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A review of leakage detection strategies for pressurised pipeline in steady-state

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ABSTRACT

Pipeline and pipe networks are the most environmentally sustainable and energy-efficient means for transportation and distribution of fluids of high social and commercial value like drinking water, oil, and natural gas. Integrity management of the pipeline through leak prevention and early leak detection is crucial for their continuous operation and also to prevent the increase in energy burden and carbon emissions. The present study focuses on the performance-oriented critical evaluation of various leak detection approaches proposed for pressurised pipeline carrying different types of fluids. Basic leak hydraulics and effective leak management strategies that facilitate leak prevention are briefly discussed. Literature review reveals the availability of an overwhelming range of leak detection methods with different technicality as well as applicability. Several different mathematical techniques and hydraulic tools have also been utilised in the proposed methods, which makes it rather challenging to evaluate all of them on a common platform and impractical to assess their technical capabilities and limitations. A comprehensive classification of the most popular steady-state based leak detection methods is carried out, based on the core methodology utilised in each technique and without emphasizing on their individual technical detailing. This type of systematic classification and evaluation of leak detection approaches is deemed to be more useful for field applications by water utility personnel. Methods developed by combining two or more diverse techniques or processes have demonstrated to be more successful in leak localization, and such hybrid methods should be further developed for future beneficial use.

1. Introduction

Transportation of fluids through pipeline and pipe networks has immensely evolved during the past century, and these technological advancements have augmented its use over other modes of fluid transport [1]. The pressurised pipeline provides a continuous mode of transportation for fluids and can perform with minimal manual effort, and material handling and are also reasonably safeguarded from harsh weather and environmental conditions [2]. Presently, it is the most rapid, highly cost-effective, energy-efficient, and environmentally sustainable mode of transfer for various fluids [3]. Efforts are also being put forward to develop a hydraulic or pneumatic capacity pipeline for transporting solid commodities by providing energy to the fluid (air or other non-reactive liquid) contained within the pipe [4]. However, pipeline systems suffer from a few limitations like rigid operational routes,

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Nomenclature

WDN	Water distribution network
NPW	Negative pressure wave
PI	Performance indicators
NRW	Non-revenue water
LPM	Leakage per meter
LPC	Leakage per connection
ILI	Infrastructure leak index
CML	Customer minutes lost
NDT	Non-destructive techniques
ILI-T	In-line inspection tools
PIG	Pipeline inspection gauge
PRV	Pressure regulation valves
HLR	Head loss ratio
GA	Genetic algorithm
AI	Artificial intelligence
RTTM	Real-time transient monitoring
GLM	Genetic linear programming
UAIT	Unmanned air borne infrared thermography
DHN	District heating networks
SVM	Support vector machine
EM	Electro-magnetic
MFL	Magnetic flux leakage
RFEC	Remote field eddy current
BEM	Broadband electromagnetic
PEC	Pulsed eddy current
PRV	Pressure residual vector
PCA	Principal component analysis
ICA	Independent component analysis
CCTV	Closed circuit television
GPR	Ground penetrating radar
DMA	District metered area
GIS	Geographic information systems
CADD	Computer aided design and drafting
SCADA	Supervisory control and data acquisition
CIS	Customer information system
AMS	Asset management system
PPA	Pressure point analysis
ANN	Artificial neural networks
BIS	Bayesian information systems
FIS	Fuzzy inference systems
KF	Kalman filter
SVR	Support vector regression
FPR	False positive rate
DFT	Discrete Fourier transform
FFT	Fast Fourier transform
STFT	Short term Fourier transform
HHT	Hilbert-Huang transform
SPC	Statistical process control
CUSUM	Cumulative sum
NKF	Non-linear Kalman Filter
EPR	Evolutionary polynomial regression
MLPNN	Multilayer Perception Neural Network
CCR	Cross-correlation ratio
EWMA	Exponentially weighted moving average

supply, and delivery points, and it can carry only a particular material for which it has been designed.

The most prevalent concern that challenges the sustainable and secure operation of any pressurised pipeline is the impending occurrence of leaks and bursts, caused either by gradually deteriorating intrinsic pipe properties or due to sudden extrinsic events like operational discrepancies, anthropogenic activities or environmental factors. Furthermore, all types of pipeline systems do not respond identically to the leak-causing stresses or undergo similar damage [5]. The impact of these factors significantly depends on the pipe material as well as pipe diameter, which has been well documented by Barton et al. in a recent study [6]. Furthermore, the geometrical leak size and shape in a pipe are also influenced by the intrinsic properties of the pipe material used [7]. Thus, the event of leakage and its complicated behavior pose a severe operation and management issue for pipeline authorities and may even lead to partial or complete system failure. It may also cause a considerable financial loss in terms of material and energy, environmental damage, and at times, loss of human life [8].

The main focus of transportation of fuels with high monetary value like oil and natural gas through a pipeline is on leak prevention strategies rather than leak detection [8]. Similarly, leakage in pipeline systems carrying hazardous substances may also trigger environmental damage and loss of human life, and hence the concept of 'leak-before-break' analysis is more relevant for such pipe systems [9]. A few sophisticated leak prevention/detection systems have already been developed and are used by oil and gas companies to trigger alarms in response to potential pipe failure [10]. Nevertheless, these techniques are still not completely developed to provide accurate location and extent of damage, which is evident from the quantum of leak-related pipeline accidents encountered yearly in this sector [11].

Unlike the reasonably simple structure of fuel transportation pipeline, pipe networks for supplying drinking water are inherently complex, with numerous consumer locations and often with multiple source points. As the population of the city expands, new pipes are added to the existing network, which results in a heterogeneous system, with components of different age, material, and size, and thereby making its leakage monitoring a daunting task. Leak prevention methodologies developed for oil and natural gas pipeline are mostly not suitable for the direct application to leak detection in the complex water networks. Real-time control of urban water networks and asset management through automated control systems are being presently developed for their integrity management for leak prevention [12,13]. Even in developed countries, efficient management of water supply systems is a pertinent issue of concern, and at present, the conventional methods of leak detection used by water companies worldwide are nothing but a combined application of water audits and acoustic-based hardware equipment [14]. Such methods cannot be utilised on a day-to-day basis for operational difficulties and high requirement of resources and time.

Leak detection techniques for water distribution networks (WDN) have been formulated and developed for more than two decades. A wide range of hardware-based leak detection equipment is now available in the commercial sector [15]. Similarly, software-based leak detection algorithms have been proposed in recent studies, both in the steady-state and transient state [16,17]. Each of the diverse techniques proposed to date has a different degree of performance efficiency, based on external or internal system conditions, and limitations of the methods itself. Revisiting all previous review-based works of literature on leak detection approaches revealed that none of them have highlighted and discussed all classes of leak detection techniques in a single work. The present review stems from this gap area.

The present study is a novel attempt to comprehensively classify and analyse the steady-state methods of leak detection in the fluid pipeline, which has not been addressed in a single platform to date. A brief discussion on leak hydraulics and available leak prevention strategies have been put forward to elucidate a complete picture of leak dynamics in a real pipeline system. A detailed classification of the significant leak detection methods along with their qualitative comparison, has been carried out to demonstrate the feasibility and concerns in this field. This study is motivated to provide a broad overview of diverse leak detection techniques in a simplified manner, which can be acceptable for water utility managers without acquainting in-depth technical know-how.

