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## INFORMATION

### Keywords:

Smart sensors  
artificial intelligence  
leak detection  
water distribution networks  
hybrid sensing  
systematic review  
PRISMA

DOI: 10.23967/j.rimni.2025.10.72902

Revista Internacional  
Métodos numéricos  
para cálculo y diseño en ingeniería

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## Smart Sensors and Artificial Intelligence for Urban Water Networks: A Systematic Literature Review (2015–2025)

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### ABSTRACT

Efficient management of urban drinking water networks is challenged by population growth, rising consumption, and leakage-related losses. This study presents a Systematic Literature Review (SLR) following the PRISMA protocol, covering research published between 2015 and 2025 on smart sensors and advanced techniques for leak detection and consumption optimization. From 788 initial records, 40 studies met the inclusion criteria. Findings indicate that acoustic, pressure, fiber-optic, and hybrid sensing enable real-time monitoring and accurate leak localization, with typical error margins between  $\pm 1\%$  and  $\pm 5\%$ , depending on sensor type and hydraulic conditions. A marked shift toward artificial intelligence (AI) and machine learning is observed for optimal sensor placement, event classification, and prediction, achieving  $>95\%$  accuracy. The cost analysis reveals a direct relationship between technological sophistication and required investment. Overall, integrating smart sensors with AI provides a promising pathway toward more sustainable, efficient, and resilient urban water management.

### OPEN ACCESS

**Received:** 06/09/2025

**Accepted:** 30/10/2025

### DOI

10.23967/j.rimni.2025.10.72902

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Smart sensors  
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systematic review  
PRISMA

## 1 Introduction

The rapid growth of the global population, combined with the exponential increase in water consumption, has led to a substantial reduction in renewable freshwater resources worldwide. Consequently, minimizing water losses in water distribution networks (WDN) has become a strategic priority for sustainable urban development. Within these networks, a significant proportion of potable water is lost through leaks that occur due to aging infrastructure, high pressure variations, corrosion, or mechanical damage [1]. These losses not only represent an economic and environmental challenge but also threaten the operational stability and reliability of urban water systems.

The urban water supply network plays a fundamental role in guaranteeing public health, social well-being, and economic productivity. However, the persistent problem of leakage continues to undermine the efficiency of these systems. Leaks not only increase water and energy consumption but also generate serious risks for water security, such as the infiltration of bacteria or chemical contaminants, pressure drops, and hydraulic imbalances that can compromise supply continuity [2].

From an operational and safety perspective, continuous monitoring is therefore essential to ensure the integrity and efficiency of the entire system [3].

Leaks aggravate the imbalance in water resource distribution, creating inequities in service delivery and posing potential threats to hygiene and urban resilience. A major challenge in managing this issue lies in the fact that many leaks remain undetected for extended periods, often until they reach a critical magnitude [4]. This invisibility contributes to high levels of non-revenue water (NRW) and prevents water utilities from achieving sustainable operational targets. Consequently, the implementation of automated and intelligent leak detection systems has become crucial to reducing losses through early detection and real-time monitoring, leading to measurable savings in both water volume and operating costs [5–7].

Over the past decade, numerous studies have explored techniques for pipeline leak detection and localization, including acoustic emission, pressure gradient, and negative pressure wave (NPW) methods [8–10]. Among these, NPW-based techniques stand out for their relatively simple measurement theory and convenient sensor arrangement, which make them suitable for medium-scale networks [11–14]. Furthermore, acoustic-based leak detection has evolved considerably: studies have evaluated different pipe materials and diameters under real WDN conditions, applying both fundamental and advanced signal processing algorithms [15–17]. For example, Refs. [18–21] proposed a correlation-based method combining numerical simulations in plastic pipes with experimental data from cast iron pipelines, achieving enhanced localization accuracy. Other authors introduced Support Vector Regression (SVR)-based pattern recognition techniques, demonstrating that combining circumferential strain data with SVR models allows the precise localization of leaks over long pipeline distances [22–25].

Despite the diversity of approaches, most traditional systems remain limited by environmental noise, the need for hydraulic model calibration, and the lack of integration with real-time data analytics. Although several detection methods have been successfully implemented, a comprehensive synthesis of the technological advances made during the last decade is still missing, particularly regarding the convergence of smart sensors, hybrid networks, and artificial intelligence (AI) algorithms for predictive water management.

In this context, the present study aims to address the following research question:

What advanced technologies have been implemented over the past ten years to manage urban drinking water networks in real time, with particular emphasis on leak detection and consumption optimization?

