WWW.IJRPR.COM

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Advancement in Underground Drinking Water Pipe Leak Detection: A Comprehensive Review and Recommendations.

M.N.H, Chikuruwo [a], S. John [b], M. Mutingi [b] M Chirasha [a], A Ditima [a]

[a] *Harare Institute of Technology, Zimbabwe.*
[b] *Namibia University of Science and Technology, Namibia.*

A B S T R A C T

Although the provision of clean water, sanitation, and hygiene is considered a basic human right, the presence of underground water pipe leaks presents substantial obstacles to ensuring access to clean water. This review paper aims to consolidate the methods used for detecting leaks in underground drinking water pipes and recommend the best leak detection strategy. The study explores sensor-less and sensor-based methods, including on-pipe and in-pipe sensors, as well as the use of artificial intelligence systems. Key findings indicate that sensor-based approaches, such as thermography infrared cameras, ground penetrating radar, and time-domain reflectometry, show promise in accurately detecting and locating leaks. Additionally, the integration of different sensor types and artificial intelligence algorithms can enhance leak detection accuracy. However, further advancements are needed to achieve real-time leak detection, localization, and control, ensuring timely attention to leaks and ensuring access to clean water for consumers. The review emphasizes the importance of addressing water losses and implementing effective maintenance strategies in water distribution networks.

Keywords: Leak detection, Pipe maintenance, Sensors, Underground pipe network, Water distribution.

1. Introduction

Nearly half of the people in the world did not access securely managed sanitation in 2020, and one in four individuals could not get safe water to drink. (World Health, 2020). According to William hope in 1892, all supplies of water have some unnecessary waste. Very few supplies exist whereby the saving of a significant portion of the waste does not result in economical advantage towards the water body. Water leaks are a global issue. Water businesses and customers around the world continue to be burdened by significant water loss levels within a distribution system. Water losses range from extremely low to unacceptably high (TAha, Sarojah, Fadhl, Mansour, & Maria, 2019). Leakages in well-maintained distribution systems, for instance, can be as low as 7% in the Netherlands while reaching up to 70% in underdeveloped nations (Beuken, Lavooij, A, & Schaap P, 2006). Since 2000, Canada has experienced close to 700 breaks in the water distribution mains and so as the United States every day, translating to above 6 billion Canadian dollars, (Fares & Zayed,2008). There is a severe water deficit that is getting worse every year in some of the developed countries (ALKadi, ALTuwaijri, & Abdullah, 2013). Because it results in severe fluid shortages, leakage generally attracts attention on a global scale (Puust, Kapelan, Savic, & Koppel, 2010). Water losses must be controlled, including by calculating actual losses and establishing reasonable loss levels and maintenance for the areas served, (Klosok-Bzan, Boguniewicz-Zablocka, Suda, EwelinaLukasiewicz, & Andres, 2021).

Public water systems with leaking pipelines fundamentally undermine the efficiency of water resources and increase pumping energy, (Avila, Francisco, Amparo, & Pérez-Sánchez, 2021). Estimated water loss from a small hole in a pipe of 6mm in diameter at 85.2psi of pressure is equal to 1800cubic metres per hour, or 1300 m3 cubic metres per month. Even though one of the goals of millennium development is to improve the poorest people's access to municipal services. Cities by their very nature spatially concentrate hundreds or millions of people's water needs into a small region, which by itself would put more strain on the limited freshwater resources close to the city center. (Howard & Bartram, 2003). (Bhagwan, 2009) Water main structural deterioration and failure are caused by a number of circumstances. (Rezaei H, 2015), claims that environmental factors, loading circumstances, material attributes, and pipe characteristics all play a role in water pipe failures. Additionally, water distribution network extensions were carried out without enough consultation, which led to major pressure problems, system head losses, low quality water supply installation workmanship, and unanticipated future demand. Real losses are caused by burst leaks from damaged pipes as well as background leaks, which are tiny breaches at storage tanks, pipe couplings, and fittings. Despite there being techniques of detecting leaks for a while, currently high tech methods have been developed. (Puust, Kapelan, Savic, & Koppel, 2010).

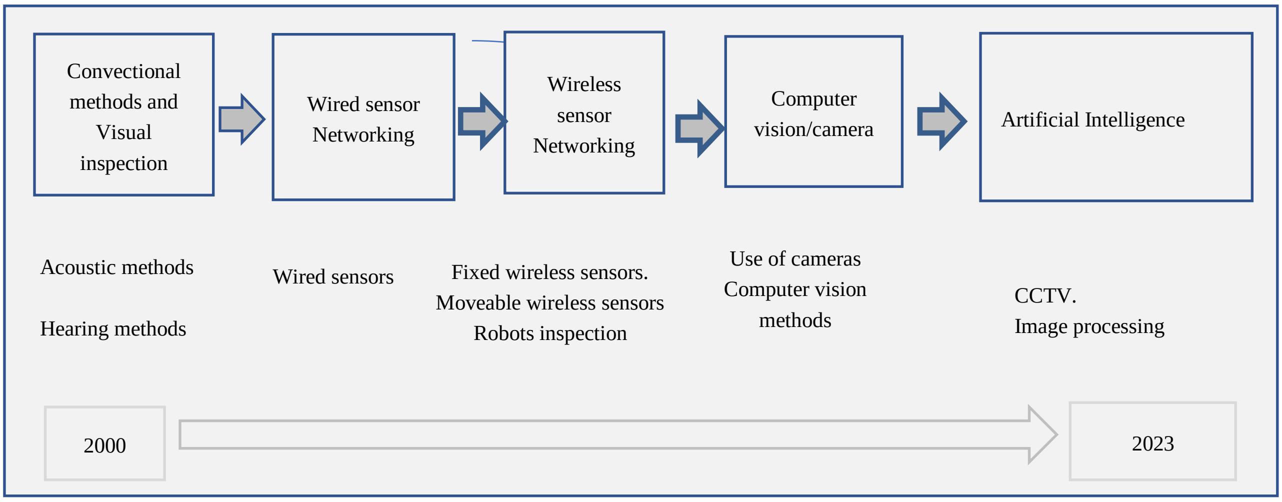

Fig 1: Graph showing historical technological advancements in underground pipe leak detecting techniques, (Ali & Choi, 2019).

