \ldots \ldots \ldots \ldots \ldots \ldots .. Equation\ (2)$$

Where t_d is the time lag, and E is the operator for maximization of t_d. The largest value of t_d can be considered the time delay estimation, t_{peak}. For real data, the BCC function can be calculated by the inverse Fourier transform of the signal. The cross-correlation function is preferred to be expressed in the normalized form, on a -1 to +1 scale, known as the correlation coefficient (Almeida et al. 2014). The highest value of the correlation coefficient will be gained when the two sensors are equidistant from the leak source, however, practically one sensor is always nearer to the leak source than the other (Gao et al. 2004). Thus, only the relative ratio between the two distance values, l_1/l_2 , is important. Gao et al. (2005) compared hydrophones with accelerometers and geophones and found that hydrophones showed the lowest sensitivity towards changes in the distance ratio as compared to others. Specifically, for good correlation, the ratio of distance should satisfy 1/10 ≤ $\frac{l_1}{l_2}$ ≤ 10.

For the GCC method, pre-filtering is done on the input signals either in time or frequency domains (Gao et al. 2009; Gao et al. 2017; Hunaidi et al. 2000). For the time domain, signals can be filtered before delay calculation and for the frequency domain, window or weighting functions can be applied to the cross-spectral density (CSD) function before the application of inverse Fourier transform. The weighting functions used for the purpose are ROTH impulse response, smoothed coherence transform (SCOT), the WIENER, the phase transform (PHAT), and the maximum likelihood (ML) estimators and help in increasing the resolution of the cross-correlation function. The GCC function, $R^{g}_{s1\,s2}(t)$ between two random signals, $s_1(t)$and $s_2(t)$ is given by Equation 3.

$$R^{g}_{s1\,s2}(t) = F^{-1}[\varphi_g(\omega)\ C_{s1\,s2}(\omega)] = \frac{1}{2\pi}\int_{+\infty}^{-\infty} \varphi_g(\omega)\ C_{s1\,s2}(\omega) e^{i\omega t} l\omega \ldots\ldots\ldots.. Equation\ (3)$$

Where F^{-1} [ ] denotes the inverse Fourier transform, $C_{s1\,s2}(\omega)$ the cross-spectral density and $\varphi_g(\omega)$ the frequency weighting function. For $\varphi_g(\omega) = 1$, the GCC=BCC. Further details of the suitability of these methods for different conditions can be seen in Gao et al. (2006) and Gao et al. (2009) which establish the effect of pipe dynamics and reflective properties of the pipe material on the cross-correlation peaks. It was found that the PHAT estimator gives the best results and can be termed as an improved GCC method or the GCC-PHAT method. It pre-whitens the modulus of cross-spectrum and leaves the phase spectrum information only, from which the time delay can then be efficiently calculated. However, the method assumes does not take coherence between two signals into account and assigns equal weights to all frequencies irrespective of signal strength. Instead of improving the GCC function, an alternate method for the time delay estimation is the generalized phase spectrum method (GPS).

The GPS method defines the best time-delay estimate as to the one for which the mean square error between the measured and estimated phase of the cross-spectral density (CSD) is minimized over a pre-defined frequency bandwidth. Brennan et al. (2007) compared the GPS method with BCC and GCC-PHAT methods and found the time and frequency domain analysis equivalent. Both hydrophones and accelerometers were used for demonstrating the GPS method. Most of the signals detected from the hydrophone ranged from 10 and 120 Hz. The coherence between signals was generally better than accelerometers. However, the phase spectrum revealed phase shifts at 60Hz and 80Hz. Such phase shifts can cause inaccurate time delays and were attributed to hydrophone mounting resonances. Thus, the frequency bandwidth was limited to 10–50 Hz for the hydrophone. Almeida et al. (2014) presented the time delay estimation using phase spectrum as per Equation 4.

$$t_{peak} = \frac{\sum_{j=1}^{i}[D_{s1s2}(\omega_j)]\theta(\omega_j)\omega_j}{\sum_{j=1}^{i}[D_{s1s2}(\omega_j)]{\omega_j}^2} \dots\dots\dots\dots. Equation\ 4$$

Among the recent studies, Almeida et al. (2014) used this method to explore the choice of acoustic sensors by experimentation on leak noise data from a test rig. It was found that in the case of their experiment, all sensors proved efficient in detecting strong leaks (high SNR). However, hydrophones were unable to detect weak leaks (low SNR) because of their invasiveness and presence of high background. This is in contrast to the findings of Gao et al. (2005) who particularly recommended the use of a hydrophone sensor for low SNR signal detection as they are least affected by attenuation. This indicates the limitation of the lack of standardization in experiments. Furthermore, Almeida et al. (2015) highlighted that for Equation 1, estimation of the speed of wave propagation,c in the pipe needs to be accurate to find the location of the leak from time-delay estimation. The study proposed an in-situ measurement of c to control error in leak localization. Furthermore, to control the resonance effects, extra peaks due to reflections, and achieve a good coherence, the PHAT correlation estimator has been demonstrated (Gao et al. 2017). Additionally, Brennan et al. (2019) examined the effect of instrumentation issues like clipping and quantization through the application of signum function and random telegraph theory. For the hydrophones, it was observed that clipping effects cause severe distortions on amplitude, coherence, and phase angle above frequency >50 Hz. However, the clipping effect has a negligible effect on the normalized cross-correlation and thus, does not affect the time delay estimation. The studies give fundamental knowledge for hydrophone use in the leak detection field. However, they only consider basic modeling and signal processing for the improvement of time-delay estimation and involve manual computations which are laborious and time-consuming.