Accordingly, the main objective is to identify and analyze the technologies applied to the intelligent management of urban water systems that enhance leak detection efficiency and optimize water use. The specific objectives are as follows:

To identify the most widely used types of sensors and advanced technologies in the management of drinking water distribution networks.

To analyze the methodologies applied for leak detection and classification.

To compare the costs associated with the acquisition, installation, and maintenance of these technologies.

To evaluate the accuracy, robustness, and feasibility of different approaches to determine their practical applicability in urban contexts.

## 2 Materials and Methods

This study corresponds to a Systematic Literature Review (SLR) based on the PRISMA 2020 methodology, which systematically analyzes research published between 2015 and 2025 on the use of sensors and advanced technologies for the intelligent management of drinking water distribution networks, with emphasis on leak detection and optimization of water consumption in urban environments.

The PRISMA framework ensures transparency, reproducibility, and methodological rigor by applying predefined eligibility criteria and a traceable selection process that minimizes bias and maximizes reliability [26].

### Eligibility Criteria

The inclusion and exclusion criteria were defined prior to the literature search to maintain methodological consistency.

**Inclusion criteria:** Studies published between 2015 and 2025, Research focused on advanced technologies and sensors applied to drinking water distribution networks (WDN), Studies addressing leak detection, smart monitoring, and/or optimization of drinking water consumption, Peer-reviewed scientific journal articles, Publications written in English or Spanish.

### Exclusion Criteria

Duplicate records, Publications not corresponding to full research articles (e.g., books, editorials, theses, conference abstracts without full text), Studies focused on non-potable, agricultural, or industrial water systems, Articles not directly related to sensor technologies, monitoring systems, or artificial intelligence applications.

### Information Sources

The review used internationally recognized databases known for their scientific rigor and thematic coverage in engineering and applied sciences: ScienceDirect, Scopus, and Web of Science (WoS).

These databases were selected because they index peer-reviewed, high-impact publications and allow the application of Boolean operators, temporal filters, and advanced search functions to ensure a precise and comprehensive retrieval of studies.

The systematic search was conducted in April 2025, covering publications from January 2015 to April 2025, to ensure the inclusion of the most recent developments and trends in smart sensing technologies for urban water management.

### Search Strategy

The search strategy was constructed using combinations of keywords and Boolean operators, adjusted for each database to ensure consistency and reproducibility. The searches targeted titles, abstracts, and keywords.

The main terms included “leak detection”, “sensors”, “water distribution networks”, “optimization”, and “artificial intelligence”, combined with AND and OR operators. Filters were applied for document type (article), language (English or Spanish), and publication period (2015–2025), The exact search equations used in each database are found in [Table 1](#).

**Table 1:** Exact search equations used in each database

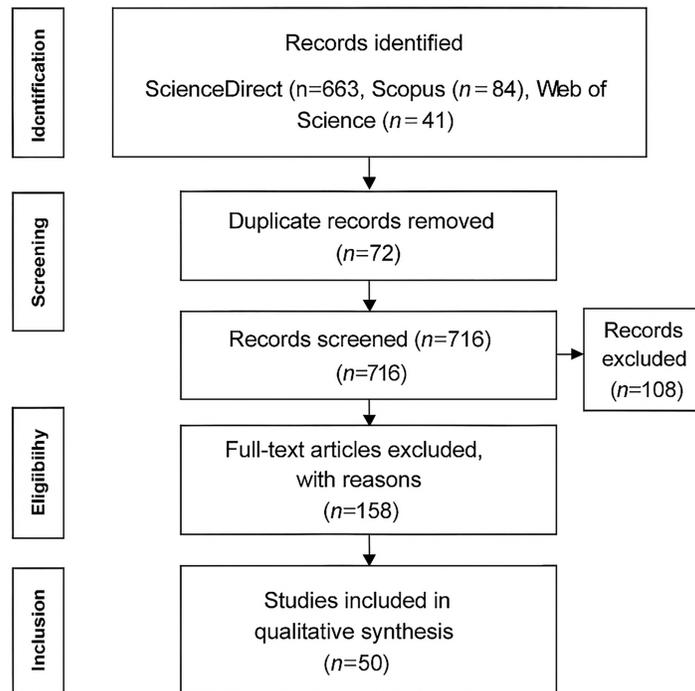
Database	Search equation	Recovered results
<b>Scopus</b>	TITLE-ABS-KEY(("leak detection" AND "smart sensors") OR ("artificial intelligence" AND "water distribution network")) AND PUBYEAR > 2014 AND PUBYEAR < 2026	246
<b>Web of science</b>	TS = ("leak detection" OR "leak localization") AND TS = ("smart sensors" OR "machine learning") AND TS = ("water network" OR "distribution system")	212
<b>ScienceDirect</b>	("leak detection" OR "sensors" OR "optimization") AND ("drinking water" OR "urban water network")	330

Note: Source: Own.