Leak detection methods in the literature show that leaks can be detected through conventional methods and visual inspection methods, with sensors outside the pipes, with sensors inside the pipes and with a combination of sensors in pipes and outside the pipes. Fig 2 shows the number of papers reviewed and the period around which they were published.

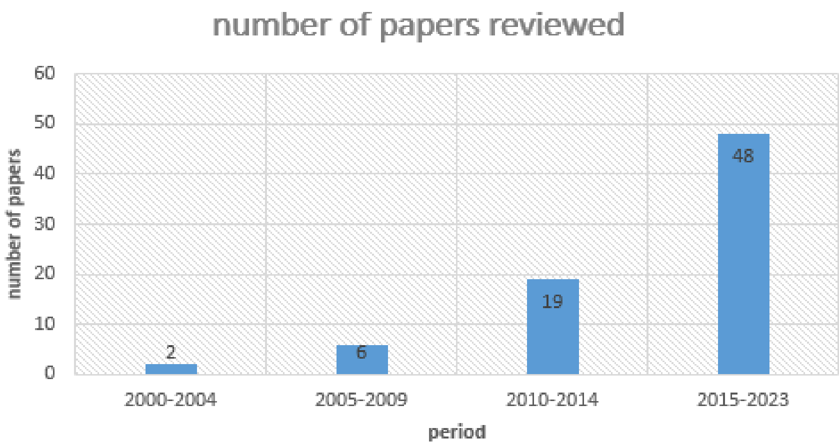

Fig 2: Graphical representation of papers used in the review

2. Methodological details

In the reviewed studies, various methodologies were employed to detect underground drinking water pipe leaks. To provide a more comprehensive understanding of the methodologies used, this paper aims to describe the experimental setups, data collection processes, and evaluation criteria employed by the researchers. Experimental setups varied among the studies, with some employing acoustic-based techniques, others utilizing ground-penetrating radar, and a few exploring the feasibility of infrared thermography. These setups involved the deployment of specialized equipment and sensors along the pipeline routes, allowing for the detection of leak-related signals or anomalies. Additional details such as sensor placement, calibration procedures, and signal processing techniques were also considered in the experimental design.

Regarding data collection processes, researchers typically recorded measurements at regular intervals or continuously monitored the pipeline network. These measurements encompassed parameters such as pressure, flow rate, temperature, and acoustic or electromagnetic signals. The collected data were then subjected to rigorous analysis, which involved various statistical and signal processing algorithms, to identify leak patterns and distinguish them from background noise or false positives. Evaluation criteria played a crucial role in assessing the effectiveness of the leak detection methods. Metrics such as detection accuracy, false positive rates, sensitivity, and specificity were commonly utilized to evaluate the performance of the methodologies. Additionally, some studies incorporated cost-effectiveness analysis and compared different techniques in terms of implementation costs, time required for detection, and ease of deployment. By presenting these methodological details, this paper aims to enhance the understanding of the approaches employed in detecting underground drinking water pipe leaks. The provided insights into experimental setups, data collection processes, and evaluation criteria will contribute to a more comprehensive evaluation and comparison of the reviewed studies, ultimately informing recommendations for effective leak detection methods."

3. Conventional pipeline Leak detection

Of all water losses experienced worldwide, leakage comes up on top of the list of reasons for water loss. Research has been carried out to curb water losses in underground pipelines without using sensors. Leak repair and pressure management have been discovered to be the main ways of reducing loses due to distribution although not fully utilised, (Amanda, Joakim, Ellen, Katrina, & Frank, 2022). Of the authors reviewed who detected leaks in pipelines conventionally, (Fahmy & Moselhi, 2009) developed a system that used thermography infrared camera (IR) to detect and locate leakages in underground pipes in 3 locations in greater Montreal area. Their work compared the ease with which thermography IR camera can detect and locate leaks in different environmental conditions. The thermography IR camera accuracy was found to be affected by camera settings, environmental conditions and the vehicle which carried the camera. Their research provided a way of investigating pipe condition in large areas effectively in a small time and can be used any time of the day. The researchers assumed that any point on the pipe has a potential of leaking. On contrary, (Wu, Sage, & Turtle, 2010), suggested that leakage hotspots exist at certain points which they identified and called nodes. Pressure dependent leakage detection method that optimized the leakage node locations using genetic algorithm were formulated. The model was tried on a trivial system and on an actual real water system in United Kingdom which was known for having a high volume of leakage records and served an area of more than 15km2 and about 3000 properties. The pressure dependent method was found to be effective for hydraulic conditions occurring very early in the morning high pressure is experienced in the morning because even though other daytime demands were lower. Lai, Chang, Sham, & Pang, (2016) used ground penetrating radar (GPR) perturbation patterns for leak detection in underground pipes which, unlike thermography infrared camera developed by (Wu, Sage, & Turtle, 2010). GPR was not dependent on the environmental conditions or time of day. These patterns of perturbation signal strength identified significant leaking points and the centrifugal wetting front vortex propagation based on the leaking points at injection times that were different. The GPR perturbation achieved leak detection and location by enabling a signature or fingerprint leaking water on metal and/or plastic pipes and propagation of the soaking front toward the desert sand. However, (Nguyen, Gong, Lambert, Zecchin, & Simpson, 2018) used signal excitation of pseudo random binary sequence (PRBS) together with time-domain IRF (impulse response function) to detect and localize leaks in pressurized water pipeline. A PRBS signal was found to have advantageous correlation properties over a step wave wave produced by a sole fast valve closure operation. The autocorrelation for other lags besides zero was minimal but slightly higher cross correlation with noise signals as well as other interferences, which led to a notable increase in the IRF signal to noise ratio (SNR), making precise for locating leaks. Both studies by Nguyen, Gong, Lambert, Zecchin, & Simpson, (2018) detected leaks in pressurised pipes, and their research was not dependent on the time of the day to be effective on leak detection.

