University of Ibadan
Journal of Science and Logics in ICT Research

A Systematic Review of Computational Approach to Pipeline Leakage Detection in a Water Distribution Network

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Abstract

The detection and localization of leakages in water distribution networks is crucial for both the conservation of resources and the efficient operation. The process network has proved to be a difficult task over years, considering the complexities inherent in water distribution networks. The enormous interconnected pipelines make the leakage detection and location process burdensome. Computational techniques play a significant role in this domain by offering advanced tools and techniques for leakage detection. This study, therefore, performed a systematic review of published articles on computational leakage detection and localization in a water distribution network. Findings show the number of recent quality studies on the computational approach to water distribution network leakage research is beginning to dwindle, considering the journal's impact factor. In the recent studies, a deep learning algorithm is beginning to trend as the most significant computational technique, as it accounts for 13.21 % (n=7) of the pipeline leakage research output. The univariable predicated studies account for 83.33%of the research output disseminated in the past five years. The invention of various efficient learning methods and network structures in deep learning algorithms makes it suitable for the realization of multi-disciplinary studies, as the multi-variable concept will reduce false positives and negatives, enhancing the overall reliability of leak detection and localization models in future studies.

Keywords: *Deep learning, Water distribution network, Systematic review, Pipeline leakage detection and localization*

1. Introduction

Water is one of the most precious and indispensable resources on our planet, efficient distribution of water is essential for the survival and well-being of all living organisms [1]. The efficient and sustainable distribution of clean and potable water is a fundamental responsibility of modern society [2]. The supply of water is not only important for everyday human needs, but in addition, for sustainable development, for the production of energy for instance in Nigeria, water is used to generate electricity, for industrial and agriculture processes [3].

Furthermore, water distribution networks are the unsung heroes of modern civilization, as these infrastructures ensure that access to clean and safe water for drinking, sanitation, and various industrial processes. Without the effective distribution of water, the industrial, and economic developments would be nearly impossible, as it often encounters with the challenge of infrastructure deterioration due the inevitable environmental and climatic factors that have evidently caused leakages in water distribution facilities. Leakages in water distribution systems are majorly classified as reported leakages, unreported leakages, background leakages. About 3281 megaliters (106) of water was wasted in the UK during 2009–2011, and about 15% of supplied drinking water was wasted each year in the US [4]. This effect takes a significant toll on resources required to supply water in distribution facilities. For instance, the process of pumping

Ojo, O.S., Akinyede, R.O., Alowolodu, O.D., and Adebayo, A. (2025). A Systematic Review of Computational Approach to Pipeline Leakage Detection in a Water Distribution Network. *University of Ibadan Journal of Science and Logics in ICT Research (UIJSLICTR),* Vol. 13 No. 1, pp. 13 – 23.

water through a network with inherent leaks will require more energy cost [5]. In another view leaks can decrease water pressure, and also allow contaminants to compromise water quality and public health [6]. Above all, leakages contribute to non-revenue water, that is water produced and lost before reaching paying customers, affecting revenue and system sustainability [7]. Therefore, there is a need to brazen existing techniques for early and accurate detection leaks in water distribution network system. This will enable agencies to evolve into preventative strategies to curb the challenges that may want surface with significant socio-economic benefits [6].

Water distribution system consists of pipes, junction joints, hydraulic devices and pumps used in delivering water to consumers in prescribed quantities at desired pressure [8]. Therefore, the process of leakage detection in a water distribution network has proved to be a difficult task over years. Foremost, the complexity of a water distribution network (WDN) with enormous interconnected pipelines make leak location process burdensome [9]. The traditional approaches to WDN leakage detection are ineffective due to the interference of ambient noise makes differential pressure fluctuations, varying flow rate, leak size and location [10], inaccessibility of network components [6], and sophisticated data collection system [11]. However, the essence of digital transformations has immensely contributed to ease the process of leakage detection in WDN.