5.2 Innovation for long-term leak detection and localization

In Cluster#2, there are 22 articles, 17 of which are published in the last 3 years. Most cited articles in cluster 2 are shown in Table 3 and Table 4 top articles with respect to total link strength. This implies that these publications can help identify the current state of research directions in the area. After an in-depth review of articles, it is apparent that the research directions focus on 1) improvements in time delay estimation methods; 2) application of advanced data analytics for automated leak detection and localization; 3) exploring innovative technologies for long-term monitoring and early detection of a leak; 4) factors of complexity in the adopted experimental approach.

In cluster#2, some studies have focused on presenting alternative methods for the pre-filtering requirement in the GCC method. Most significant work in the cluster in terms of link strength shown in Table 5, Gao et al. (2018) introduced the differentiation process (DIF) as an improved version of the generalized cross-correlation (GCC). Instead of adopting the pre-whitening methods of the GCC, the DIF method modifies the pipe system characteristics by applying a higher-order frequency weighting function, $\varphi_f(\omega) = \omega^n$ before the cross-correlation. This makes the pipe system act as a high-band pass filter, making available more information than what could be achieved through pre-whitening GCC methods and BCC. This reduces the effect of resonance and ambient noise effect at low frequencies and allows for a more reliable cross-correlation peak. The method works well with hydrophones but has limited application for accelerometer-based noise correlators due to the diminishing effect on SNR. It is previously established that time delay estimation can be done using the phase spectrum (Almeida et al. 2014). In related work, Ma et al. (2019) further developed a novel method for time delay estimation (TDE). They developed a new frequency response function (FRF) using only the phase information of the leak signals and proposed an adaptive phase transform (ADPHAT) algorithm based on it for TDE. Time delay can be estimated by taking the inverse Fourier transform of the FRF given by equation 5 as $h(n) = F^{-1}\left[\sqrt{H_{12}(\omega)H_{21}(\omega)}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 5$

It is worth mentioning that the method is an improved version of the least mean square (LMS) method and can estimate time delay even without information on spectral characteristics of the signals.

Currently, novelty detection methods have become appealing for the application of long-term leak detection and localization. These methods identify novel or anomalous events from a normal set of data in any machine learning system using either statistical approaches or neural network approaches (Markou and Singh 2003; Markou and Singh 2003). These methods are data-driven and only require the signal data for leak diagnostics. For fully supervised training, historical data for both leaks and the no-leak condition is required. However, for semi-supervised training, only the normal state data is required to detect anomalies (Cody et al. 2018). As the historical data sets for leak data might not be available, semi-supervised approaches seem more attractive to leak detection practitioners (Cody et al. 2020). In this regard, Cody et al. (2018) used single-spectrum analysis (SSA) and a one-class support vector machine (OCSVM) for leak detection. This is a non-parametric approach to effectively decompose signals into components showing promising ability to detect leaks in strong background noise. However, the method does not apply to leak localization. Similarly, Harmouche and Narasimhan (2019) employed association rules (AR) mining, a non-parametric unsupervised learning approach for leak detection. In this study, a mean-shift clustering was used for finding the ARs based on which a leak index matrix is then established. This leak index then serves as a reference model for detecting any new leak in the system with high sensitivity. On the contrary, Cody et al. (2020) uses a linear prediction (LP) method for leak detection and localization. This is a parametric signal processing method assuming a Gaussian mixture model for novelty detection from a baseline. The detected leak is localized using cross-correlation.

One commonality between these studies is the use of feature engineering during the pre-processing of hydro-acoustic data. In feature extraction, domain knowledge is applied to extract relevant features from a dataset acting as an input for the algorithm or analysis being used for leak detection (Zheng and Casari 2018). Though effective for lab experiments, the variability of the features over a real WDN is not established. Additionally, repeating this step for each new location can be tedious and complex. Cody et al. (2020) avoided the use of feature engineering through a novel approach applying auto encoders based on deep learning. The technique uses spectrograms of hydro-acoustic data for novelty detection. In the study, a convolution neural network (CNN) is used with a variational autoencoder (VAN) using which the spectrograms are used as training sets for normal data. The approach neither requires prior training of data sets nor any feature extraction for leak detection. This is the only study for hydro-acoustic data applying the neural network-based novel detection. A 97% classification accuracy was achieved during testbed experiments under realistic noisy conditions. A unique feature of the experiment design of the study is the use of only a single hydrophone installed at the base of the hydrant for data collection.

Based on a detailed review, it is evident that various factors affect signal propagation of leaks determining the accuracy of cross-correlation. These factors are either internal or external. Internal factors are related to internal flow and pipe system characteristics including flow rate, line pressure, wave propagation speed, pipe size, leak size, pipe material, pipe geometry, pipe condition (old or new), unknown discontinuities in the pipe network, number of leaks in the pipe, and whether the leak is old or new (Butterfield et al. 2018; Butterfield et al. 2018; Gao et al. 2009; Gao et al. 2005; Martini et al. 2017). External factors include the surrounding factors like soil pressure due to backfill in buried pipes, placing of sensors on the pipe, type of sensor, season, time of sounding, traffic and other background noise, the experience of engineers, and the conditions during experimentation (Butterfield et al. 2018; Hunaidi and Chu 1999; Zhao et al. 2020). There are, however, very few studies among existing which have explored such attenuation factors or incorporated these effects in their calculations. In cluster#2 various studies have focused their attention on expanding the complexity of experimentation to include such factors. For example, Khalifa et al. (2012) established some important factors affecting acoustic wave propagation in pipelines like the effect of sensor placing from the leak source, the effect of changes in flow conditions like line pressure, and flow rate.