Generally, thermography infrared cameras have shown promise in detecting and locating leaks, although their accuracy can be influenced by various factors. Pressure-dependent methods and ground penetrating radar (GPR) have also been effective in detecting leaks, with GPR offering advantages of independence from environmental conditions and time of day. Additionally, signal excitation techniques, such as the use of pseudo random binary sequences, have demonstrated improved leak detection and localization in pressurized pipelines. These non-sensor-based approaches provide valuable insights into leak detection and can be applied effectively regardless of the time of day.

4. Leak detection using sensors

Besides detecting leaks through sensor-less methods, leaks can also be detected with sensors outside or inside the pipes, or with a combination of sensors in and outside the pipes.

4.1 Leak detection using sensors on pipes

(Martini, Troncossi, & Rivola, 2017) developed an automatic leak detection system which used vibration measurements using a method that calculates the simple standard deviation from the raw signals coming from vibration sensors. Their research however was mainly centred on buried small diameter plastic pipes. Through trials, it was demonstrated that the algorithm they devised could deal with a variety of problems that could impair data, such as brief environmental perturbations or saturation effects. (Lakshmi & Gomathi, 2015) developed an alternative method of leak detection using various types of sensors linked through ZigBee technology. ZigBee technology allowed for wireless transmission of data over a 75-meter range to a distant base station. There was no need for calibration of sensors since the method was centred on change in pipe relative pressure, which suggests that sensors can be placed far apart. The proposed system, however, could not be implemented because of the need to utilize quick advancements in technology, instrumentation, interpretation, and communication. The pressure change in the profile of the pipe made it unnecessary to have the sensors calibrated. (Cataldo, et al., 2016) nonetheless, completed a real-world application of their time-domain reflectometry (TDR) centered leak detection method. In contrast to leak detection systems proposed by (Wu, Sage, & Turtle, 2010) and (Nguyen, Gong, Lambert, Zecchin, & Simpson, 2018), which only worked on pressurized pipes, the system was implemented in underground pipes and could function on different pipe material and also on pipes including low pressure pipes. The suggested TDR system is a potential option for leak detection in sewer systems and other low pressure systems since it can identify leaks on non-pressurized pipes. The TDR system circumvented many of the obstacles that often hinder the effectiveness of conventional leak detection systems, such as noise, pressure, and environmental factors, because it was based on electromagnetic (EM) waves rather than acoustic waves.

(Golsham, Ghavamian, & Abdulshaheed, 2016) conducted research on the use of lamb waves for detection and pinpointing leakage in water pipes. With active sensing technologies like Lead Zirconate Titanate (PZT) for synchronized actuation and guided wave sensing, their research identified defects over a wide area. To stop water leaks, Kumar and Jagadeep (2022) created a smart water pipeline monitoring system. In their system, a turbidity sensor and a water flow sensor were both employed in the pipeline to monitor water contamination. (Muhammad, Mohammad, Akil, Hasibul, & Samin, 2019), also used water flow sensor albeit their system using an Arduino UNO microcontroller. (Martini, Troncossi, & Rivola, 2017). On the other hand, a test bed was used to conduct an experimental campaign to examine the sensitivity of Acoustic Emission (AE) in monitoring leaking pipe. Pipe breaks were induced to a pipe made of polyethylene pipe at specified points in relation to acoustic emission transducer. They came to the conclusion that the soil surrounding the sensor and the pipe material significantly attenuated the AE signal, making it very hard to identify leaks even relatively close to the sensor. Nonetheless, experiments were done to establish how sensitive the Acoustic Emission (AE) monitoring were to water leaks. Damages were intentionally caused to a polyethylene pipe at various distances from the AE transducer. They came to the conclusion that the AE signal was significantly attenuated by the surrounding medium of earth and pipe material, making it difficult to identify leaks even when they were very close to the sensor. The effectiveness of the suggested strategy in terms of root mean square deviation (RM SD) and peak-to-average ratio (PAR) was demonstrated through field measurements carried out with a real-world leak detection system. The approach proposed by (Choi, Shin, Song, Han, & Park, 2017) may help to create a management system that is automated to gather data on leaks, alerts about the possibility of leaks, and provides information on leak localization. (Sadeghioon, Metje, Chapman, & Anthony, 2018) built a system that could use temperature data, distributed relative pressure monitoring, and anomaly detection algorithms to identify water pipeline breakdown. Water pipeline breakdown was discovered using relative pressure sensors that were fixed in combination with temperature readings of wall of the pipe and the soil.

Various non-sensor-based methods have been explored for leak detection in underground pipelines. These methods include vibration measurements, ZigBee technology for wireless transmission, time-domain reflectometry (TDR), lamb waves, and acoustic emission (AE) monitoring. Each method has shown potential in detecting leaks, but challenges such as environmental perturbations, calibration requirements, and attenuation of signals by surrounding soil and pipe material need to be addressed. Further advancements in instrumentation, technology, and data interpretation are necessary to develop effective and reliable automated leak detection and localization systems.