Detecting and addressing leakages in water distribution networks is crucial for both conservation of resources and the efficient operation of these systems, in which computational approaches play a significant role in this domain by offering advanced tools and techniques for leakage detection. This study therefore, performed a systematic review of published articles on computational to leakage detection in water distribution network, with the aim of evidence-based study of the identified research gaps in order to contribute to the growing body of knowledge in computational leakage detection.

1.1 Motivation

Recognizing the critical importance of addressing leakage in water distribution [12], one of the critical challenges faced by water utilities is the timely detection and localization of leakages in a network, as undetected leaks can lead to significant water loss, increased operational costs, and potential environmental hazards. Most computational studies on leakage detection adopt a data driven technique for locating leakages using single modal approach (i.e. a unimodal approach). The unimodal methods are limited in their capacity to accurately detect leakages, due to the spatial-temporal complexity of water distribution networks. However, Attallah [13] emphasized the benefits of multimodal approach to improve leakage detection and localization performance. This study therefore, seeks to perform a systematic review to identify the computational approaches and different factors considered to detect and localize pipeline leakages.

2. Methodology

The systematic review of papers in the detection of leakages in WDN using machine learning techniques was performed to identify how scholars conducted and reported their findings in this field of study. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses [14] was used as the reporting checklist. Furthermore, the papers published from January 2019 to October 2023 were searched in SCOPUS and IEEE databases using the query string shown in figure 1. The string was composed using SCOPUS and IEEE advanced search, and the search terms contains “Pipeline Leakage Detection”, “Water Distribution Network”, "Machine learning" "Deep learning", and "Simulation" in the article’s tittle, abstract and keywords. The identified records were exported to an MS Excel spreadsheet. The papers dated before the stipulated period of January 2019 was discovered to be included in the identified record, however, it was observed that such categories of articles have significantly high citation index, they were therefore retained for the purpose of this study..

Two reviewers independently screened the tittles, abstracts, and keywords of the literature's records to exclude papers that do not implement their methodologies on computational approach to pipeline leakage detection in WDN. Papers based on review, empirical, descriptive, and conceptual findings were discarded. Thereafter, the two reviewers performed eligibility assessment of the remaining papers in the thorough screening of the full texts. During the full text, the articles that are not open access were excluded from the study. In this phase, conflicts between reviewers were discussed and jointly resolved. The third reviewer was engaged in the case of unresolved arguments. Papers with at least no citation within a time frame of three years were included. We included papers with at least no citation within a time frame of three years.

More items inferred from the study objectives were added to MS Excel spreadsheet for data management. Most specifically, the application of the pipeline network considered, the inherent leakage problem, the computational approach for leakage detection, determining the hybridization status of the computational approach, the optimization technique engaged, premise of computational approach, and the results. One author classified the included papers using the inferred items, while the second author analyzed the data obtained. Conflicts were resolved by discussion, and all the included papers were carefully reviewed to extract and code the data (Table 1,2). This study reviewed **54** research papers. The study selection process has been summarized in Figure.2. While the literature search against the SCOPUS and IEEE databases resulted in 116 records, 62 records were initially eliminated as the pipeline problems discussed in the articles were not related to computational approach to leakage detection in a water distribution network.

Furthermore, empirical and review studies were also excluded from the study. The full texts of the remaining 56 articles were carefully screened and 1 more studies were excluded, as they have been published for more than three years, and are yet to be cited. Table 1 reports the journals/proceeding name, impact factor (IF) rating and year of publication of the included articles. The findings show that researches on the computational approach to water pipeline leakage detection is growing over time, and the highest percentage of the studies were observed to have been published in year 2023, with almost 55% of the articles disseminated in high and moderately impact factor rated (**i.e. IF>1**) journals/proceedings. This implies that there is improvement in the quality of studies, and however, it was realized that the following itemized factors (Figure 2) were discussed in the full text of the retrieved articles:

"TITLE-ABS-KEY ("Pipeline Leakage Detection" OR " Water Distribution Network" AND "Machine learning" OR "Deep learning" OR "Simulation") AND (LIMIT-TO (SUBJAREA , "COMP")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (OA , "all")) AND (LIMIT-TO (EXACTKEYWORD , "Water Distribution Systems"))"