One impending challenge is the scale and scope of leak experiments as very few real network-based studies can be found in the shortlisted publications (Bracken and Cain 2012; Butterfield et al. 2018; Lechgar et al. 2016; Ma et al. 2019). In lab conditions, standardization of experiments to study the impact of any single factor is difficult. In real networks, there can be multiple leaks in the system at the same time, the pipe geometry can involve bends, valves, fittings, discontinuities, varying diameters, and corresponding line pressure depending on pipe functions, and differences in pipe material within the network. In this regard, Butterfield et al.

(2018) investigated the effect of different pipe materials on the efficacy of sensors for cross-correlation of leak localization. The experiments were done on a real WDN using artificially created leaks and showed poor cross-correlation results for plastic pipes using vibration. However, the use of hydrophones has been encouraged to get better results.

In cluster#2, in addition to such methodical and analytical improvements, technological innovations are also discussed. These innovations are briefly explained in section 3 as a case of technological innovation for overcoming instrument capability issues, Khulief et al. (2012) designed a novel experiment for leak detection using a free-swimming hydrophone. Although the use of a free-swimming sensor allows the long-distance survey of pipe network and greater reach to less approachable pipeline sections, the applicability has some limitations as well. Past experiment scenarios based their findings on a comparison of the *leak* and *no leak states*. So, in this case, data will be needed to be collected in a leak-free pipe section as well, or correlation using a multi-sensor system will be needed. Additionally, uninterrupted access to GPS and continuous recording of sound data are dependent on battery life. Design and access limitations also exist in terms of navigating around sharp bends and narrow pipe diameters.

Apart from innovation in the method of deployment of hydrophones, alternatives to piezoelectric materials for fabrication are also being explored for better precision, low cost, and smaller size e-g MEMS-based and Fiber-optic hydrophones. The application of hydrophones for metal pipes and long-term monitoring is also a new endeavor due to its capability of long-range detection. Recently, Guo et al. (2019) demonstrated a long-term monitoring system for leakage in water pipes by deploying four fiber-optic-based hydrophones on the pipe walls of a real network of ductile cast iron pipes. The hydrophones monitor the pipe condition in real-time and trigger an alarm upon any leak. The positioning accuracy of leak localization was 99.829%. The error in estimation increases with the distance of the sensor from the leak. Xu et al. (2019) used microelectromechanical system (MEMS) hydrophones for leak detection and pinpointing. The sensors were installed both inside and outside the pipes to study attenuation effects on correlation. It was found that inside installation had a lower chance of false alarms and the setup can detect both old and new leaks for flow rate as low as 30L/min. Although the feasibility of MEMS and FOH hydrophones is demonstrated for leak detection and pinpointing, the technologies are still in the testing stage.

5.3 Use of hydrophones in real networks

In cluster#3 9 articles are dealing with 1) leak detection and localization of in-service pipes and 2) the Implementation of hydrophones in real networks. Among these, Martini et al. (2017) have a total link strength (TLS) of 193 with 21 citations. The study has explored longitudinal leak development in high-density polyethylene (HDPE) service pipes. As the leaks in this pipe are difficult to detect due to the low flow rate, making the service leaks one of the significant components of pipe losses. There are very few studies that deal with this pipe type. The analytical approach adopted in the study is a statistics-based novelty detection method. But the difference between this study and the studies in Cluster#2 is that this study only adopts the basic statistical feature analysis for leak detection. The parameter used for detection is the standard deviation of raw signal for various condition changes. It was observed that hydrophones and accelerometers performed similarly on these pipes, with hydrophones being able to detect leaks farther away than accelerometers. In a similar work, Martini et al. (2017) presented a leak monitoring index (MI) and compared the monitoring index efficiency of both hydrophones and accelerometers for leaks induced in small diameter polyethylene pipes. It was observed that hydrophones showed much better performance than accelerometers for long-distance leaks. However, accelerometers are still commonly much cheaper than hydrophones. In another related work, Martini et al. (2018) further demonstrated the successful use of the autocorrelation method for detecting and pinpointing water leaks in service pipes using vibro-acoustic measurements. Meanwhile, Muntakim et al. (2017) and Lechgar et al. (2016) both performed experiments on hydro-acoustic data on real network cases in Canada and Casablanca, respectively. Muntakim et al. (2017) focused on leak identification using coherence of two acoustic signatures from sensors installed on the fire hydrants as part of a setup called LeakFinder-ST. The leak is further localized using advanced commercial correlation software. Lechgar et al. (2016) on the other hand presented a unique case study for demonstrating artificial intelligence as a potential way for the optimal placing of hydrophones for fast and efficient leak detection in real networks. As otherwise, full coverage of the network using hydrophones is not financially viable as compared to cheaper accelerometers. The method used the greedy algorithm and SLOTS algorithms as inputs for the genetic algorithm for leak detection. Such case studies serve as good examples for future demonstration of developed methods on real networks.

5.4 Hydrophone measurements and pipe flow dynamics

Overall, there are very few studies that have focused on studying the attenuation characteristics of a submerged plastic pipe. Thus, cluster#4 studies are unique in their theoretical contribution to understanding the pipe and water interaction in buried plastic pipes. In this regard, Muggleton and Brennan (2004) developed a theoretical model for wave attenuation for plastic pipes and investigated its validity via laboratory experiments. As leak-generated acoustic energy is buried water pipes propagate at a low frequency, so it is useful to study the pipe flow dynamics at frequencies less than 200 Hz (Muggleton et al. 2002). At lower frequencies than the ring frequency, acoustic energy dissipates in different wave types. Out of these, most of the leak energy is concentrated in the axisymmetric (n=0), fluid-borne wave (s=1), the behavior of which is studied in relevant studies in the cluster (Pinnington and Briscoe 1994). The axisymmetric, fluid-borne wave is denoted by the wavenumber, n=0, s=1 in the literature (Gao and Liu 2017). Using an assembly of three hydrophones suspended along a centerline inside an MDPE pipe, the attenuation effects were experimentally compared with the theory. It was found that for low frequencies, the wave propagation speed and attenuation pattern are almost the same whether the pipe is suspended in air, or submerged in water or soil.