4.2 Leak detection using sensors in pipes

Although acoustic sensors have limits in terms of cost, sensitivity, reliability, and scalability, leaks in water pipes are known to produce acoustic secretions that can be detected by on-pipe sensors to locate and diagnose leaks. (Chatzigeorgio, YoucefToumi, Khalif, & Mansour, 2011) developed an in-pipe traveling leak detection system to get around these restrictions. The traveling sensor was seen to give distinct signals depending on whether water spilled into the soil, the air, or the water since it could make a louder sound in the soil and the water than in the air. To detect a leak acoustic signal, Wenming et al., (2021) developed a system for an in-pipe detector. The findings of their design showed that the intensity of the signal increases in the event of a leakage, as pressure in the pipe increases while the velocity of the flow had very little effect if any on the signal strength. An ANN model for prediction of leaks was created to increase the recognition exactness, and 18 cases were chosen through extra testing to evaluate the model's accuracy. Another study (Tianshu, Zhoumo, Xinjing, Jian, & Hao, 2021) developed a method for identifying pipeline leaks in spherical detectors based on fusing variational mode decomposition with support vector machines. Their study also involved efficiently training neural networks to detect leaks, with detection accuracy reaching up to 93% and a satisfying specificity of 89.6%. 3.3 Leak detection using both in and on pipe sensors.

(Sun, et al., 2011) contended that their magnetic-based induction wireless sensors, which they used to detect subsurface leaks, were unaffected by extreme climatic conditions. By combining the information from various sensor types that were placed in and around the underground pipes, their system discovered and pinpointed leakages. A wireless subterranean sensor network powered by magnetic induction was used to communicate the readings made by the exterior on pipe sensors. Additionally, the researchers employed pressure and acoustic sensors, which they placed in the pipes at checkpoints and pumping stations. Phase one of leak detection through the use of transient-based technique in the MISE-PIPE framework of operation, depended on the quantity and positions of sensors for pressure in the pipes, hence this method required sensors to be put close to one another.

The use of both in-pipe and on-pipe sensors shows promise in detecting and localizing leaks in water pipelines. Magnetic-based induction wireless sensors, in combination with pressure and acoustic sensors, have demonstrated effectiveness in detecting subsurface leaks regardless of extreme climatic conditions. Additionally, the fusion of variational mode decomposition with support vector machines and the application of artificial neural networks have shown potential in improving leak detection accuracy. Further research is needed to optimize sensor placement and enhance the scalability, reliability, and cost-effectiveness of these leak detection systems.

5. Artificial intelligent (AI) systems for leak detection

Artificial intelligence systems are now widely researched on for leak detection and localization of various industries including underground water pipes. Artificial intelligent algorithms can analyse large amount of data from sensors to enable leak detection. Some of the AI method used for leak detection are:

5.1 Artificial Neural Networks

Artificial intelligence (AI) can be defined as the study, creation, and design of intelligent agents. John McCarthy, who first used the phrase in 1956, describes AI as the engineering and science of creating intelligent machines. Artificial neural networks (ANN) are among the most significant methods for leak identification and location. Mounce & Machell, (2006) used data from water infrastructure to build a burst detection system by incorporating artificial neural networks. To categorize time series patterns from the perspective of locating leaks, two neural architectures time delay and static were used in their creation. Static ANNs had leaks and bursts that could be learned and so was time delay, even though the time delay network outperformed the static network. Ignacio, Luis, Rueben, and Adriana, (2009) proposed a method based on ANN for diagnosis and detection of leaks by identifying the pattern of flow using only the intake and output flow. For the purposes of developing, evaluating, and validating a system based on ANN, a nonlinear mathematical pipeline model was used. Li, et al., (2016) employed a four layered deep neural network with four layers to train on sound inputs and learn how to identify minor breaches quickly. However, the technique was utilized for a gas pipeline in the production of semiconductors. In 2017, Li, Song, and Zhou conducted an experimental investigation on employing back propagation algorithm for leak detection in WDS. However, their research was restricted to the identification of leaks vulnerable to socket joint failure. Although all of the aforementioned authors employed ANN to their desired ends, it was not without faults. Hardware dependence, unexplained network behavior, and the challenge of communicating an issue to the network were noted by (Mijwel, 2018) as some of the application of ANN's significant drawbacks. Na et al., (2018) created an adaptive leak detection approach that merged BP neural network with generalized cross correlation to address the drawbacks. The technology was able to distinguish leak signals from noise and other acoustic sources that weren't leaks. It also enhanced the localization of leaks.

Artificial neural networks (ANN) have proven to be a significant method for leak identification and location in various applications. However, challenges such as hardware dependence, unexplained network behavior, and communication issues need to be addressed for the effective implementation of ANN-based leak detection systems. The integration of ANN with other techniques, such as the generalized cross-correlation, shows promise in overcoming these limitations and improving the accuracy and localization of leak detection. Further research and development are necessary to enhance the reliability and practicality of ANN-based leak detection approaches.

5.2 Fuzzy logic

A form of thinking that closely matches human reasoning is fuzzy logic (FL). Fuzzy logic control is a type of expert control, knowledge-based control, or intelligent control. As an assessment and prediction tool, fuzzy sets were used by, Mamlook & Jayyousi, (2003). Fuzzy logic (FL) is a way of thinking that closely resembles human reasoning Yin & Huang, (2015) created a system that used fault line and fuzzy positivistic C-means clustering to anticipate faults. However, to predict water loss in subterranean pipes, (Birek, Petrovic, & Boylan, 2014) used evolving Takagi-Sugeno (eTS) algorithms, a fuzzy method. A recursive variant of the subtractive method is the eTS algorithm. On the other hand, an artificial neural fuzzy system was used by Wachla, Przystalka, & Moczulski, (2015) to design leak localisation method in water pipe networks. To pinpoint the precise site of leakages, a collection of neural fuzzy classifiers was applied. Aydogdu & Firat, (2014) also created a system that projected the failure rate of water networks and used fuzzy logic to determine the relationship between the components that affect failure rates. Besides using FL for condition monitoring, (Hernandez & Hidalgo, 2020) implemented FL in organizational management. In order to accurately locate leaks in water distribution, a fuzzy neural network which invvolves fuzzy production rule system was used for rapid identification of water pipe gusts by (Katasev & Kataseva, 2016). For ensuring that the performance of a sytem is not degraded and that required points are reached in spite of faults and disturbance, Patel & Shah, (2018) developed a fault tolerant control strategy with a proportional integral controller centred on Fuzzy logic. Mazzoleni, et al., (2022) monitored industry 4.0 manufacturing process by through the use of fuzzy logic. In conclusion approaches based on fuzzy logic is applicable in monitoring pipe condition and fault detection of a system, (Suganthi j, 2018). It allows modelling of complex dynamic systems in a more intuitive way and has an aptitude to deal with nonlinearities and uncertainties in systems.