Figure 1: Shows the query string used for literature search

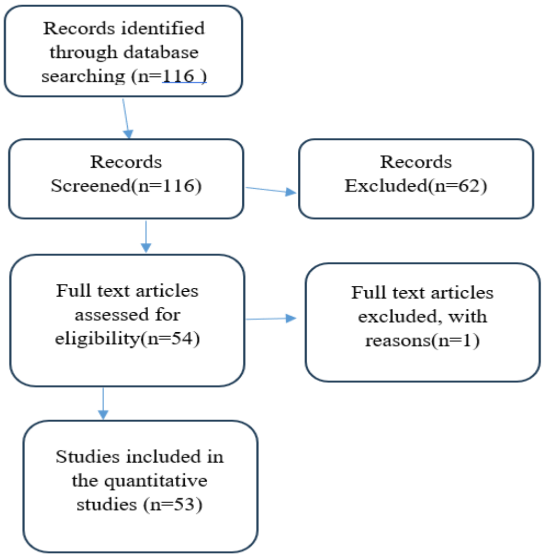

Figure. 2. study selection process

2.1 Pipeline leakage

Adequate and efficient functioning of water distribution networks is vital for sustaining urban life, ensuring public health, and promoting environmental conservation. The major channel through which the water gets to the consumer is through the water distribution network, which comprises of linked pipes, junction joint, pump and hydraulic devices [8].Therefore, it is necessary to develop an effective water delivery system to residential, commercial, and industries premises through the buried pipeline [15]. The existence of leakages poses a significant challenge to compromising not only the availability of water resources but also the structural integrity of the network itself. Water escaping from pipes, plumbing fixtures, faucets, valves, and fittings is a prevalent issue in buildings and structures, representing a significant contributor to water wastage. Studies indicate that an average home lose significant amount of water annually due to leaks. Some leaks, such as those from dripping faucets and water heaters, are readily apparent. Furthermore, corrosion of pipes due to chemical reactions with the fluid being transported or with the surrounding environment can weaken the pipe walls, leading to leakage corrosions.The other factors imminently responsible for leakages in pipe network are much, and not limited to the following: high water pressure, joint failures, materials defect, physical damage temperature fluctuations, chemical compatibility and Natural causes.

2.2 Computational Approach

*I*n recent years, the integration of computational techniques has emerged as a promising avenue for enhancing the efficiency of leakage detection in water distribution networks. Traditional methods often rely on manual inspection and statistical analyses, which can be time-consuming and prone to errors. The utilization of computational and other technological approach is perceived to enable of real-time monitoring, early detection, and precise localization of leakages, thereby mitigating potential damages and optimizing resource utilization. Several authors have worked on variety of technologies to detect leakages in WDN with plausible results. It is important to be aware of the state of art computational trend, explore the strength and weakness, and make propositions to improve leakage detection process in WDN.

2.3 Hybridized Computational Approach

The convergence of computational methods with other technologies has enabled a leap forward in the efficiency of different disciplines. In WDN leakage detection process, the integration of multiple traditional methods with computational algorithms to enhance the reliability of leakage detection systems. Having implemented the traditional leakage detection process such as detection of leakages sound, mathematical analysis of flow pressure and hydraulics modeling, with technologies which includes remote sensing, internet of things, geographical information systems, acoustic sensor, and cloud computing, are progressively being combined with computational models, optimization techniques, signal processing and other heuristics.

2.4 Optimization Technique

Aside the use of computational optimization methods to generalize the fitness of computational models on WDNs' historical leakage information, variant optimization techniques and heuristics have been engaged to accurately appropriate the installation of critical infrastructures in complex WDN, that will aid early detection of pipeline leakages.

2.5 Multidisciplinary Research

In view of the uncertainty caused by the novel mutations of modern times, multidisciplinary research is being used to understudy most natural phenomenon. In the case of development of WDN leakage detection system, that ability to quantify uncertainty can be realized through the study of climatic and environmental impact on leakages. The observations from the multidisciplinary technique will be invaluable to guide the WDN utilities installations and leakage detection.