However, it should be noted that the soil type has an impact on the attenuation effects. Sandy soil may have air pockets in them creating similarly high attenuation as occurring in-air pipe. These relationships can further judge the attenuation impacts on hydrophone collected leak signals and improve process efficiency. For example, In cluster#4, Gao and Liu (2017) have the highest TLS of 228 with 4 citations. The study has a theoretically developed relationship between internal pressure and wave propagation and demonstrated using two accelerometers and one hydrophone. The relationship between internal pressure and radial displacement in the pipe wall for the s=1 wave is given in equation 6 as: $P_{s1} = \frac{\omega^2 \rho_f}{k_{s1}^r\, J_o(k_{s1}^r a)} W_{s1} \ldots\ldots Equation\ 6$

Where $P_{s1}\, and\ W_{s1}$ denote the acoustic pressure and radial pipe displacement, respectively. k_{s1}^r is the radial wavenumber of s=1 wave, J_o is the Bessel function of order zero and a is the radius of the pipe.

For any noise-free case, the ratio between distances of two sensors (l_1/l_2) from the leak should be less than about 10 (or greater than 1/10) for pressure responses and less than 3 or greater than 1/3 for acceleration responses. In this regard, Gao and Liu (2017) practically demonstrated that the pressure signals from the hydrophone can be detected at two locations between 10-93m from the leak source. For accelerometers, the range was 26-77 m from the leak source. This implies that instead of the absolute distances of the sensors from the leak source, the ratio of the two distances is more meaningful while deploying sensors for data collection. Further, Li et al. (2019) developed a theoretical model for the effect of pipe wall thickness and radius on wave attenuation. For a higher radius/thickness ratio, the radial vibration of the pipe wall increases, creating a strong power dissipation to the surrounding medium, causing higher wave attenuation. Further, using the findings on asymmetric wave propagation, Sun et al. (2020) compared new polyvinylidene fluoride (PVDF) wire sensors as a non-intrusive, in-expensive, and easily deployable alternative to commercially available piezoelectric hydrophones for leak detection and localization.

6 Highlights, research gaps, and future directions

Although the scholarly works have been discussed in-depth in section 4.4, it is pertinent to highlight some notable features of the research to guide practitioners looking to use hydrophones as their sensor choice for leak detection. Such features are presented in this section and shown in Fig.6, identifying the gaps and future direction of the research.

6.1 Method of Analysis

Many models have been identified in literature which can be combined with other analytical methods and signal processing techniques to identify and locate the leak. As shown in Table 5, two main kinds of methods can be found: Time delay estimation (TDE) and Novelty Detection Methods. For TDE, various signal processing models have been developed following the correlation principle and very few studies use the phase spectrum information to locate the leak. Moreover, the adoption of an automated GPS approach called the ADPHAT method is limited. But automated approaches with less computational and pre-processing requirements can increase the feasibility of hydrophones for long-term leak detection and localization. Conversely, novelty detection methods detect anomalies in a normal system through fully supervised or semi-supervised machine learning approaches. But very few studies utilize statistical modeling and machine learning-based algorithms to analyze hydro-acoustic data. Table 5 shows that such models are innovative and require further work for efficient leak detection and precision pinpointing. Future studies can further improve the limitations of the discussed methods as presented in Table 5.

6.2 Application to Real Networks

There are studies available that demonstrate the leak detection methods on real networks (Cody et al. 2020; Martini et al. 2018). However, the authors observe two limitations: 1) Most studies demonstrate their developed methods on a lab or testbed scale and do not discuss the performance of their analysis methods on real networks. 2) The experiments presented for real networks provide limited insight into the implementation issues, and experimental designs they followed for other practitioners to follow. In real water distribution networks (WDNs), the results might not same (Hamilton and Charalambous 2020). In real networks, there can be multiple leaks in the system at the same time, the pipe geometry can involve bends, valves, fittings, discontinuities, varying diameters, and corresponding line pressure depending on pipe functions, and differences in pipe material within the network. In this regard, Butterfield et al. (2018) investigated the effect of different pipe materials of a real WDN on the efficacy of sensors for cross-correlation of leak localization and results showed poor cross-correlation results for plastic pipes using vibration, unlike expectation. Therefore, it is important to apply the developed model to the WDN network.

The selection of leak detection techniques for real network testing is not straightforward. Various factors like life cycle cost, efficiency, time duration required for leak detection are involved in this decision-making. Additionally, every technology has associated advantages and limitations. For example, leak noise correlators have high accuracy but have high investment costs (Lai et al. 2016). Hydrophones can locate very difficult leaks but their installation in the field is difficult due to access issues (Khulief et al. 2012). Vibro-acoustic sensors like accelerometers result in very clear correlation results, however, they get affected by obstructions, and background noise (Brennan et al. 2019). Leak noise loggers prove to very effective but report the problem of false alarms (El-Abbasy et al. 2016). Hydrophones generally have a difficult deployment method and are considered invasive if they are directly inserted in water. On the contrary, accelerometers can be connected to the pipelines using duct tape or magnets and are thus considered non-invasive and convenient to use in the field. Accelerometers are not considered very efficient for leak detection in plastic pipes or conditions of low SNR whereas, hydrophones perform well for detecting small leaks, and leaks in plastic pipes.