The use of fuzzy logic in conjunction with other techniques, such as fuzzy neural networks and fuzzy production rule systems, has shown promise in accurately locating leaks, anticipating faults, and achieving fault-tolerant control. The intuitive nature of fuzzy logic allows for a closer resemblance to human reasoning, making it a useful tool for assessment, prediction, and decision-making in diverse domains.

5.3 Genetic algorithm (GA).

Search heuristics called genetic algorithms (GA) mimic the course of ordinary evolution. They create a search algorithm with some of the charm of human search by combining survival of the fittest among string structures with a structured yet random information exchange. They also use fuzzy logic in determining the correlation of failure factors. (Datta, Garai and Das, 2012). Genetic algorithms were used by various researchers in engineering to dignose faults and for condition monitoring. Cerrada, Zuirita. Cabrera, Sanchez, Artes and Li (2015) developed a system that used Genetic algorithm and a classifier in a supervised environment to diagnose faults in spur gears. Lu, Yan and de Silva (2015) also used GA to diagnose faults of rotor-unbalance vibration and bearing corrosion even though the used GA in conjunction with an empirical mode decomposition strategy. A research which used MapReduce based Parallel Niche Genetic Algorithm (MR-PNGA) in water quality monitoring and at the same time detect pollution was developed by (Hu, Zhao, Yan, Zeng, & Guo, 2015) combined GA and support vector machine (GA-SVM), to provide a way for on line monitoring voltage instability. They effectively use historical data to make predictions about potential new search areas with enhanced performance. The combination of GA with other techniques, such as fuzzy logic and support vector machines, enhances their capabilities and provides efficient solutions for online monitoring and prediction tasks.

6. Leak localization

Successfully locating leaking points is important in reducing the effects of leaks in underground water pipes and to that effect, Mashford, De Silva, Marney, & Burn, (2009) used support vector machine to predict leak size and locate leaks with reasonable accuracy. Beuken, Lavooij, A, & Schaap P, (2006). Candelieri, Soldi, Conti, & Archetti, (2014) also used support vector machines together with spectral clustering to manage and localize leakages. Srirangarajan, et al., (2013) created a wavelet-based method for locating and detecting burst events in water delivery systems. Their solution included a localization algorithm that utilized the onset time of pressure transient at multiple measurement locations in water pipelines so as to locate the exact location of the pipe break. Casillas, Garza-Castanon, & Puig, (2015) developed a technique to place sensor to enable localizing leaks in WDNS using leak signature space (LSS) approach. This approach depended on changing the residual vector, which was discovered by contrasting pressure data with estimates made by a hydraulic model. (Cugueró-Escofet, Puig, Quevedo, & Blesa., 2015) provided additional support for the sensor placement strategy. Through the use of a relaxed isolation index and the best pressure sensor placement, they successfully identified and localized leaks. Ristik, Bugaronovic, Virtunski, Govedarica, and Petrovacki (2017) combined ground penetrating radar (GPR) technology with thermal imaging for pinpointing the site of leakages. Their method provided a fast and inexpensive way of leak detection and localisation. The method was however developed for a district heating network. Moors, Scholten, van der Hoek, & Besten, (2018) developed a factorized distribution, which enabled the allocation of demand comparably throughout nodes of consumption based on specific data, and a matching distribution, which equally allocates demand throughout all consumption nodes. As a first step toward smart cities, Rojek & Studzinski, (2019) created a method for leak identification and leak localisation using neural network multi-layer perceptron and Kohonen neural network. The method was created using the geographic information system, the supervisory control and data acquisition (SCADA) system, and a hydraulic model of the water supply network.

Support vector machines (SVM) have proven to be effective in predicting leak size and locating leaks accurately. Additionally, methods combining SVM with spectral clustering, wavelet-based algorithms, and sensor placement strategies have been developed to manage and localize leakages in water distribution networks. The integration of technologies such as ground penetrating radar (GPR) and thermal imaging has provided fast and cost-effective solutions for pinpointing leak sites, although some of these methods were developed for specific network types, such as district heating networks.

7. Discussion of Challenges

While the reviewed studies present promising methods for detecting underground drinking water pipe leaks, it is important to address the challenges that can affect the performance and practical implementation of these techniques. The challenges in underground drinking water pipe leak detection include the high prevalence of water leaks globally, ranging from low to unacceptably high levels of water loss; the need for effective maintenance strategies and leak repair to reduce water losses; the complexity of detecting leaks in underground pipes due to various environmental conditions and pipe characteristics; limitations of conventional leak detection methods and visual inspection techniques; the need for advanced sensor-based approaches and integration of different sensor types; the requirement for accurate and real-time leak detection, localization, and control; and the importance of addressing water losses to ensure access to clean water for consumers.