2. Leak hydraulics and leakage prevention

2.1. Anatomy of a leak and its signature on hydraulic properties

Before delving deeper into the leak detection technologies, it is imperative to understand the hydraulic implication of a leak. A sudden and unexpected drop in pressure is an indication of either some unknown leak or an un-documented demand. A leak is essentially a hydraulic phenomenon whose occurrence in a pipeline alters its hydraulic properties, that can be detected directly or indirectly using specific sensors [18]. The features concerning a leak are (a) presence of one or more leaks – *leak detection* (b) assessment of the severity of the leak – *leak magnitude*, and (c) pinpointing the exact location of a leak – *leak localization*. A practically applicable leak detection methodology has to sense one or more of these features with significant accuracy. Some of the fluid properties utilised to detect a leak indirectly or directly are pressure, flow-rate, acoustic vibration, gas sampling, optics, or temperature [19]. Out of these, pressure and flow variables are most commonly used as leak indicators [20]. Pressure monitoring devices, as well as inlet and outlet flow meters, are integral for the regular operation of the pipeline, and any change in these parameters is the most obvious indicator of potential pipe breaks. Theoretically, as soon as a leak arises, an equivalent pressure drop takes place in its vicinity, which in turn induces the release of a set of pressure waves at the leak location and then traveling along the pipe in opposite directions, with a specific velocity corresponding to the leak size. This set of waves is known as a negative pressure wave (NPW) and is an ideal vehicle for leak analysis in several studies [21]. A leak also produces an evident decrease in the upstream pressure and downstream flow-rate in the straight pipeline. However, in the case of a pipe network, the concept of outlet and inlet pressure becomes ambiguous. Barring a few exceptions, most studies do not investigate flow-rate to identify leakage features directly, although high inflows do signify a potential burst downstream of the loggers.

Computational fluid dynamics-based simulations have revealed the flow and turbulence field patterns in the leak locality. Leak induced pressure drop may be detectable only for the leaks larger than a certain magnitude, but the corresponding pressure gradient variations are more apparently recognizable even for smaller leaks [14]. However, such leak induced characteristics are system-specific, depend significantly on the line pressure and leak size, and change substantially with the physical dimensions of the pipeline. Escaping fluid also generates an acoustic signal, which can be detected by acoustic sensors, accelerometers, microphones, and dynamic transducers. Properties of acoustic waves used for generic fault detection are reflection, interference, refraction, and diffraction [22]. Temperature is also a critical criterion in the pipeline design stage. In extremely low-temperature regions, temperature change acts as a precursor for leak occurrences, and such changes can be detected by optical fibers [23].

2.2. Pipeline maintenance for leak prevention

Periodic failure of the pipe segments is unavoidable and could be caused due to several factors like corrosion, lousy workmanship, high-pressure surge, loosening of joints, soil conditions, natural disasters [24]. However, it has been practically observed during the

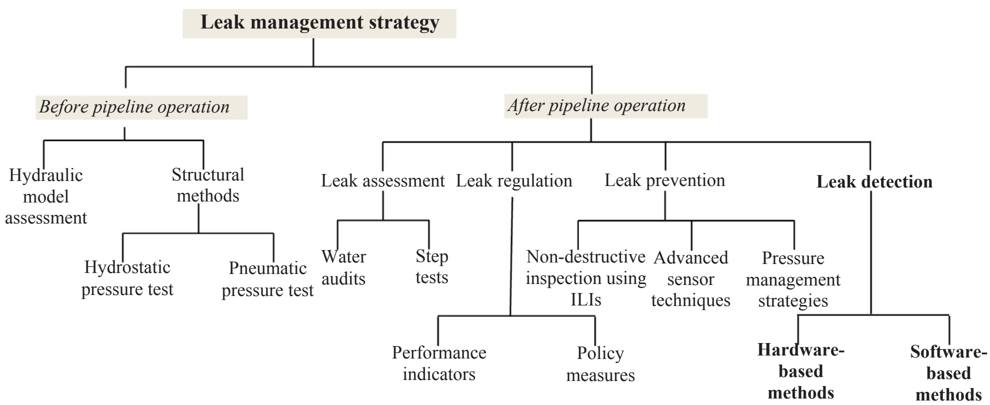

Fig. 1. Effective leak management strategies for integrity management of pipeline.

operation of real systems that a considerable number of leaks may be prevented through proper management and monitoring practices [25]. The structural integrity of the pipeline can be ensured through effective leakage management strategies, as presented in Fig. 1. One such initial method adopted by modern utilities is to prepare software models of pipe networks and simulate them to verify their hydraulic stability and check the robustness of the design before construction. Several hydraulic platforms are now available, the most popular ones being *EPANET, WaterGEMS, InfoWorks (WS), SIMULINK, Synergi Gas,* which can fairly emulate steady-state, extended period, fire-flow analysis and other operational scenarios of the real network. By representing the actual topology and other structural parameters of the network as accurately as possible in the model, it is attempted to estimate the critical hydraulic parameters and redesigning it to circumvent the issues of concern, if any. Once the network is designed and analysed, high-quality construction of the pipeline is the first line of defense against pipe failures. The structural integrity of the pipeline is checked

Table 1
Summary of review-based works of literature on leak detection methods in pipeline systems.

Key focus	Classification of techniques	Pipeline reviewed	Papers reviewed	Remarks	Ref.
		Steady-state			
Varied leak detection techniques	RTTM Pressure monitoring Statistical analysis	All types of pipeline	35	Limited techniques evaluated	[82]
Statistical methods for pipe break analysis	Time linear model Time exponential model GLMs, Logistic GLMs	Water pipeline	20	A few statistical methods are comparatively evaluated Statistical methods are not exclusively studied	[83]
Condition assessment using robotic devices	Motion & sensing Autonomy Energy & Control Communication	Water, wastewater, oil and gas pipeline	70	In-pipe methods discussed in elaborate details	[40]
Comprehensive water loss management	Hardware methods Model-based methods	Water pipeline	69	Loss assessment and control discussed only in brief Leak detection methods vaguely discussed	[31]
Conventional NDT and advanced sensor techniques	Direct methods Indirect methods Robotic methods	Water pipeline	66	Smart pipe and intelligent robots discussed Suitable methods for different pipe materials mentioned	[37]
Diverse fault detection techniques	Hardware methods Software methods Hybrid methods	Oil, water and gas pipeline	61	Fault detection methods covered No proper categorization done Transient methods not included	[10]
Data-driven leak detection methods	Classification Prediction-classification Statistical methods	Water pipeline	67	Comprehensive review of data-driven steady-state techniques	[27]
Leak detection and localization	Hardware methods Non-technical Software methods	Industrial pipeline	25	Segregation is vague and incomplete and do not consider all approaches	[84]
Leak detection, defect prediction	Physics-based ILI-T Data-driven ILI-T	Oil and gas pipeline	232	Detailed review of ILI-T only	[85]
Leak detection	Model-based Data-driven UAIT methods	District heating networks	61	DHNs being functionally different, these methods are not applicable in other pipeline	[86]
		Unsteady-state			
Transient based lead detection	Inverse transient methods Direct transient methods Frequency domain methods	Water pipeline	79	All major transient-based techniques elucidated Related mathematical schemes for analysis also discussed	[18]
		Combined			
Pattern recognition for leak detection	Neural networks SVMs	Water pipeline	73	Leak detection techniques are not discussed exclusively	[42]
Gas leak detection and localization	Hardware methods Non-technical methods Software methods	Gas pipeline	85	Software based methods not discussed in entirety All types of hardware methods not discussed	[19]
Pressure based leak monitoring methods	Steady Unsteady Hybrid	Oil and water pipeline	58	Review not inclusive of all techniques Several methods not covered	[21]

before its commissioning by carrying out hydrostatic or pneumatic pressure tests using water or any other non-reactive liquid [21]. These pre-commissioning tests are very crucial to ensure safety, reliability and leak tightness of the pipeline.

Once in operable condition, customary pipeline inspection (assessment and regulation) is crucial for leak management as it can help in identifying the potential leak-inducing situations beforehand. Volume-based balance sheets can be prepared to evaluate the total water loss from the pipeline system [26]. At times, the step test procedure is carried out in the water networks, wherein the water loss in a specific area within the network is obtained. Leakage monitoring in pipe systems can also be initiated by the computation of performance indicators (PIs), by utilising the data collected from the system. These PIs are very useful to compare different aspects of performance assessment amongst several systems. Some of the standard leak-related PIs used in the water industry are non-revenue water (NRW), leakage per meter (LPM), leakage per connection (LPC), infrastructure leak index (ILI), customer minutes lost (CML). Apart from this, several policy-level initiatives may be undertaken by the utilities to ensure overall leakage reduction in the system through better co-operation between customers and service providers [27]. Leak prevention approaches become more relevant once the system becomes old. Age induced phenomena of deterioration of pipeline like pipe corrosion, fatigue, sedimentation, and erosion, which increase the propensity of pipe breaks, can be detected early to avoid the actual damage [28]. Corrosion or electrochemical deterioration is one of the prime causes leading to pipe leaks, especially for older pipeline buried in corrosive soils or for a pipeline carrying corrosive fluids [29]. Periodic pipeline inspection for age-related damage can be carried out by using sophisticated non-destructive techniques (NDT) [30]. Once detected, adequate steps to manage and repair damaged pipeline can be undertaken to prevent actual pipe damage.