2.6 Leakage detection system performance

A reliable performance metric is essential for comparative evaluation of feasible computational techniques and combinations applicable for early detection of WDN leakages. It is paramount to harmonize the efficiency indicators of each leakage detection technique to support evidence-based study for improved early leakage detection in a WDN utility.

3. Results and Discussion

3.1 Results

The results of our analysis clearly indicate that there is an unstable increase in the number of studies performed on computational approaches to leakage detection in a water distribution network (see figure 3). It was observed that there is improvement in the quality of studies published on the research, as almost 55% of the articles disseminated in 2023 were published in high and moderately impact factor rated (**i.e. IF>1**) journals/proceedings. In the full-text review of the existing literature, the factors itemized in section 4 were consistently observed to have contributed to the improvement of the reproducible quality studies. The findings of the reviewed articles are summarized in Table 2.

The leakage problem-solving techniques identified in this study are divided into nine (9) categories, however, leakage detection, leakage localization and the combined leakage detection and localization techniques are unprecedented at 20.76(%),15.09(%), 37.74(%) respectively. Meanwhile, 64.29(%) of studies published in 2023 are based on leakage detection and localization problems.

Furthermore, in the computational approach used to analyze water pipeline leakage, researchers have mostly engaged the classical machine learning techniques at 15.09(%) compared to the overall identified techniques in more than five years. However, with the recent studies, deep-learning appropriate computational combination discovered to accurately detect and localize leakages in a water distribution network. Meanwhile, the deep learning and classical machine learning architectures were respectively organized in ensemble and federated learning frameworks.

From the overall hybridization of the computational approach (n=30) identified; the simulation, signal processing, and IoT components were used solely for leakage data collection, while 35.85(%) (n=19) studies discussed ensemble and federated learning frameworks used to drive more fractal representations of WDN leakages to improve leakage detection and localization performance. Furthermore, 35.85(%)(n=19) of the studies emphasized the importance of computational optimization to the training of WDN leakage detection and localization models.

The leakage detection and localization research have been evolving in this direction because the highest number of articles in the computational optimization context of leakage research was recently published in 2023. However, what is yet to be determined in studies, is the comparative study of how different categories of the optimization techniques performed in improving the accuracy of the developed model.

Table 1: A summary of the names of the journals and year of publication of the included reviews.

Journal / Conference Proceedings	Impact Factor (IF) rating	<2019	2019	2020	2021	2022	2023	Total
Engineering Applications of Artificial Intelligence	9.36	-	-	-	-	-	1	
IEEE Transactions on Cognitive Communications	9.1	-	-	-	1	-	-	