8. Conclusion

In conclusion, underground drinking water pipe leak detection poses significant challenges due to the widespread occurrence of water leaks, the need for efficient maintenance and repair strategies, the complexities of detecting leaks in underground pipes, limitations of conventional methods, and the demand for advanced sensor-based approaches. Overcoming these challenges is crucial to reduce water losses, ensure access to clean water, and enhance the sustainability of water distribution systems. Continued research and development efforts in improving leak detection technologies, integrating multiple sensor types, and enabling real-time and accurate leak detection and localization will be essential for addressing this global issue and optimizing water management practices.

References

Ali, h., & Choi, J.-h. (2019). A Review of Underground Pipeline Leakage and Sinkhole Monitoring Methods Based on Wireless Sensor Networking . Sustainability 11(15), 4007.

ALKadi, T., ALTuwaijri, Z., & Abdullah, A. (2013). Wireless Sensor Networks for Leakage Detection in Underground Pipelines: A Survey Paper. Procedia Computer Science 21 (pp. 491 – 498). Elsevier.

Amanda, R., Joakim, W., Ellen, B., Katrina, J., & Frank, L. (2022). Untapped potential: leak reduction is the most cost-effective. Environmental Research Letters.

Avila, M., Francisco, R., Amparo, J., & Pérez-Sánchez, M. (2021). Leakage Management and Pipe System Efficiency. Its Influence in the Improvement of the Efficiency Indexes. Water.

Aydogdu, M., & Firat, M. (2014). Estimation of Failure Rate in Water Distribution Network Using Fuzzy Clustering and LS-SVM Methods. Water Resource Management.

BenSaleh, M., Manzoor, Q. S., Obeid Abdulaziz, M., & Alberto, G.-O. (2013). A Review on Wireless Sensor Network for Water Pipeline Monitoring Applications. IEEE.

Beuken, R., Lavooij, C., A, B., & Schaap P, G. (2006). Low Leakage in the Netherlands Confirmed. Conference: Eighth Annual Water Distribution Systems Analysis Symposium (WDSA) (pp. 1-8). Cincinnati, USA: (ASCE).

Bhagwan, J. (2009). A Compedium of best practices asset management. Global Water Research Coalition.

Birek, l., Petrovic, D., & Boylan, J. (2014). Water leak forecasting: The application of a modified fuzzy evolving algorithm. Applied Soft Computin Journal, Volume 14 (Part B), 305-315.

Candelieri, A., Soldi, D., Conti, D., & Archetti, F. (2014). Analytical Leakages Localization in Water Distribution Networks Through Spectral Clustering and Support Vector MACHINES.The Icewater Approach. 16th Conference on Water Distribution System Analysis, WDSA 2014, 1080-1088.

Casillas, M. V., garza-Castanon, l. E., & Puig., V. (2015). Sensor Placement for Leak Location in Water Distribution Networks using the Leak Signature . IFAC-PapersOnLine 48(21, 214-219.

Cataldo, A., Benedetto, E., Cannazza, G., Musciullo, A., Giaquinto, N., G, D., . . . Mirraglia, D. (2016). Recent advances in the TDR-based leak detection system for pipeline inspection. Elsevier, 09-017.

Chabn, F., Taleb, R., A, & Benbouali, M. B. (2016). The Application of Fuzzy Control in Water Tank Level Using Arduino. (IJACSA) International Journal of Advanced Computer Science and Applications Vol. 7, No. 4,, 261-265.

Chatzigeorgio, D., YoucefToumi, K., Khalif, A. E., & Mansour. (2011). ANALYSIS AND DESIGN OF AN IN-PIPE SYSTEM FOR WATER LEAK DETECTION. Proceedings of the ASME 2011 International Design Engineering Technical Conferences &Computers and Information in Engineering Conference. Washington, DC, USA: ASME.

Chen, Z., Zhang, X., Wang, X., Liu, R., & Xue, A. (2017). Leakage Point Algorithm Based on Generalized Mutual Correlation in Underground Water Pipeline. Proceedings of science. Shanghai, China.

Choi, J., Shin, J., Song, C., Han, S., & Park, D. (2017). Leak Detection and Location ofWater Pipes Using Vibration Sensors and Modified ML Prefilter. Sensors.

Cobacho, R., Arregui, F., Soriano, J., & Cabrera, E. (2015). Including leakage in network models: an application to calibrate leak valves in EPANET. Journal of Water Supply: Research and Technology—AQUA |, 130-138.

Colombo, A. F., & Karney B, W. M. (2002). Energy and Costs of Leaky Pipes:. JOURNAL OF WATER RESOURCES PLANNING AND MANAGEMENT, 441-450.

Cugueró-Escofet, M. A., Puig, V., Quevedo, J., & Blesa., J. (2015). Optimal Pressure Sensor Placement for Leak Localisation Using a Relaxed Isolation Index: Application to the Barcelona Water Network. IFAC-PapersOnLine Volume 48, Issue 21,, 1108-1113.

Dong, H., Jin, X., Lou, Y., & Wang, C. (2014). Lithium-ion battery state of health monitoring and remaining useful life prediction based on support vector regression-particle filter. Journal of Power Sources 271, 114-123.

Fahmy, M., & Moselhi, M. (2009). Detecting and locating leaks in Underground Water Mains Using Thermography. 26th International Symposium on Automation and Robotics in Construction (ISARC).

Fares, T., & Zayed. (2008). “Hierarchical fuzzy Expert System for Risk of Failure of Water Mains.”. Journal of Pipeline Systems Engineering and Practice,, 53 – 62.

Fayaz, M., Ahmad, S., IUllah, I., & Kim, D. (2018). A Blended Risk Index Modeling and Visualization Based on Hierarchical Fuzzy Logic for Water Supply Pipelines Assessment and Management. Processes 6, , 1-21.

Golsham, M., Ghavamian, A., & Abdulshaheed, A. M. (2016). Pipeline monitoring system by using wireless waves. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), 43-53.

Guo, L., Li, N., Jia, F., Lei, Y., & Lin, J. (2017). A recurrent neural network based health indicator for remaining useful life prediction of bearings. Neurocomputing.