Regulation of operational parameters of the pipeline can also help prevent or reduce the occurrence of pipe breaks and leaks. Preventive measures for leak occurrences in pipe networks are mostly pressure management strategies based on its minimization (or optimization), and it is perhaps the most cost-efficient method [31]. Pressure in oil or natural gas pipeline remains almost constant for a specific flowrate throughout its operational life, whereas pressure in a WDN may fluctuate every hour due to the varying consumer demand. Pressure optimization is somewhat difficult for a WDN, and it is regulated for different demand volumes using pressure regulation valves (PRV). An advanced control module for PRVs was put forward called the ‘WDNetXL Pressure Control Module’ for planning the remote operation of their real-time control based on daily pressure fluctuations [32]. Apart from this, several pressure-related indicators like minimum, maximum, and average pressures, and pressure range, variability, variation, and variation rate were analysed for their apparent correlation to the probability of pipe breaks in a study by Martínez-Codina et al. [33]. The operational pressure range was observed to be the most influential parameter for leak prevention. Another leak detection indicator called Head Loss Ratio (HLR), which is the ratio of the difference in pressure at different network locations, was developed by utilising pressure data from three or four network nodes [34]. The maximum value of HLR was obtained for a leaking pipe, and in this manner, the problematic pipe section can be narrowed down [35]. Thus, the knowledge of pressure behavior in a leakage scenario can be collectively applied to develop adequate pressure management strategies for the maintenance of the pipeline.

3. Classification of significant leak detection techniques

An overwhelming volume of leak detection techniques has been put forward by researchers, which makes it rather difficult to consider all of them in a single unified study. For their practical comparative evaluation, the first step would be to classify the

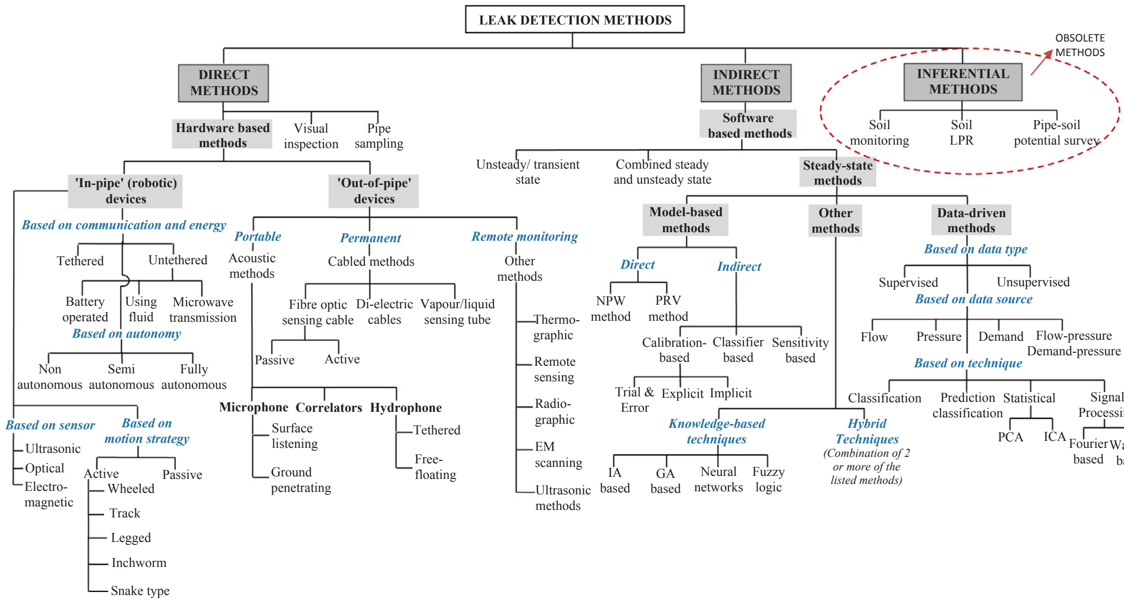

Fig. 2. Classification of major leak detection techniques.

developed leak detection techniques into different coherent categories. Uncovering of leakages in water pipes above a certain threshold of volume loss is the main focus of the leak detection methods developed for water networks, whereas leak prevention or locating potential leak-causing anomalies by increasing structural reliability of the system is the main goal for a pipeline carrying high-value and hazardous fluids [24,36]. Irrespective of the type of fluid carried, the core methodologies pursuing leak detection may be generalized for comparative study under some broad categories. Hence, for the sake of simplicity and interchangeability, relevant leak detection approaches developed for pipeline carrying different types of fluids are not segregated in this study. A few of the review-based studies that emphasize on the classification of various leak detection approaches are summarized in Table 1. However, the overlapping nature of most of the methodologies has not been captured entirely in any of these previous classifications. All of these studies have categorized only a few detection methodologies in isolation, which do not facilitate a complete understanding of their comparative advantages and drawbacks. In the present study, the knowledge acquired from these previous classifications is utilised, and several criteria for classification are merged for simplicity of understanding and applicability. A diagrammatic representation of classification of the major leak detection methods is shown in Fig. 2, where these techniques are categorically placed to understand each of them with relation to the broader domain of leak detection methods available. The criteria for each of the proposed class and sub-class of leak detection approaches was based on the core methodology utilised or the unifying characteristics of the techniques defining each class. The classification criteria for the hardware-based methods is the characteristics of the devices used, whereas the classification basis for software-based methods are computational approaches and data utilization. The 'in-pipe' devices mostly include portable physical instruments and hence the standard of classification for these methods was based on the physical aspects of these devises, like structure, mobility, placement, as well as energy and sensor capabilities. On the other hand, the most important criteria for 'out-of-pipe' devices for leak detection is its proximity from the pipeline systems and hence the basis of classification was the relative placement of the devices with respect to the pipeline. The software-based methods mostly rely on soft computing techniques and data acquisition, and hence, the basis of classification was chosen as the type, use, and application of the data acquired as well as the soft computing tools utilised. Thus, the proposed method encompasses several basis of classification in a common platform, to include diverse techniques in a single unified study.

Almost all leak detection techniques may be broadly classified as direct methods, indirect methods, and inferential methods. Most hardware-based approaches can be classified as direct methods of leak detection, whereas software-based methods are usually indirect or inferential. Simple inferential methods that merely indicate the probable presence of a leak but do not aid leak detection are rarely used nowadays and hence not discussed in this study. The hardware-based methods include several commercial leak detection tools and are further classified as 'out-of-pipe' (external or non-intrusive) and 'in-pipe' (robotic or intrusive) devices. Acoustic devices form the largest group of equipment in the 'out-of-pipe' category. These systems rely on the detection of vibration or noise signals released due to leaks that can be registered from outside the pipe environment. Apart from the 'out-of-pipe' techniques, this category also includes an enormously large number of other equipment for leak detection, each of which operates on different principles of detection [37]. Cabled techniques for leak detection commonly used in oil and natural gas pipeline comprises of optical, dielectric, or fluid sensing cables laid all along the pipeline route. 'Out-of-pipe' techniques are also, at times, segregated as optical and non-optical methods [19]. Ground-penetrating radar imaging is also one of the most popular methods for identifying water leaks in the pipeline [38,39]. However, these techniques are best applicable only for greenfield areas with little concrete surfaces. 'In-pipe' or robotic devices form a vast sub-class of devices for conditional assessment of pipes and have been extensively discussed in a few previous works of literature [40]. These devices can be further classified based on their specific characteristics of operation and are mostly segregated as active and passive, depending on the movement mechanism of the device. Other modes of classification for these devices are based on the type of communication and energy transmission, type of sensor used, and the extent of autonomy. Likewise, pipeline inspection gauges (PIGs) are also available for detailed inspection and even cleaning of pipe interiors. These tools can be classified based on their specific functions as geometry tools, mapping tools, metal loss (corrosion) tools, and crack detection tools [30].