and Networking								
Advanced Engineering Informatics	8.8	-	-	-	-	-	1	
IEEE Transactions on Industrial Electronics	8.41	1	-	-	-	-	-	
Journal of Ambient Intelligence and Humanized Computing	6.163	-	-	-	1	-	-	
IEEE Transactions on Instrumentation and Measurement	5.97	-	-	-	-	1	-	
Control Engineering Practice	5.58	2	-	-	-	-	-	
Computers and Chemical Engineering	5.11	1	-	-	-	-	-	
IEEE Transactions on Network Science and Engineering	5.05	1	-	-	-	-	-	
IF rating > 5 Journals/proceedings (11 Listed)		**5 (50%)**	**0 (0%)**	**0 (0%)**	**2 (20%)**	**1 (10%)**	**2 (20%)**	**10 (100 %)**
Journal of Process Control	4.83	1	-	1	-	-	-	
IEEE Transactions on Control of Network Systems	4.347	1	-	-	-	-	-	
IEEE Sensors Journal	4.325	-	-	-	-	1	1	
Sensors (Switzerland)	3.9	-	1	1	-	-	-	
Sensors	3.9	-	-	-	-	1	2	
IEEE Access	3.9	1	-	-	2	-	-	
Journal of Imaging	3.2	-	-	-	-	-	1	
2021 International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA)	1	-	-	-	1	-	-	
IF rating < 5 , >1 Journals/proceedings (10 Listed)		**3 (20%)**	**1 (6.67 %)**	**2 (13.33 %)**	**3 (20%)**	**2 (13.33 %)**	**4 (26.67%)**	**15 (100 %)**
2019 6th International Conference on Control, Decision and Information Technologies, CoDIT 2019	0.71	-	1	-	-	-	-	
Conference on Control and Fault-Tolerant Systems, SysTol	0.61	-	1	-	1	-	-	
2019 IEEE AFRICON	0.47	-	1	-	-	-	-	
IF rating < 1 Journals/proceedings (10 Listed)		**0 (0%)**	**3 (75%)**	**(0%)**	**1 (25%)**	**0 (0%)**	**0 (0%)**	**4 (100 %)**
2021 IEEE 16th International Conference on Industrial and Information Systems (ICIIS)		-	-	-	1	-	-	
2023 IEEE International Conference on Consumer Electronics-Asia (ICCE-Asia)	-	-	-	-	-	-	1	
2023 International Conference on Distributed Computing and Electrical Circuits and Electronics (ICDCECE)	-	-	-	-	-	-	1	
2022 3rd International Conference on Smart Electronics and Communication (ICOSEC)	-	-	-	-	-	1	-	

2023 IEEE International Smart Cities Conference (ISC2)	-	-	-	-	-	-	1	
2019 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)	-	-	1	-	-	-	-	
2020 IEEE International Conference on Progress in Informatics and Computing (PIC)	-	-	-	1	-	-	-	
2019 International Conference on Advancements in Computing (ICAC)	-	-	1	-	-	-	-	
Proceedings - 2022 IEEE International Conference on Big Data, Big Data 2022	-	-	-	-	-	1	-	
2023 International Conference on Emerging Trends in Networks and Computer Communications (ETNCC)	-	-	-	-	-	-	1	
Intelligent Service Robotics	-	-	-	-	-	1	-	
2019 International Conference on Advanced Mechatronics, Intelligent Manufacture and Industrial Automation (ICAMIMIA)	-	-	1	-	-	-	-	
2023 International Conference on IT Innovation and Knowledge Discovery (ITIKD)	-	-	-	-	-	-	1	
2023 International Conference on Sustainable Computing and Smart Systems (ICSCSS)	-	-	-	-	-	-	1	
2023 14th International Conference on Computing Communication and Networking Technologies (ICCCNT)	-	-	-	-	-	-	1	
2015 International Conference on Soft-Computing and Networks Security (ICSNS)	-	1	-	-	-	-	-	
2021 International Electronics Symposium (IES)	-	-	-	-	1	-	-	
2017 IEEE/ACS 14th International Conference on Computer Systems and Applications (AICCSA)	-	1	-	-	-	-	-	
18th IEEE International Multi-Conference on Systems, Signals and Devices, SSD 2021	-	-	-	-	1	-	--	-
2017 International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS)	-	1	-	-	-	-	-	
2019 4th International Conference on Computational Systems and Information Technology for Sustainable Solution (CSITSS)	-	-	1	-	-	-	-	-

2019 IEEE 5th International Conference for Convergence in Technology (I2CT)			1	-	-	-	-	-
2022 12th International Conference on Cloud Computing, Data Science & Engineering (Confluence)	-	-	-	-	-	1	-	-
2023 International Conference on Sustainable Communication Networks and Application (ICSCNA)	-	-	-	-	-	-	1	-
N/A IF rating Journals/proceedings (10 Listed)	-	**3(12.5%)**	**5(20.83%)**	**1(4.17%)**	**3(%)**	**4(12.5%)**	**8(%)**	**24**(33.33%)
Total		11(20.75%)	9(16.98%)	3(5.66%)	9(16.98%)	7(13.21%)	14(26.42%)	53(100%)