Gupta, A., & Kulat, K. (2018). A Selective Literature Review on Leak Management. Water Resource Management, 3247–3269.

Hernandez, A., & Hidalgo, D. (2020). Fuzzy Logic in Bussssiness and Management. Open Journal for Bussiness and Management, 2524-2544.

Herzallah, R., & Abdulla, M. (2013). Pipeline leak detection using artificial neural network: Experimental study. Research Gate.

Hope, W. (1892). The waste of water in public supplies, and its prevention. Minutes of the Proceedings, 110, 260–275.

Howard, J., & Bartram, G. (2003). Domestic Water Quantity,. Geneva, Switzerland: World Health Organization.

Hu, C., Zhao, J., Yan, Z., Zeng, D., & Guo, S. (2015). A MapReduce based Parallel Niche Genetic Algorithm for Contaminant Source Identification in Water Distribution Network. Ad hoc Networks, 116-126.

Ignacio, B., Luis, C., Rueben, M., & Adriana, M. (2009). Leaks Detection in a pipeline Using Artificial Neural Networks. Iberoamerican Congress on pattern Recognition., 636-644.

Jia, F., Lei, Y., Lin, J., Zhou, & XLu, N. (2015). Deep neuralnetworks:Apromisingtoolforfaultcharacteristic mining andintelligentdiagnosisofrotatingmachinery with massivedata. MechanicalSystemsandSignalProcessing.

Katasev, A., & Kataseva, D. (2016). Expert diagnostic system of water pipes Gusts in Reservoir Pressure Maintenance Processes. 2nd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), 1322-1327.

Katasev, A., Kataseva, D., & Yu, L. (2016). Neuro-fuzzy Model of Complex Objects Approximation with discrete Output (ICIEAM). 2nd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), 1-5.

Ki-moon, Bokova, I., Jarraud, M., & Miletto, M. (2015). Water for a sustainable world. France: United Nations Educational, Scientific and Cultural.

Klosok-Bzan, I., Boguniewicz-Zablocka, J., Suda, a., EwelinaLukasiewicz, & Andres, D. (2021). Assessment of leakage management in small water supplies using performance indicators. Environmental Science and Pollution Research, 41181–41190.

Lai, W., Chang, R., Sham, J., & Pang, K. (2016). Perturbation mapping of water leak in buried water pipes via laboratory. Tunnelling and Underground Space Technology 52 (2016), 157–167.

Lakshmi, V., & Gomathi, J. (2015). An Enhanced underground Pipeline Water leakage monitoring and Detection System using Wireless Sensor Network. International Conference on Soft-Computing and Network Security. Coimbatore: IEEE.

Lee, H., Chung, K.-Y., & Jhang, K.-S. (2013). A Study of Wireless Sensor Network Routing Protocols for Maintenance Access Hatch Condition Surveillance. J Inf Process Syst, Vol.9, No.2,.

Lei, Y., Li, N., Gontarz, S., Radkowski, S., & Dybala, J. (2016). A Model-Based Method for Remaining Useful Life Prediction of Machinery. IEEE TRANSACTIONS ON RELIABILITY.

Li, J., Fan, X., Chen, G., Gao, Z., Chen, M., & li., L. (2016). A DNN for Small Leakage Detection of Positive Pressure Gas Pipelines in the Semiconductor Manufacturing. Proceedings of ICOACS, 384-388.

Li, N., Lei, Y., Lin, J., & Ding, S. X. (2015). An Improved Exponential Model for Predicting Remaining Useful Life of Rolling Element Bearings. IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS.

Liao, L. (2013). Discovering Prognostic Features Using Genetic Programming in Remaining Useful Life Prediction. IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 61, NO. 5,.

Liao, L., & F, K. (2014). Review of Hybrid Prognostics Approaches for Remaining Useful Life Prediction of Engineered Systems, and an Application to Battery Life Prediction. IEEE TRANSACTIONS ON RELIABILITY, VOL. 63, NO. 1,.

Lim, j., Kim, J., Friedman, J., Lee, L., Viera, L., Rosso, D., . . . Srivasta, M. (2011). SewerSnort: A drifting sensor for in situ Wastewater Collection System gas monitoring. Elsevier, 1456–1471.

Mamlook, R., & Jayyousi, O. (2003). Fuzzy sets for leak detection in infrastructure systems: A proposed methodology. Clean Tech Environ Policy 6, 26-31.

Manzungu, M., & Collin, E. (2004). 'Status of Water Governance in Urban Areas in Zimbabwe: Some Preliminary Observations from the City of Harare'. Physics and Chemistry of the Earth 29, 1167-1172.

Martini, A., Troncossi, M., & Rivola, A. (2017). Leak Detection in Water-Filled Small-Diameter Polyethylene Pipes by Means of Acoustic Emission Measurements. Applied Sciences.

Mashford, J., De Silva, D., Marney, D., & Burn, S. (2009). An approach to leak detection in pipe networks using analysis of monitored. 3rd International.

Mazzoleni, M., Sarda, K., Acernese, A., Russo, L., Manfredi, L., Glielmo, L., & Vecchio, C. D. (2022). A fuzzy logic-based approach for fault diagnosis and condition monitoring of industry 4.0 manufacturing processes. Elsevier: Engineering Applications of Artificial Intelligence.

Mekid, S., Wu, D., Hussain, R., & Youcef-Toumi, K. (2017). Channel modeling and testing of wireless transmission for underground in-pipe leak and material loss detection. International Journal of Distributed.

Mijwel, M. (2018). Artificial Neural Networks Advantages and Disadvantages. Research Gate.

Moors, J., Scholten, L., van der Hoek, J., & Besten, J. (2018). Automated leak localization performance without detailed demand distribution data. Urban Water Journal 15:2, 116-123,.