Some form of sophisticated software programming package using mathematical techniques forms the basis of all software-based leak detection techniques. Most software-based techniques of leak detection can be categorized under indirect or inferential methods. The hydraulic state of the pipeline system plays a crucial role in these leak detection systems, based on which these methods may be classified as steady-state, transient-state, and hybrid methods. The focus of the present study being chiefly on the steady-state methods, transient-based approaches are not discussed here. Software-based methods under steady-state are divided into two broad sections as model-based techniques and data-driven techniques. Model-based techniques are typically classified as direct methods (simple and straightforward comparison of pressure) and indirect methods (using complex mathematical operations to distinguish anomaly from pressure data).

On the other hand, data-driven techniques can be further classified based on (a) type and source of raw data utilised in the method, and (b) mathematical and computational techniques employed to extract leak information from the raw data (Fig. 2). Based on the type of training imposed on the collected data, these methods are also classified as supervised and unsupervised [41]. Apart from these, several other methods which can be called hybrid methods, using a combination of two or more different core techniques and knowledge-based methods based on advanced computational formulations like GA, fuzzy logic, neural networks, and AI have also been proposed, although these are not discussed elaborately in this study (Fig. 2).

Although a plethora of leak detection methods is available, none of these approaches are generically suitable for all types of the fluid pipeline. The suitability of a particular leak detection method for specific pipeline system may be analysed through several criteria like cost-benefit ratio, ease of applicability, and operability. Hence, the actual field conditions of the pipeline systems need to be taken into account before choosing the most suitable leak detection equipment. Besides, it is also beneficial to have adequate knowledge about the applicability and limitations of the leak detection techniques used.

Table 2
Comparison of commercial hardware-based methods of leak detection.

Technique	Accuracy	Advantages	Disadvantages	Dependency factors	Application
External of 'out-of-pipe' methods					
Cable-based methods	–	Most sensitive hardware methods Very specific	Very costly; inapplicable in existing pipeline Affected by reflection property of background	The temperature difference between fluid and ground	Natural gas & oil pipeline
Acoustic emission detectors	–	Commonly used and popular among utilities	Poor results in large dia. pipes Less accuracy for deeply buried pipes	Noise interference, Sensors frequency Range of detection, Soil type & conditions	Water pipe networks
Radiographic Method	–	Cost & time effective Applicable to paved surfaces	Object temp., weather conditions affects the accuracy	Speed of camera Height of camera	Water transmission pipes
SONOTEC (Ultrasonic methods)	Locate within 150m	Can be effectively used for small	Very costly Not for underground pipes	Variable detection range depending on surrounding environment	Sealed pipes and vessels
GPR (Electromagnetic method)	–	Well applicable for metallic pipes with large diameter	Time consuming Lower accuracy	Performance dependent on soil conditions	Water pipeline
Aquascan (Acoustic correlators)		Better results mostly in metallic pipes	Poor results in large dia. pipes	Distance between two accessible points for attaching correlators	Water pipeline
Internal or 'in-pipe' methods					
Explorer (Visual, untethered)	–	Can negotiate diameter changes, bends, tees, etc. Modular design	It is designed for 6 inch and 8 inch diameter pipes	Data recording upto 10 h Challenge remains to develop the platform for commercial use	Natural gas pipeline & network
Pipescan (MFL, Tethered, passive)	–	Portable device for rapid screening and corrosion detection	Cannot tolerate bends and change in diameter	Data recording upto 8 h Cable length of 5 m	Pipes and small dia. vessels
Sahara® (Acoustic, Tethered, Passive)	1 L/h leak rate	Applicable in large diameter pipes > 300 mm	Cannot maneuver bends easily and complicated set-up	Length of tethered cables Presence of in-line components, Network profile, and layout	Water mains
SmartBall® (Acoustic, Passive, Untethered)	0.11 L/min leak-rate & 1.8 m dist.	Can detect fairly small leaks in long-distance pipeline including PCP	More applicable in larger diameter pipeline (250 mm min diameter)	Data recording upto 12 h (can be increased) Adequate headroom required for insertion Inspection range upto 40 km	Water/wastewater pipes

4. Hardware-based leak detection techniques

It is a rather difficult task to monitor the actual physical conditions of the pipe interiors without interrupting services and removing them partially for inspection. At present, real-time monitoring of pipeline infrastructure around the world mostly employs non-intrusive hardware-based leak detection devices. As shown in Fig. 2, these devices can be broadly classified as 'out-of-pipe' or external devices and 'in-pipe' or robotic devices. Hardware-based 'out-of-pipe' leak detection methods were some of the first technical equipment developed for leak inspection of the buried pipeline [42]. These traditional 'out-of-pipe' methods which facilitate inspection of only a small percentage of the network are costly and time-consuming, although their accuracy is comparatively high. They also require skilled and experienced manpower to operate and infer leak locations using these kinds of devices.

On the other hand, 'in-pipe' methods are high in accuracy, less time consuming, and comparatively cost-effective [14]. Compared to 'in-pipe' devices, 'out-of-pipe' equipment is more diverse with respect to installation sites and the principle of operation. A comparative summary of the most common hardware-based methods is described in Table 2.

'Out-of-pipe' devices that detect leaks by sensing specific properties from the pipe exteriors can be based on different principles of operation [43]. These may be installed permanently alongside the network (like cabled sensors) or as portable devices fixed temporarily to the pipe for inspection (like acoustic listeners) or even remotely to a traveling land or air vehicle (like remote sensors). Based on the site of installation, these devices capture different aspects of a possible leak signal in the pipeline. Acoustic devices being most common in this category, 'out-of-pipe' devices are often categorized as acoustic and non-acoustic [44]. Vibration signal emitted from a leak travel along the pipe wall, through the fluid column or escape through the cracks, which can be then detected by different acoustic instruments. Standard acoustic leak detection instruments are acoustic listening devices/rods, accelerometers (for pipe surface detection), leak noise correlators, and tethered/untethered hydrophone systems (for insertion into pipes), like aquaphones or geophones. These devices give a reasonable performance only in case of metal pipes and have limited capability in plastic pipes, and hence the inter-distance between the devices used in plastic pipes has to be significantly reduced to detect the leaking signals [42]. These devices may also become ineffective in detecting leaks in deep-laid underground pipes and even pipeline carrying natural gas [45].

Moreover, there is also a probability of interference with other buried objects or nearby pipeline, which may affect the inspection process, although these interferences can be eliminated to a certain extent through signal amplifiers and noise filters fitted to the acoustic devices. Listening devices may be placed on the surface directly over the buried pipeline location, or listening probes may be used to penetrate the soil to reach nearer to the pipes to detect acoustic signals escaping a possible leak and traveling to the surface. On the other hand, acoustic correlators and accelerometers perceive signals that travel through the pipe wall from two or more locations simultaneously to locate the leak. The third type of device called hydrophones (tethered or untethered for data transmission) is inserted to come in contact with the fluid column of the pipeline through hydrants, valves, or other such access points to detect acoustic leak signals traveling along with the fluid. In spite of several demerits, these methods are still most widely used for leak detection in real systems. Improvements have been put forward to increase the sensitivity of these methods through the utilization of computer-based, cross-correlation techniques and signal processing in combination with these devices [46].

Non-acoustic methods can be further classified into optical-based methods, thermal-based methods, etc. In the case of optical methods, a fiber optic sensing cable has to be installed throughout the entire length of the pipeline. The cabled sensing elements based on optical techniques for leak detection can be classified as active and passive mode, depending upon the source of radiation used for illumination. Active optic devices utilize an external source of light, whereas passive devices primarily exploit the background radiation or radiation emitted by the leak itself. Most optical techniques are temperature-based and are frequently used in oil and natural gas pipeline. However, the typical optical techniques for oil/gas pipeline leak detection cannot be applied directly to water networks, and these methods cannot be implemented easily in the old and existing pipeline. Some of the other non-acoustic techniques are thermographic methods, tracer gas detection, radiographic methods, ultrasonic and electromagnetic methods and remote sensing [14,37]. The main underlying disadvantage of all such devices is that they are not capable of carrying out a cost-effective survey of long reaches of water transmission pipes. All the major types of devices in this category cannot cater to the needs of a remotely managed and automated city-wide water supply system. Their overall drawbacks of being user-dependent, slow in progress, influenced by pipe material and labour intensiveness, for application in a water supply system, has been evident. However, these methods are reasonably effective for inspection of oil and natural gas pipeline as they provide a better cost-benefit for expensive fluids transported through straight-line pipes.