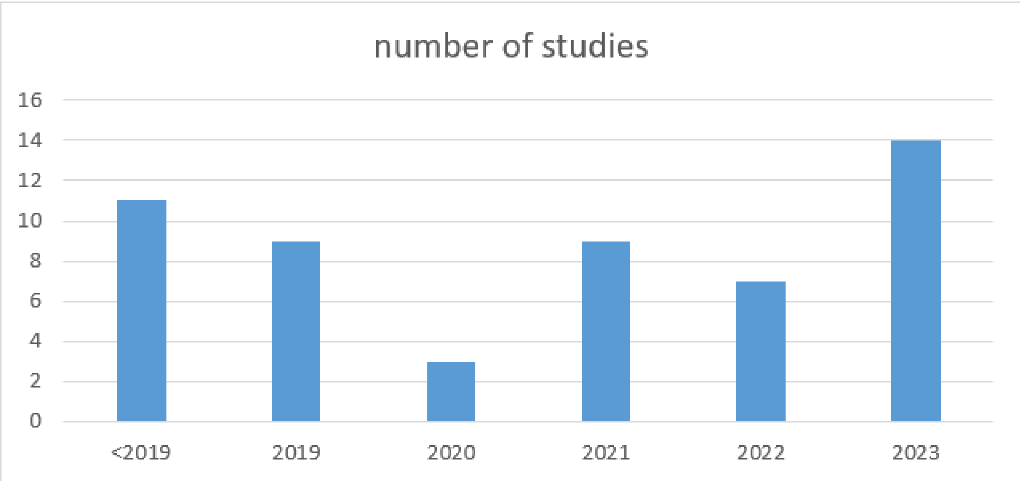

Figure. 3. Histogram shows annual publication pattern

Table 2: A summary of the assessment of the included reviews.

Year	**<2019**	**2019**	**2020**	**2021**	**2022**	**2023**	**Total**
No. of included papers	11	9	3	9	7	14	53(100%)
Leakage problem solving techniques							
Hydraulic analysis	1	-	-	-	-	-	1(1.89%)
Leakage localization	3	1	-	-	2	2	8(15.09%)
Leakage detection	-	2	2	4	1	2	11(20.76%)
Leakage detection and localization	6	5	1	4	3	9	28(37.74%)
Node pressure prediction		1	-	-	-	-	1(1.89%)
Night flow Analysis	-	-	-	-	-	1	1(1.89%)
Long distance inspection	-	-	-	-	1	-	1(1.89%)
Leakage monitoring and detection	1	-	-	-	-	-	1(1.89%)
Leakage detection and sensor location	-	-	-	1	-	-	1(1.89%)

Computational Approach							
deep learning	-	2	-	-	1	4	7(13.21%)
IoT & deep learning	-	-	-	1	-	-	1(1.89%)
IoT devices & Classical ml		1		1			2(3.78%)
Data analysis		1					1(1.89%)
distributed computing	-	-	1	-	-	-	1(1.89%)
IoT & distributed computing		1					1(1.89%)
Mathematical	1	-	-	-	-	-	1(1.89%)
Signal processing	2	2		1		1	6(11.32%)
Simulation, Signal processing &Heuristic algorithm					1		1(1.89%)
Deep learning & Classical ml	1						1(1.89%)
Classical ml	1	-	1	3	3	-	8(15.09%)
Classical ml & Simulation	2	1			1		4(7.55%)
Classical ml & Signal processing			1	1		2	4(7.55%)
Dimensionality reduction	1			1			2(3.78%)
Classical ml & Dimensionality reduction		1					1(1.89%)
Game theory & Graph algorithm	1					1	2(3.78%)
Classical ml & Graph theory						1	1(1.89%)
Classical ml & Graph algorithm						1	1(1.89%)
Classical ml & heuristics				1			1(1.89%)
Deep learning & Signal processing						1	1(1.89%)
IoT & Data analysis						1	1(1.89%)
IoT & Signal processing	1					1	2(3.78%)
						1	1(1.89%)
Signal processing & simulation	1						1(1.89%)
Micro controller				1			1(1.89%)
Hybridized Computational Approach	6	5	1	4	5	9	30(56.60%)
Optimization technique	5	3	1	2	3	5	19(35.85%)
Premise of computational approach							
Univariate	6	9	3	9	6	12	45(83.33%)
Multivariate	4	0	0	0	1	2	7(12.96%)