Mounce, S., & Machell, J. (2006). Burst detection using hydraulic data from water distribution systems with artificial neural networks. Urban Water Journal, 3:1,, 21-31.

Muhammad, U., Mohammad, H., Akil, a., Hasibul, S., & Samin, Y. (2019). Leakage Detection in Water Pipeline Using Micro-. 1st International Conference on Advances in Science, Engineering and Robotics Technology.

Na, S., Liu, J., Li, Q., Liu, Y., & Ti, Y. (2018). An adaptive method for water pipeline leak localization. Advances in Engineering Research, volume 173, 146-153.

Na, S., Liu, J., Li, Q., Liu, Y., & Tie, Y. (2018). An adaptive method for water pipeline leak localization. Advances in Engineering Research, volume 173, 1-8.

Nguyen, N., Gong, J., Lambert, M., Zecchin, A., & Simpson, A. (2018). Least squares deconvolution for leak detection with a pseudo. Mechanical Systems and Signal Processing 99 (2018), 846–858.

Patel, H., & Shah, V. (2018). Fuzzy logic based passive fault tolerant control strategy for a single-tank system with system fault and process disturbances. 5th International Conference on Electrical and Electronic Engineering (ICEEE), 257-262,.

Puust, R., Kapelan, Z., Savic, D. A., & Koppel, T. (2010). A review of methods for leakage management in pipe. Urban Water Journal 7:1,, 25-45,.

Qian, Y., & Ruqiang. (2015). Remaining Useful Life Prediction of Rolling Bearings Using an Enhanced Particle Filter. IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT.

Rahmat R, S. I. (2017). Water Pipeline Monitoring and Leak Detection using Flow Liquid Meter Sensor. IOP Conference Series: Materials Science and Engineering (Vol. 190, No. 1), 012-036.

Rein L, C. J. (2017). Multi-bearing RUL collaborative prediction: A deep Learning Approach.

Rezaei H, R. B. (2015). Pipe failure analysis and impact of dynamic hydraulic conditions water supply networks. 13th Computer Control for Water Industry Conference, CCWI 2015 (pp. 253 – 262). Coventry CV1 2LZ, United Kingdom: Elsevier.

Rojek, I., & Studzinski, J. (2019). Detection and Localization ofWater Leaks in Water Nets Supported by an ICT System with Artificial Intelligence Methods as aWay Forward for Smart Cities . Sustainability , 518-531.

Rostek, K., Morytko, L., & Jankowska, A. (2015). Early detection and prediction of leaks in fluidized-bed boilers using artificial neural networks. Energy, 1-10.

Sadeghioon, A., Metje, N., Chapman, D., & Anthony, C. (2018). Water pipeline failure detection using distributed relative pressure and temperature measurements and anomaly detection algorithms. Urban Water Journal, Vol. 15, No. 4,, 287–295.

Sanz, G., Perez, R., & Escobet, A. (2012). Leakage location in water networks using Fuzzy Logic. 20Th Mediterranean conference on control and automation (MED), 646-651.

Srirangarajan, S., Allen, M., Preis, A., Iqbal, M., lim, H. B., & Whittle., A. J. (2013). Wavelet-based Burst Event Detection and Localization in Water Distribution Systems. Journal of Signal Processing Systems, 1-16.

Suganthi j, N. G. (2018). Fuzzy Logic Based Coolant Leak Detection. International Journal of Pure and Applied Mathematics, Volume 118 , 825-832.

Sun, Z., Wang, P., Vurn, M., AlRodhaan, P., AlDhelaan, M., & Akyildiz, I. (2011). MISE-PIPE: Magnetic induction-based wireless sensor networks for underground pipeline monitoring. Elsevier, 218-227.

TAha, A.-W., Sarojah, S., Fadhl, A.-N., Mansour, H., & Maria, K. (2019). Monitoring Non Revenue Water Performance in Intermittent Supply. Water.

Tianshu, X., Zhoumo, Z., Xinjing, H., Jian, L., & Hao, F. (2021). Pipeline leak detection based on variational mode decomposition and support vector machine using an interior spherical detector. Process Safety and Environmental Protection, Volume 153,, 167-177.

(2009). Urban Water Security Research Alliance.

van der Walt, J., Heyns, P., & Wilke, D. (2018). Pipe network leak detection: Comparison between statistical and machine learning techniques. Pretoria: Center of Asset Integrity Management.

Wachla, D., Przystalka, P., & Moczulski, W. (2015). A Method of Leakage Location in Water Distribution Networks using Artificial Neuro-Fuzzy System. International Federation of Automatic Control PapersOnLine 48-21 , 1216–1223.

Wambui, G. (2013). FACTORS INFLUENCING REVENUE GENERATION AMONG. Nairobi.

Wenming, W., Haibo, S., Jianqiang, G., Liyun, L., Shide, W., & Jifeng, Z. (2021). Experimental study on water pipeline leak using In-Pipe acoustic signal analysis and artificial neural network prediction. Measurement, Volume 18.

WHO. (2010). Progress on Sanitation and Drinking-Water. Geneva, Switzerland.: World Health Organization and UNICEF,.

World Health, O. (2020). Billions of people will lack access to safe water, sanitation and hygiene in 2030 unless progress quadruples – warn WHO, UNICEF. New York: World Health Organisation.

Wu, Z., Sage, P., & Turtle, D. (2010). Pressure-Dependent Leak Detection Model and Its Application to a District Water System. JOURNAL OF WATER RESOURCES PLANNING AND MANAGEMENT, 116-128.

Yin, S., & Huang, Z. (2015). Performance Monitoring for Vehicle Suspension System via Fuzzy Positivistic C-Means Clustering Based on Accelerometer Measurements. IEEE/ASME Transactions on Mechatronics, 2613-2620