'In-pipe' or robotic inspection devices have been developed for carrying out leak inspection by maneuvering (in active or passive mode) through the insides of pipes [19]. Most simplistic 'in-pipe' devices are perhaps the CCTV cameras, which are commonly used for inspection of sewers and stormwater pipes but are seldom used in water pipes. 'In-pipe' devices, which may function on different principles of operation, are temporarily inserted into the pipeline for data compilation and periodic inspection from within the network. Some of the common commercial 'in-pipe' leak detection devices are individually designed to be inserted into the pipe interior through specific openings and moved within it to detect pipe anomalies. While such robotic devices are inherently sophisticated and complicated to construct, once built these instruments are relatively simple to use. These devices can be further subcategorized based on the motion mechanisms, sensing capabilities, communication mode, energy management and autonomy (Fig. 2) [40]. 'In-pipe' devices are more commonly used in the wastewater pipeline as well as oil and natural gas pipeline. The range of inspection span and accuracy can be substantially augmented through further research on these robotic devices. Most of these devices are still in the stage of research and development and available as a testing prototype only. Their use in the water pipeline is still at a nascent stage. Some of the commercial 'in-pipe' devices presently available for use in water networks are *Smartball, Sahara, MRINSPECT, Explorer, Pipeguard* [47–50]. The use of robotic inspection devices for water networks is particularly complicated because of its mesh-type pattern, with different diameter pipes and numerous bifurcations. Only a few modern ‘in-pipe’ devices can move through restrictive connections, varying diameter range, and pipes of different materials [37]. Some of the devices tested in real networks were observed to be fragile, large in size, and weak in data retrieval. The recent development of wireless sensor-based ‘in-pipe’ robotic devices eliminates a few limitations of previous techniques, but these are more suitable for larger diameter pipes, require specialized deployment-retrieval equipment and pose a risk of potential contamination [51]. Strategic insertion points need to be pre-installed in the pipe network for using 'in-pipe' devices, which may not exist in an old network.

5. Software-based leak detection techniques

The presence of a leak and quantification of loss (i.e., leakage assessment) can be straightforwardly assessed for a hydraulically isolated part called DMA of a water network by using water audits and comparing the input flow data and consumer meter readings during the period of low flow [52]. However, determining the approximate location of a leak in a complex network is the more crucial step, which is time-consuming and labor-intensive when any traditional hardware-based method is used. Background leaks and small-sized leaks, which are more detrimental to the network in the long run, mostly remain undetectable on using the currently available hardware-based techniques. Ideally, the software-based methods are a promising platform in this respect towards providing

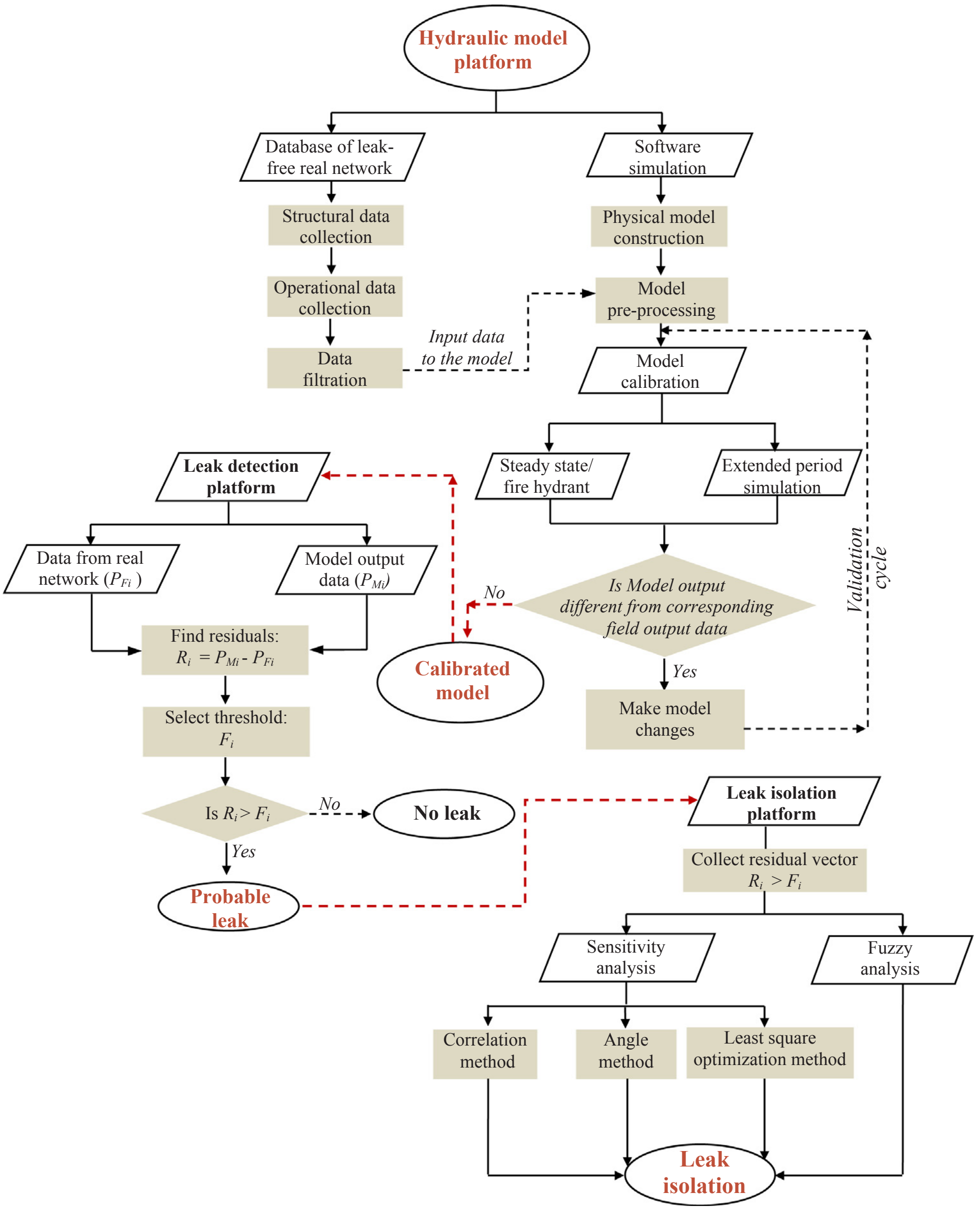

Fig. 3. Methodology for model-based leak detection approach.

a near-complete solution for leak management for leaks of all sizes. In spite of these genuine benefits, software-based leak monitoring and detection approaches are still not popularly used by utility services as they are hugely data-intensive and require an adequate number of data measurement sensors to be installed in the pipeline system [53].

Presently almost all software-based leak detection approaches utilised in real systems are operated under steady-state conditions [54]. These techniques are primarily based on the analysis of flow, pressure, consumer demand, or acoustic data, collected from an ample number of sensors to compile adequate information from the pipeline systems. Over the last two decades, various software-based methodologies have been developed and tested in experimental or field pipeline for leak detection. These software-based techniques are further divided into model-based and data-driven methods (Fig. 2). In case of the availability of an extensive amount of historical data from the real network, data-driven methods are more appropriate. Whereas, model-based methods are preferred when less data is obtainable from the actual network, but its hydraulic model is readily available.