To develop a best practice or optimized approach, hybrid solutions for leak detection may be of interest. Such hybrid approaches can be created in two ways: by mounting multiple sensors on the same device or by combining different sensors in the system during the data collection. Either way, compatible methods of analysis need to be developed. For example, from Equation 15, it should be noted that as the pressure and wall displacement are directly proportional, acceleration signals can be obtained by double differentiating the pressure signals from hydrophones (Gao et al. 2018). Thus, there is potential to combine the accelerometers with the hydrophones for leak detection and localization. Similarly, more comparative studies are encouraged to develop best practices framework. Such a framework can serve as a guiding tool for the selection of technology as per conditions. For example, Hamilton and Charalambous (2020) have developed a guide for practitioners for the selection of technology as per the pipe diameter, flow conditions, and pipe material. Based on such a framework, hybrid mechanisms for efficient long-term leak detection monitoring can be enabled in realtime.

6.3 Practical implications for the use of hydrophones

As limited real-time testing has been reported, the situations where hydrophones will be the best choice can not be recommended with certainty. Still, some reasonable deductions regarding their use can be made through literature as follows:

6.3.1 Frequency ranges, hydrophone type, and pipe material

Three hydrophone technologies have been reported in the literature: piezoelectric, fiber-optics, and MEMS. In earlier studies, mostly piezoelectric hydrophones were used which worked well for low-frequency signal ranges within the threshold range of 5-50 Hz. This made them effective for use in high attenuation conditions like that of plastic pipes or large diameter mains (Gao et al. 2005; Hunaidi and Chu 1999). Though this can serve as a good thumb rule, however, Guo et al. (2019) recently demonstrated their potential application for detecting high-frequency water leaks in metal pipes through fabrication technology improvements. They used a new custom fiber-optic hydrophone in their experiment. As fiber optics is a new technology, it is relatively expensive than other commercially available hydrophones. As an alternative, Xu et al. (2019) and Phua et al. (2020) have recommended the use of MEMS-based hydrophone which is low-cost, low-power, and smaller in size. It is easier to deploy than commercial piezoelectric hydrophones and is compatible with IoT technology. This implies that with certain innovations, the testing difficulties for the use of hydrophones in long-term leak detection systems may be overcome.

6.3.2 Detection, localization, or pinpointing

As shown in Fig. 4, most studies related to the use of hydrophones deal with either leak detection or localization, or both. There are very few studies dealing with the use of hydrophones for pinpointing a leak. The studies using a hydrophone for pinpointing use a free-swimming hydrophone. Also, some of the methods presented in Table 5 are limited to application for leak detection only. Further work on such machine learning-based methods for real networks should be demonstrated for the detection of both old and new leaks.

6.3.3 Experimentation Complexity and Variations

One of the main drawbacks of studies conducted on the subject is the lack of standardization of experiments. Many designs for experiments are available offering different flow and line pressure conditions, pipe geometries, and hydrophone types that exist in the literature. However, the consideration for pipe bends and discontinuities is rarely considered. The number of sensors that should be used for specific conditions is also vague. From the literature, it seems that for locating small or difficult leaks, a single swimming hydrophone can be used. For step surveys, the use of a typical two-sensor assembly looks plausible. However, for real scenarios like villages or small towns where two hydrants are not spaced within 100m distance of each other, what strategy should be adopted?

Additionally, whether the hydrophone can be fitted onto the hydrant/ valve, or be installed in the pipe with help of a tether will also affect the design. Such scenarios have not been considered while designing the experiments. Moreover, there is no guideline to choose the best design of the experiment for testing the use of hydrophones for leak detection. For this purpose, further review of experiments needs to be carried out to select appropriate conditions for testing. It is observed that none of the studies related their results with the sensor specifications, sensitivity, or directional abilities. To optimize the design, the impact of model selection needs to be considered. Moreover, most of the experiments use simulated leaks in the test-rig for testing the hydrophones. This is beneficial but results may differ for real leaks. A summary of the main findings of sections 4.4 and 5 is presented in Fig. 6.

6.3.4 Comparison of hydrophones with other sensors

As elaborated in section 5.1, hydrophones have been currently compared with accelerometers, geophones, pressure transducers, and PVDF wire sensors (Almeida et al. 2014; Gao et al. 2005; Khalifa et al. 2010; Sun et al. 2020). They have been reported to show either better or similar performance to these sensors. Hydrophones offer a significant advantage in being less prone to ambient noise and high attenuation due to in-pipe measurement producing high-quality data reducing chances of false alarms. Accelerometers and PVDF wire sensors, although non-invasive but can face serious issues in the real environment due to slippage, pipe bulging, and ambient noise. Hydrophones are not prone to such issues and offer high sensitivity to low-frequency data as compared to accelerometers and geophones. Accurate prediction of leak location, however, relies on wave speed. Wave speed estimate changes with temperature variations changing Young’s modulus of pipe material making the season during data collection relevant. The data collection for vibro-acoustic sensing devices are affected by ambient noise. This is a frequently identified drawback and overcome by taking data in low usage hours during the night or early morning. The process can be further automated using a data logger and cloud system with the hydrophone for efficient data transfer.

7 Conclusion

The current study conducts an in-depth review of hydrophone applications for water leak detection. Main research directions, gaps in the literature, and future directions of work were identified to aid practical implementation. Presently, the acoustical characteristics, pipe flow dynamics, and attenuation properties for various pipe materials and flow conditions for water leak detection have been studied for hydrophones. Hydrophones perform well for high attenuation conditions and have a long-range of leak detection. Additionally, they collect data directly from water, thus showing less sensitivity to background noise and reduced chances of false alarms. Hydrophones, however, face limitations for sensing high-frequency noise, or detecting leaks in metal pipes and should be combined with other approaches to enhance efficiency. Future work requires the development of hybrid approaches for multiple-sensing technologies. Further, the sophistication of experimental designs, real-world case studies, and new fabrication technologies like MEMS and fiber optics need to be tested for performance improvement.