The univariable predicated studies account for 83.33(%)(n=45) of the research disseminated in the past five years. This implies handful of WDN leakage detection and localization models were developed using a multivariable approach**.** The adoption of a multivariable study offers the benefit of extracting features from more than one domain, which is projected to improve the model's performance. The comprehensive incorporation of the multivariable concept has fostered the development of robust deep-learning models to tackle uncertainties inherent in phenomena such as WDN leakage study. The implementation of the multivariable concept in the development of leakage detection and localization models can be realized through the development of multi-variable deep learning architectures. It utilizes a combination of data sources, such as pressure, flow, and acoustic signals, leading to higher accuracy in leak detection compared to relying on a single variable alone.

This approach reduces false positives and negatives, which will enhance the overall reliability of leak detection systems. The analysis of multiple variables will increase sensitivity to small leaks that may go undetected when using only one parameter. This concept is crucial for early detection and prompt repair of leaks, minimizing water loss and infrastructure damage. Also, the use of multiple variables allows for the establishment of baseline patterns and deviations, enabling the detection of anomalies indicative of leaks at an early stage. Early warning systems help utilities take proactive measures to address leaks promptly, minimizing water loss and potential service disruptions [16]. Besides its' growing adoption in computational WDN leakage detection and localization, the invention of various efficient learning methods and network structures in deep learning algorithms makes it suitable for the realization of multi-disciplinary studies in WDN leakage detection and localization [17]. The multi-variable research is perceived to enable creativity that will unearth the causal effect of environmental factors on WDN leakages.

This study raises doubts concerning the evaluation metrics employed by some of the authors [18]. Most importantly, there was concern about the non-uniformity of the metrics used to evaluate the accuracy of leakage detection and localization, which inhibited the synthetized analysis of the result of various computational approaches observed in the study

4. Conclusion

A comprehensive comparative analysis is made on the following issues Pipeline leakage, computational approach, hybridized computational approach, optimization, technique, Computational premise, and the results. The results show that research on pipe leakage is trending because of its significance to life. The deep learning approach has been utilized by many researchers as the most significant computational technique.

The classical machine learning techniques were observed to have been blended with other approaches such as deep learning, simulation, and signal processing to entrench the appropriate combination to accurately detect and localize leakages in a water distribution network. There were also research instances, when the deep learning and classical machine learning architectures were differently harnessed in ensemble and federated learning framework. Also, hybridization of the computational techniques, the simulation, signal processing, and IoT components were used solely for the purpose of leakage data collection, while the ensemble and federated learning frameworks were aimed to enable more fractal representations of WDN leakages for improved leakage detection. However, what is yet to be determined in studies, is the comparative study of how different categories of the optimization techniques performance in improving the accuracy of the developed model.

Therefore, it is concluded that various optimization should be tested with machine learning technique to improve on the accuracy. Furthermore, the study shows that the adoption of multivariable has not been effectively utilized which offers the benefit of extracting features for more than one domain, hereby to improve on the accuracy and performance models.

The comprehensive incorporation of multivariable concept has proved to foster the development of robust deep learning models to tackle uncertainty inherent phenomenon such as WDN leakage research. The implementation of the multivariable concept in the development of leakage detection and localization models can be realized through the development of multi-variable deep learning architectures. It utilizes a combination of data sources, such as pressure, flow, and acoustic signals, leading to higher accuracy in leak detection compared to relying on a single variable alone. This approach reduces false positives and negatives, enhancing the overall reliability of leak detection systems.

It is concluded that using machine learning for leakage detection in water distribution is right option but the various ways of optimizing the result should be employed. Therefore, a multimodal approach should be adopted to improve on the accuracy and extracting features from various domain should be employed to improve on the sensitivity of leakage detection and localization.

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