5.1. Model-based leak detection techniques

The earliest model-based technique was proposed by [55] way back in 1992, wherein leak detection was posed as a least-square parameter estimation problem. This technique proved to be rather ineffective for a water network operating under steady-state conditions. From then onwards, significant development of the model-based techniques has taken place. Irrespective of the different techniques and mathematical applications used, all model-based methods are the assemblage of three crucial stages - (i) model building, (ii) model calibration and validation, and (iii) leak detection analysis. The first two stages are technically similar for most methods, while the third stage will vary based on different strategies adopted for leak detection, depending on the specific data analysed, and the mathematical techniques used. Model-based techniques substantially rely on a numerical model for simulating the real pipeline, and the success of these methods largely depend on the quality of the simulated models. The calibration of these models with actual data from the real system using different types of optimization techniques is integral to these methods. A generalised framework for all model-based approaches has been represented in Fig. 3, encapsulating several diversified approaches within a holistic algorithm.

5.1.1. Model building

The construction of hydraulic models is the first stage of any model-based technique. It includes the selection of a suitable modeling software simulation engine and the creation of the map of pipe networks, with all its included features. Fluid flow models are empirical due to their non-explicit nature and are solved only by numerical processes. Several software platforms are available for creating hydraulic models suitable for different fluids, with different hydraulic capabilities and operational modules, as depicted in Table 3. Some of the commercial software available for WDN also has an inbuilt leak detection module, which operates on the principles of optimization using GA (Example: *WaterGEMS*). Leaks are represented as emitter coefficients in the potential leak nodes of the network, wherein larger values of emitter co-efficient signifies a higher leak volume. The structural and operational database of the pipeline system functions as the input information to the hydraulic model. This input information needs to be obtained for a leak-free condition of the real system, which can be assembled through several different software and information systems like Geographic Information Systems (GIS), Computer-aided Design and Drafting (CADD), Supervisory Control and Data Acquisition (SCADA), Customer Information System (CIS) and Asset Management System (AMS) and so on.

5.1.2. Model calibration and validation

Calibration in any model-based technique is carried out in two stages – comparison of modeled data versus real data and model re-modification. The prepared hydraulic model should emulate the actual network in its structural and operational properties as closely as possible. Model pre-processing is carried out before calibration to reduce potential candidates for the calibration process, as the

Table 3
Hydraulic model platforms for the design of pressurised fluid pipeline and pipe networks.

Hydraulic models	Fluid type	Leak detection module	License type
		Single-phase flow	
EPANET	Water	Unavailable	Free
LOOP	Water	Unavailable	Free
CADRE flow	Water	Unavailable	Commercial
Pipe Flow Expert	Water	Unavailable	Commercial
Synergi Pipeline Simulator	All fluids	Available	Commercial
InfoWorks WS	Water	Available	Commercial
WaterGEMS	Water	Available	Commercial
NextGen Simulation Suite	Gas	Available	Commercial
		Multi-phase flow	
Aspen PIPE™	All fluids	Available	Commercial
PIPEPHASE	Oil, gas, steam, CO_2	Unavailable	Commercial
OLGA software	All fluids	Available	Commercial

simulation complexity of the process is directly proportional to the number of candidates for calibration [54]. Two scenarios are considered in the calibration phase – steady-state test (instantaneous test) and an extended period (long term test). If any significant discrepancy is observed during both the simulations, adjustments, and modifications are made to the model properties to match the field results better. As the calibration process is iterative, it may need several steps of comparison and modification [56,57]. Traditionally, pipe friction factors and nodal consumer demands are adjusted in the hydraulic model, to minimize the discrepancy in measurements with the real network. Other factors that may be readjusted are connectivity, operational configurations, flow patterns, and elevations. After calibration is over, the model simulated results are again compared to field data using specific indicators like water levels in storage tanks, pump operation, roughness coefficients, static and residual pressures, obtained for a different set of operational scenarios, to validate the calibrated model. Thus, a structurally accurate and well-calibrated model of the real pipeline which is the basic necessity for the successful implementation of this approach, is obtained.

5.1.3. Leak detection strategies

The most straightforward model-based methodology for pipeline leak detection under steady-state conditions is based on the extrapolation of pressure information from several locations of the real network and its comparison with the simulated pressure at the corresponding locations in a hydraulic model developed for the same network. This methodology is broadly termed as pressure residual vector (PRV) method, and it is the underlying philosophy for model-based methods of leak diagnosis [58]. The difference in real and simulated pressure values at the same location of the real and simulated network is termed as residuals, and when these residuals are higher than a certain threshold (selected based on model uncertainty using statistical or set-based methods), the occurrence of one or more leaks is anticipated [59]. To ensure the robustness of the developed technique, the selected threshold should be adaptive in the time domain according to the input information as well as system dynamics [58]. For the successful implementation of this method, a high and instantaneous pressure drop is a pre-requisite, whereas the slowly occurring, small-sized leaks remain largely undetectable.

Indirect model-based methods are more sophisticated in nature. In the calibration stage, leakage information can be coupled with the calibration process and utilised to locate the leak [57]. Evolutionary optimization techniques like GA are used in conjunction with calibration for leak identification, by modeling leakage as a pressure driven demand [56]. Sensitivity-based techniques may also be applied in the leak detection stage. Based on the pressure sensitivity of a well-calibrated hydraulic model to a leak and non-leak situation, a leakage sensitivity matrix is generated which is then compared to the residual vectors having values higher than its threshold. Columns of leak sensitivity matrix which have the highest correlation with the residual vector indicate the potential leak locations [54]. Similarly, the angle between the residual vector and leak sensitivity matrix columns (angle method) may be obtained to isolate leak locations [60]. A comparative summary of a few significant model-based studies has been tabulated in Table 4. Presently model-based approaches have been validated for simplistic networks using synthetic data and for field networks with real data under controlled conditions.

5.2. Data-driven techniques

Data-driven techniques have a promising applicability for leak detection in pipeline systems that are equipped with an ample number of monitoring sensors. These methods are capable of avoiding the technical complexities of direct hydraulic modeling, and hence the structural and operational complexity of the pipeline (especially in a water network) does not impact its applicability. In simple terms, these techniques strive to locate the outliers in the data presumably caused by an abnormal event like a leak, from the usual pattern recorded in a pipeline system. The simplest of data-driven methods use straightforward measurements of flow and

Table 4
Model-based leak detection studies for pipeline.

Specific technique used	Data used	No. of sensors	Type of network	Software tool used	Ref.
		Calibration based			
Non dominated sorting GA (NSGA II)	Pressure Flow	16	Real network	EPANET; MATLAB	[56]
Leak membership method	Pressure Flow	5	Real network	EPANET	[57]
Particle filter technique, SPC-CUSUM	Pressure Flow	NA	Real network	EPANET	[87]
		Pressure sensitivity analysis			
Classifier based, angle method	Pressure	3	Real network	EPANET	[59]
Correlation matrix	Pressure Inlet flow	8 2	Real network and pilot DMA	EPANET	[54]
Angle method	Pressure	6	Real network	EPANET; MATLAB	[59]
Sensitivity matrix of pipe flow	Pressure	–	Network model	EPANET	[88]
		Principal component analysis			
Filtering of structured residuals and threshold testing	Pressure Flow	4 1	Simulated	SIMULINK	[89]

pressure variables to locate the leaks. The negative pressure wave (NPW) based technique analyses the detection time of leak-induced acoustic waves by sensors in proximity, and Pressure Point Analysis (PPA) based methods detect the leak based on the decrease in pressure values owing to leaks [58,61]. These methods are more suitable for straight pipeline and are likely to fail to register pressure changes accurately in large WDN. Mathematical pre-processing is vital for the data-driven methods, and a diverse range of mathematical techniques, especially machine learning and statistical analysis are used in these approaches. In the most recent methods developed, multivariate analysis, as well as clustering techniques, are also being utilised which facilitate better treatment of uncertainty in these approaches. Several other sophisticated techniques have been developed and tested in WDN, showing promising results [27]. A typical process methodology of a data-driven method is illustrated in Fig. 4.