Data Availability Statement

All data support the findings of this study are available from the corresponding author upon reasonable request.

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Figure Captions

Fig. 1. Research Methodology

Fig. 2. Year-wise Analysis

Fig. 3. Study types and scale of experiment for leak detection through hydrophones

Fig. 4. Study Focus w.r.t leak detection phases addressed in the publications

Fig. 5. Bibliographic Coupling of Shortlisted Publications

Fig. 6. Summary of main findings

Table 1. Most significant articles w.r.t. no. of citations and total link strength in Cluster 1

Rank	Most Significant Articles	No. of Citations
1	Hunaidi and Chu (1999)	149
2	Hunaidi et al. (2000)	124
3	Gao et al. (2004)	95
4	Gao et al. (2005)	91
5	Gao et al. (2006)	78

Table 2. Most significant articles w.r.t to total link strength in Cluster 1

Rank	Most Significant Articles	Total Link Strength
1	Gao et al. (2018)	220
2	Li et al. (2018)	161
3	Cody et al. (2020)	150
4	Butterfield et al. (2017)	146
4	Butterfield et al. (2018)	107
5	Ma et al. (2019)	107

Table 3. Most significant articles w.r.t. no. of citations in Cluster 2

Rank	Publications	Citations
1	Hunaidi and Chu (1999)	149
2	Hunaidi et al. (2000)	124
3	Gao et al. (2004)	95
4	Gao et al. (2005)	91
5	Gao et al. (2006)	78

Table 4 Most significant articles w.r.t. total link strength in Cluster 2

Rank	Publications	Total Link Strength
1	Almeida et al. (2015)	184
2	Gao et al. (2006)	172
3	Gao et al. (2009)	161
4	Brennan et al. (2019)	157
5	Gao et al. (2017)	149

Table 5. Methods for leak detection and localization/pinpointing application for hydrophones

Type	Method	Advantages	Limitations	References
Time Delay Estimation	Basic Cross-Correlation	i. Computationally simplistic approach ii. Less sensitivity for system resonance giving more robust results for time delay	Fundamental approach and pipe conditions like discontinuities and background noise can lead to errors. Thus, quiet conditions are required.	(Almeida et al. 2018; Gao et al. 2009)
	Generalized Cross-Correlation (GCC)	i. Applicable to multiple leak detection technologies. ii. Pre-filtering enhances the signal resolution, suppresses background noise, and sharpens the correlation function to make accurate detection of a leak.	i. Manual pre-processing is tedious. ii. Continuous data from two sources is required for long-term monitoring which proves expensive. ii. Variables and conditions need to be known a priori.	(Gao et al. 2017)
	GCC-PHAT Methods	The differentiation method can control resonance effects at low frequency for a more reliable TDE in real networks	May reduce the SNR limiting application to leak detection through hydrophones	(Gao et al. 2018)
	Generalized Phase Spectrum Methods (GPS)	i) No resolution problems like in GCC ii) Only phase spectrum information is required iii) Independent of sensor used for detection iv) No pre-filtering or pre-whitening efforts required in comparison to GCC v) The adaptive PHAT method based uses the least means square (LMS) algorithm also effective for low SNR.	Only considers the phase information of signals so can ignore the dispersion during leak noise propagation in a pipe	(Brennan et al. 2007; Ma et al. 2019)
Novelty Detection Methods	Basic Statistical Feature Analysis	Automated leak detection enabled for small diameter HDPE service pipes. In-pipe measurements can also be made for pinpointing using a swimming hydrophone.	i. Reliance on basis statistical features increases sensitivity for baseline conditions. ii. Applicability of identified features may not apply to real conditions. iii. Large scale application difficult due to tedious feature analysis for each location	(Khulief et al. 2012; Martini et al. 2017)
	Parametric	i. Potential for autonomous long term leak detection and localization ii. Applicable for complex pipe geometries iii. Can even detect small leaks	i. Multiple leaks and pipe backfill conditions cause significant deviations during real application ii. Depends on the minimum threshold selection iii. Historical data is required for training sets	(Cody et al. 2020)
	Non-Parametric	i. Completely data-driven ii. Computationally efficient iii. Early leak detection for small and difficult leaks	i. Limited to leak identification only ii. Can only detect new leaks	(Cody et al. 2020)

Figure Captions

Fig. 1. Research Methodology

Fig. 2. Year-wise Analysis

Fig. 3. Study types and scale of experiment for leak detection through hydrophones

Fig. 4. Study Focus w.r.t leak detection phases addressed in the publications

Fig. 5. Bibliographic Coupling of Shortlisted Publications

Fig. 6. Summary of main findings

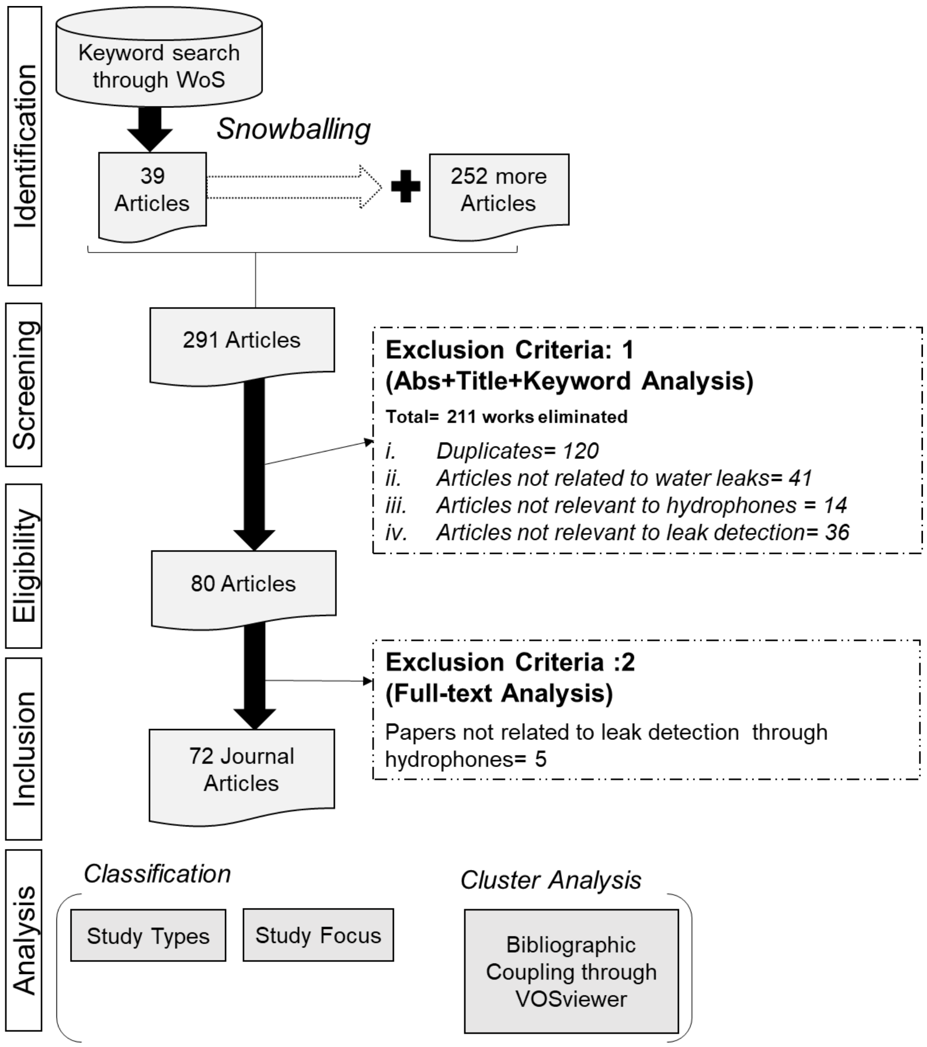

Fig. 1. Research Methodology

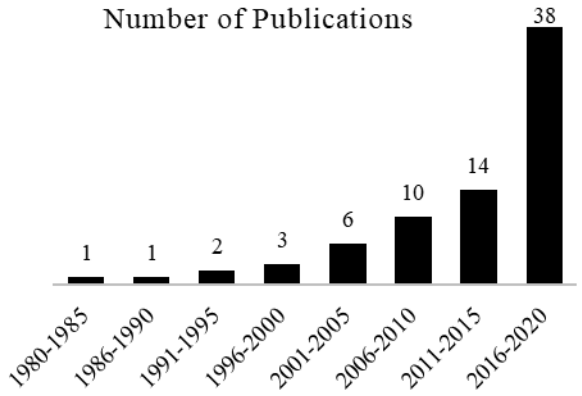

Fig. 2. Year-wise Analysis

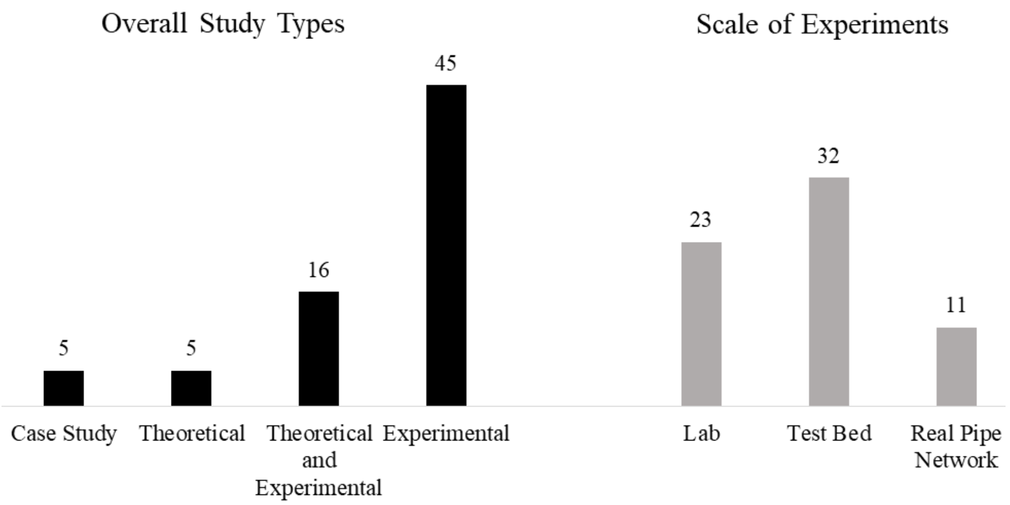

Fig. 3 Study types and scale of experiment for leak detection through hydrophones