5.2.1. Data collection, pre-processing and transformation

Data-driven techniques utilize primary information of one or more parameters of the pipeline system collected through sensors, to

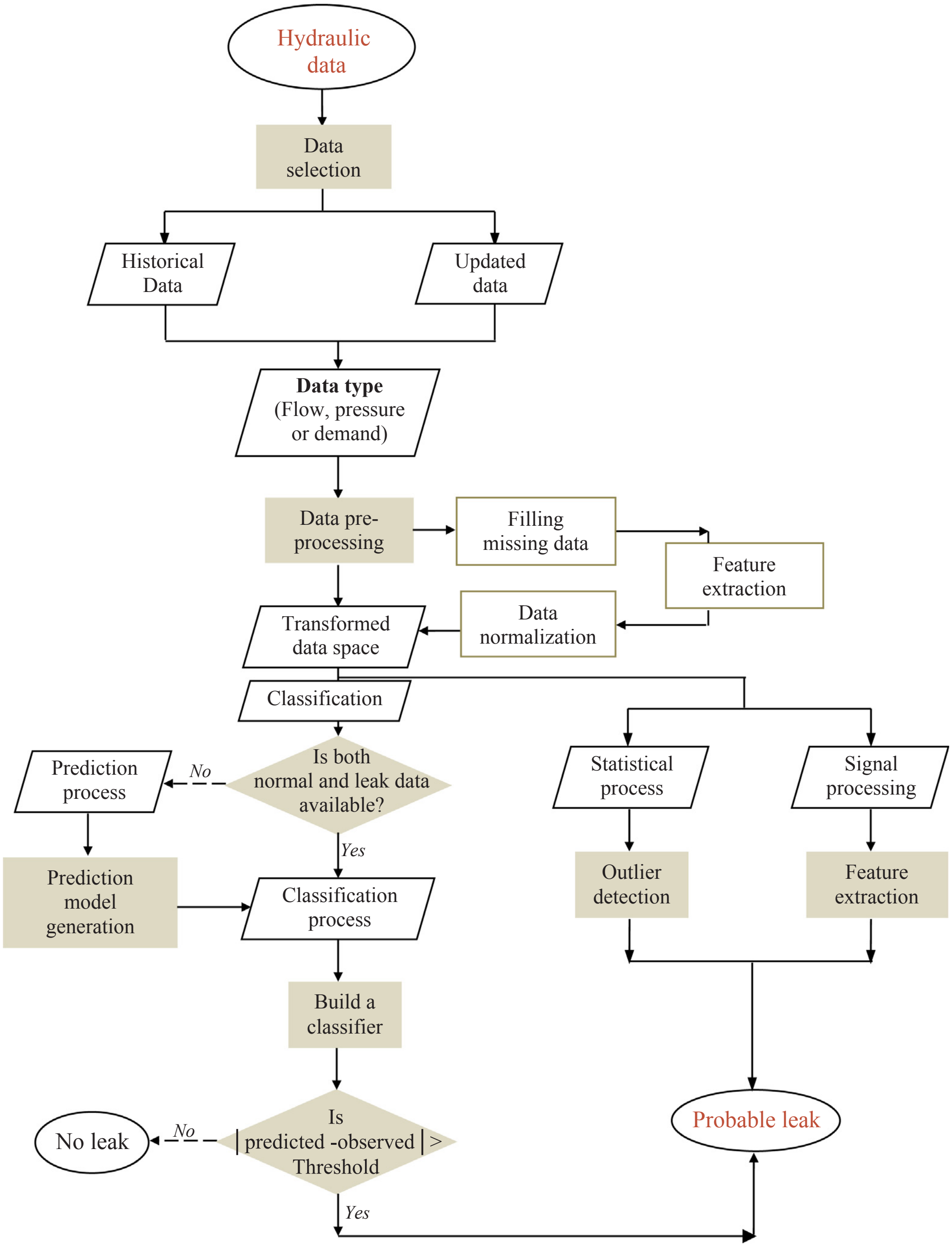

Fig. 4. Methodology for data-based leak detection approach.

Table 5
Data-driven techniques for leak detection in pipeline.

Category	Mode of data	Volume of data	Broad technique used	Type of test pipeline	Sampling rate (min)	Detection efficiency	Ref.
			Flow-based Data				
Classification	Offline real data	Hourly data for 10 days	ANN – static and time delay	Water	1	FPR = 98.69%	[66]
Prediction-classification	Synthetic	241 days	Fourier series, CUSUM		5	FPR = 94.5%	[90]
Statistical	Offline real data	Hourly 6 months	PCA and SPC		5	5% of average flow	[91]
Clustering	Offline real data	6 months	Unsupervised clustering algorithm		5	FAR = 0.61%	[62]
			Pressure-based Data				
Signal processing	Pressure signals	–	Wavelet analysis	Gas	30	Relative error = 5%	[92]
			Demand-based Data				
SPC methods (Univariate) SPC methods (Multivariate)	Offline real data and synthetic data	452 days of continual data	WEC, KUSUM, EWMA Hotelling T^2, MCUSUM, MEWMA	Real water networks and hydraulic models	5	Highest detection efficiency of EWMA based methods	[65]
			Flow and pressure-based data				
AI & Statistical	Offline real data	11 months	ANN, SPC and BIS	Water network	15	FAR = 8%	[68]
Statistical	Offline real data	92,257 data points	Neural networks and clustering	Experimental water network	1	Error = 1.1%	[20]
Signal processing	Synthetic	Second data for 10 hours	Statistical & Wavelet & Feature fusion	Hydrocarbon	0.0167	CCR = 92%	[63]
Signal processing	Synthetic	Second data for 10 hours	D-S Classifier fusion & MLPNN classifiers	Hydrocarbon	–	CCR = 95%	[64]
			Demand & pressure-based Data				
Heuristic method	Historic burst data	44 burst events over two years	Adaptive demand & pressure forecast model	5 water networks	0.167	FAR = 3.33%	[93]

isolate the probable leaks. The sampling rate for primary data typically varies from 1 min to 15 min. Two main aspects of the data – source and length of time series are crucial for the success of the process [60]. Most data-driven methods use either flow or a combination of flow and pressure records. Consumer demand can also be used in leak analysis, although it is effective only in detecting relatively large leak flow-rates [27]. In some circumstances, data can also be obtained from a model, simulated using a competent software [63,64]. Data pre-processing is the most time-consuming step for any data science process which consists of cleaning and organizing the collected data and ensuring it fit for use in the chosen algorithm. Working with real data poses several issues of variability and uncertainty which can be condensed to some extent by pre-processing or transforming it. Pre-processing does not follow a systemized protocol and depending on the nature of raw data and specific requirements of the algorithm used, different transformation techniques are used. The primary aim of data processing is to eliminate the erroneous or missing data from the time-series and subsequently arrange it in a requisite manner for further analysis. In fact, the successful implementation of the leak detection algorithm is mostly dependent on the adequate and efficient pre-processing of the original data.

5.2.2. Leak detection strategies

Data-driven techniques of leak detection can be classified based on technical procedures used, such as simple classification, prediction-classification or statistical analysis, and also signal processing techniques (Fig. 2). Techniques developed under each category may utilize different system variables as input information, which may also be used as a criterion for classification. A summary of a few data-driven techniques (based on data source) has been evaluated in Table 5. Statistical analysis is the most common technique utilised in data-driven methods, and both univariate and multivariate methods have been used [65]. Statistical procedures like Principle Component Analysis (PCA) and Independent Component Analysis (ICA) are used for condensing the data spatially without losing valid information. Machine learning tools like Artificial Neural Networks (ANN), Support Vector Machines (SVM) have also been extensively used along with the newer methods based on multivariate analysis and data clustering algorithms [16,62]. The most straightforward classification technique for distinguishing outlier data caused by leaks is by computing the absolute difference between predicted and observed data, whereas sophisticated technologies like Bayesian Inference Systems (BIS) and Fuzzy Inference Systems (FIS) are also available. Filtering techniques like linear Kalman Filter (KF), as well as support vector regression (SVR) and ANNs, are extensively used in the prediction stage in several studies [66–70], after which classification technique is routinely applied. Classification techniques require data to be captured from the real system under normal as well as leak operation. However, prediction-based techniques can be utilised even with base data of the leak-free network. Irrespective of the techniques used, a high false-positive rate (FPR) is one of the main disadvantages of these methods [27]. Moreover, identification of leak-indicating outliers from the data-set is comparatively easier than determining the temporal location as well as the severity of the leak event. Presently, only large-sized bursts are more effectively detected by this approach.