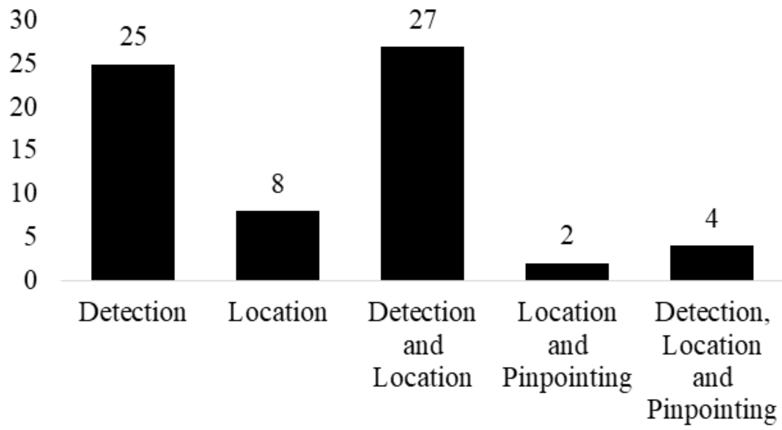

Fig. 4 Study Focus w.r.t leak detection phases addressed in the publications

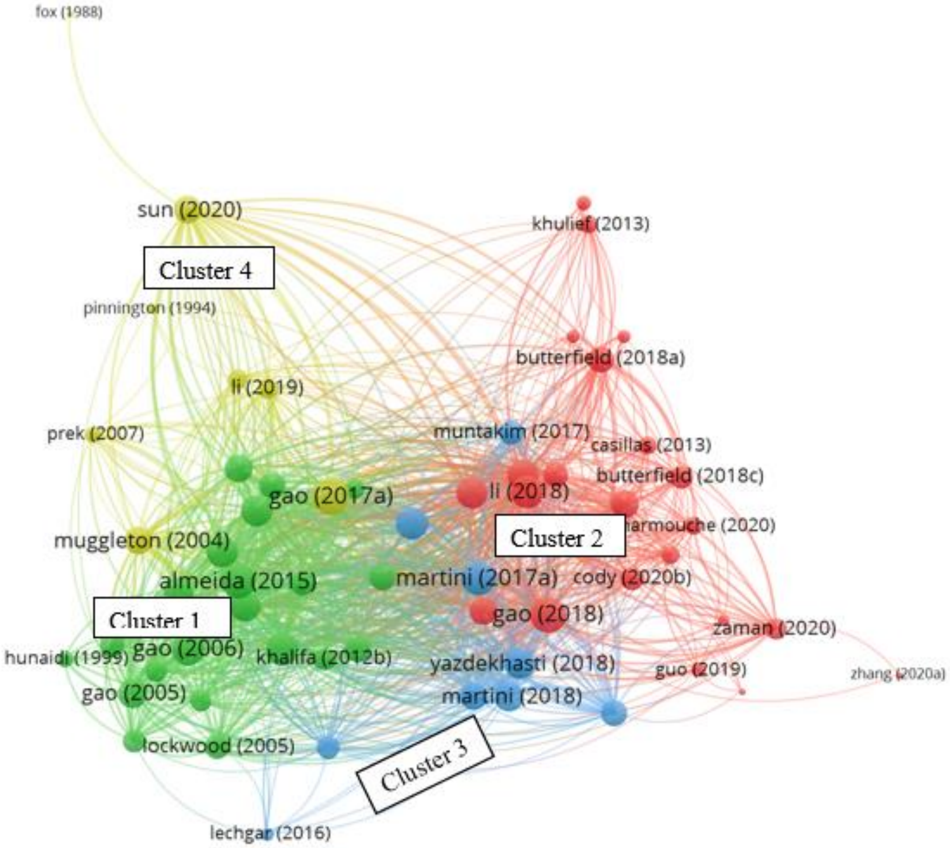

Fig. 5 Bibliographic Coupling of Shortlisted Publications

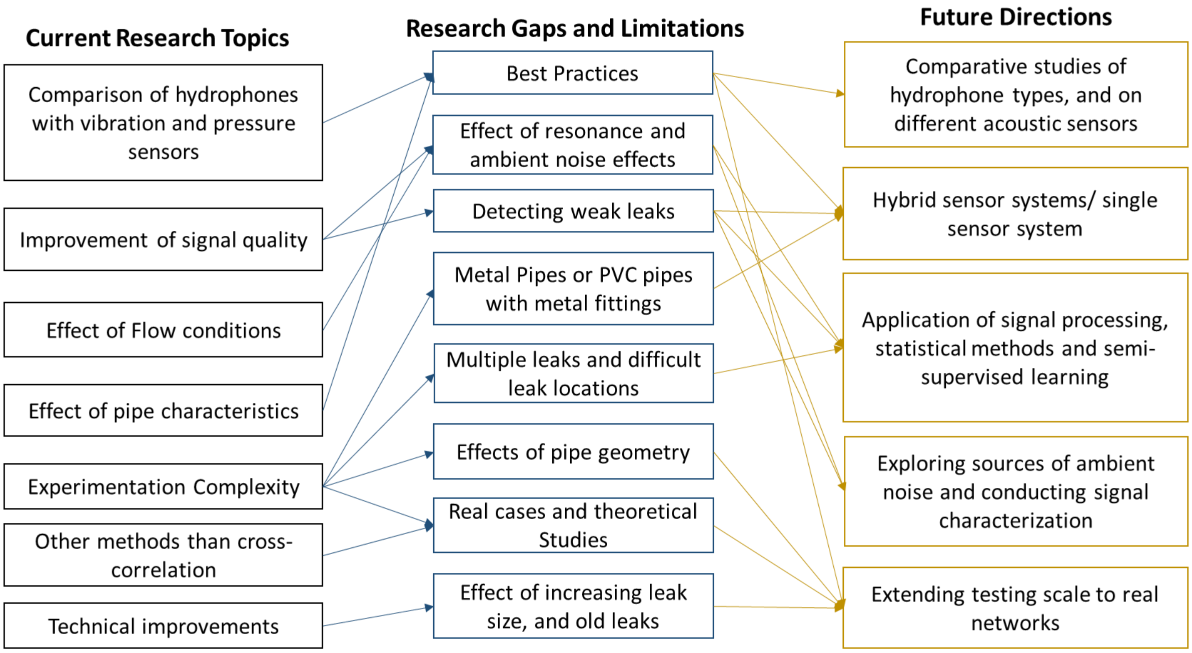

Fig. 6 Summary of main findings