Digital signal processing uses the pressure or the acoustic signals obtained from the pipeline for feature extraction to identify leakage signatures. Signal processing techniques have been observed to provide better detection and location of leaks than the more commonly used NPW technique, as a sharper transition of the signal is attainable in the former [71]. However, there exists severe restriction on bandwidth for signal analysis owing to pipeline resonance [43]. The selection of the mother wavelet for carrying out wavelet transforms on any concerned signals is of significant importance in signal processing techniques [72]. Some of the common examples of wavelet functions used are Haar Wavelet, Meyer Wavelet, Morlet Wavelet, Mallet Wavelet, and Daubechies Wavelet. Digital signal processing was first used by [73] (1999) in conjunction with electronic transducers to digitize and process the signals recorded using Discrete Fourier Transform (DFT). Different techniques of signal processing used to analyse leak signals are Fast Fourier transform (FFT), Short term Fourier transform (STFT), wavelet transform (WT) and Hilbert-Huang transform (HHT) [22]. Application of wavelet transform to identify the singularities in pressure signals is a common technique to discover leaks or breaks [63,64]. Wavelet transform reduces noise signal and locates the sharp transitions potentially caused by leaks. Formulations using wavelets provide more accurate localised temporal and frequency information. Wavelet transform can be effectively utilised to identify leak related shifts and spikes in the pressure data [74]. Both time and frequency domain information and analysis can be considered simultaneously to extract local as well as global information about the leak sensitive features of the signal.

5.3. Hybrid leak detection techniques

A few studies have combined two or more different approaches or techniques to formulate a better performing leak detection methodology, which may be termed as 'hybrid leak detection techniques' [75]. In this regard, data-driven and model-based approaches have been utilised in conjunction to take into account the strength of both in a singular technique [76]. Pressure residuals for the real network can be obtained by the model-based approach in the first stage, and then in the second stage, a classifier can be applied to these residuals, similar to the data-driven approach [77]. A combination of RTTM and NPW techniques have been effectively used to locate leaks in an experimental gas pipeline with an error of less than 10% [75]. Two or more data processing schemes have also been fused to enhance leak detection in a few studies. [63,64] put forward an integrated approach wherein different data processing schemes – statistical process, machine learning, and signal processing have been combined to enhance the effectiveness of leak detection. Similar methods have been proposed in other studies combining diverse techniques like graph theory and neural network [78], wavelet analysis and Lagrangian model [79], chaos characteristics and SVM [80], rough set theory and artificial bee colony trained SVM [81]. At times, raw signal data from multiple signals may be combined to generate a new 'integrated signal' of lower signal-to-noise ratio and thereby enhancing the detection capabilities of the subsequent leak algorithm [71]. Thus, any two leak detection techniques that may be categorically different but performing complementary to each other can be associated for developing a hybrid method. Irrespective of the participating techniques, this approach has been observed to significantly increase the probability of locating and sizing leaks accurately, whereas most straightforward software-based methods fail to recognize both with appreciable precision.

6. Discussion

Continual monitoring of pipeline infrastructure, which is mostly built underground, for identifying structural defects like leaks, burst, loosening of joints within a short period through physical means is implausible. The water industry still lacks a comprehensive automated leak detection methodology that is practically applicable in real-time networks, which depicts the need for a detailed study of the available techniques on a common platform. Techniques developed for the detection of such anomalies in pipeline systems are widely varied in nature, applicability, technical limitations, and system configuration, as well as hydraulic conditions. Both commercially available tools (hardware-based), as well as those approaches which are still in the research stage (software-based), have different advantages and limitations, concerning different pipe systems and environmental factors. Hardware-based techniques have an immense scope of applicability, and based on the dissimilarities in properties of various fluids, these devices can be tailor-made for leak detection in a pipeline carrying a specific fluid. These methods can be evaluated based on time of assemblage and detection, total cost and accuracy of the set-up. However, these devices often cannot provide for continuous monitoring, and their testing cycles are longer than software-based methods. Several external factors like seasonality, ambient temperature, soil characteristics, and movement may also cause fluctuations in the accuracy of the results, which need to be ascertained before using them. These methods require the continual involvement of several skilled personnel and dealing with heavy equipment, every time a pipeline leak inspection is planned. Investigation of the available hardware-based methods clearly indicates that there is still a pressing need to come up with a pipeline monitoring system, especially for the water distribution sector that can identify any operational anomalies like blockages, leaks and so on at a faster and cheaper rate and with a satisfactory level of accuracy.

The software-based methods, although of great promise, are still underdeveloped, and present techniques are far from ideal. These methods need to address the issue of detection of smaller leaks by increasing their sensitivity and eliminating the interfering signals from the pipeline itself. Software-based methods are primarily classified into model-based and data-driven techniques. When the number of pressure measurement sensors are way less for a sizeable network, model-based techniques prove to be significantly useful. Unlike data-driven methods, these techniques require fewer data to accomplish leak detection, provided a nearly accurate base model is available. However, well-calibrated models are not always available for most of the old utilities, as the estimation of parameters for these models is not easy, and data pertaining to the status of valve operation is unavailable to a full extent for most real networks. Several un-representable parameters and constraints are involved with hydraulic network models with numerous uncertainties. Hence, the maintenance of hydraulic models becomes very cumbersome as the calibration process of water network models is strictly dependent on the availability of appropriate data from real networks. As the name suggests, the data-driven techniques are heavily reliant on the quality and quantity of data available from the pipeline systems, and hence non-availability of adequate data of superior quality is its main drawback. Data collection needs to be carried out over long periods from several locations of the network, to capture the leak-induced hydraulic modifications in the system operational parameters. Moreover, most data-driven methods have been more successful in leak detection rather than in leak localization.

Compared to hardware methods, software-based techniques are in a broad sense, less costly, and labour as well as time-efficient. Once calibrated, optimized, and validated, software methods do not require more than a few personnel, working mostly from a computer system to utilize the developed leak detection strategy for continual monitoring of the pipeline system. Inference provided by software-based methods is primarily not dependent on the technical competence or skill of the operator, as in the case of most hardware-based methods. The best result in leak detection and localization is perhaps exhibited by improvising on an integrated method - combining two or more complementary techniques or approaches. Many recent studies proposed using such hybrid techniques have been more accurate than standalone software-based techniques, with lower error and false alarm rate. At present, these techniques are few and most of them deal with the combination of two complementary techniques.

7. Conclusion

In the present work, a systematic and hierarchical classification of existing leak detection approaches, comparative assessment of hardware and software-based methods, along with an extensive background study of the integrity management strategies for pipes was attempted. Given the primary concern regarding the previous studies in connection to the absence of a comprehensive classification technique, the review formulates a benchmark for several approaches by framing a proper classification and comparison protocol. Furthermore, the two major domains of software methods, i.e., model-based techniques and data-driven techniques, have been critically analysed, highlighting the theoretical advancements and drawbacks. Comprehensive and generalised frameworks for both methods were developed, encapsulating the diversified approaches within a holistic algorithm. These algorithms can catalyze the improvement of existing software-based methods concerning the selection of appropriate data structure and computational tools.

The present review identified that the combination of several techniques to formulate a hybrid technique provides better performance concerning the accuracy in leak detection and lesser error in terms of false alarm. The heterogeneity of these systems facilitates to obtain a leak detection procedure with stronger computational ability than that of a standalone software-based system. It eventually demands that the research needs to be concentrated towards the development of these hybrid techniques that combine the principles of different hardware and software-based tools, with synergistic sensing and computational capabilities. On the other hand, most of the developed techniques have shown better performance on a smaller scale. Hence, the impetus of the research community should be directed towards real-field testing and application of such technologies. The present review has tremendous significance in selecting the appropriate leak detection approach by the water utility authorities as well as directing the systematic research to promote the development of more robust techniques devised by appropriate computational tools.

Declaration of Competing Interest

We declare that we have no significant competing financial, professional, or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

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