### Study Selection Process (PRISMA Flow)

The study selection process followed the PRISMA 2020 guidelines and comprised three main stages: Identification, Screening, and Inclusion.

All steps were recorded in the PRISMA flowchart (Fig. 1), ensuring transparency and consistency between the textual and visual data.



**Figure 1:** PRISMA process flowchart

**Identification phase:** 788 records were initially identified across all databases.

After automatic and manual duplicate removal ( $n = 28$ ), 760 unique articles remained.

**Screening phase:** Titles and abstracts were reviewed to assess relevance and alignment with the inclusion criteria.

690 articles were excluded for being unrelated to the scope (e.g., irrigation, desalination, or wastewater systems), leaving 70 articles for full-text review.

**Eligibility and inclusion phase:** Of these, 30 articles were excluded after full-text evaluation (due to incomplete data or lack of methodological rigor).

The remaining 40 studies met all inclusion criteria and were incorporated into the final synthesis and analysis.

This corrected sequence ensures internal consistency:

788 total  $\rightarrow$  28 duplicates  $\rightarrow$  760 screened  $\rightarrow$  690 excluded  $\rightarrow$  70 full texts  $\rightarrow$  30 excluded  $\rightarrow$  40 included.

### **Data Extraction**

Data extraction was performed using a structured Excel matrix based on the PRISMA data extraction template, which allowed for uniform recording and cross-verification of key study characteristics.

Each author independently reviewed the full texts and completed the dataset, which was then cross-checked to ensure accuracy and consistency.

### **The Variables Extracted from Each Article Included**

Author(s), Year of publication, Article title, Research objective, Type of sensor used, Technological approach (acoustic, pressure, optical, hybrid, AI-based), Reported accuracy or performance metrics, Country or study setting, Source database.

### **Risk of Bias and Quality Assessment**

A quality evaluation matrix was applied to assess potential sources of bias, ensuring that each selected article demonstrated coherence between objectives, methodology, data analysis, and reported results.

The criteria evaluated included study design, sampling strategy, instrument calibration, and reproducibility of findings.

Each reviewer independently rated the methodological soundness using a three-level scale (high, moderate, low).

Disagreements were resolved by discussion to maintain objectivity.

### **Synthesis Methods**

A qualitative thematic synthesis was performed to interpret the extracted data. Studies were grouped according to their methodological approach, type of sensor, and use of artificial intelligence or hybrid algorithms.

Patterns, recurring challenges, and technological innovations were identified across the corpus, allowing the review to highlight dominant trends and research gaps.

This structured synthesis provided a comprehensive response to the main research question and established a robust foundation for identifying future lines of inquiry in the digital transformation of urban water management systems.

### 3 Results

This chapter presents the results obtained from the process of searching for and selecting studies, following the phases of the PRISMA method

#### Selection of Studies

The distribution of the articles identified in each database during the search process is presented below. The [Table 2](#) shows the absolute, relative frequency and the corresponding percentage.

**Table 2:** Article frequency for each database

Database	Frequency		
	Absolute	Relative	Percentage
Science direct	663	0.84	84%
Scopus	64	0.08	8%
Web of science	61	0.08	8%
Total	788	1.00	100%

Note: Source: Own.

To represent the different phases of inclusion and exclusion applied in this systematic review, the PRISMA flowchart was used. [Fig. 1](#) presents this diagram, which shows the selection process and the interrelation of the criteria used to identify the articles relevant to this research.

[Table 3](#) summarizes studies selected through the PRISMA screening process, covering the decade 2015–2025, and representing the evolution of methodologies, sensor technologies, and analytical models for leak detection and localization in water distribution networks (WDN). Each entry identifies the study year, main objective, and key findings, allowing comparative insight into technological progression across temporal and methodological dimensions.

**Table 3:** Articles on the use of sensors and advanced technologies

Item	Year	Title	Key findings
[1]	2023	A fault-based approach to leak localization in water distribution networks, using a Bayesian classifier array model	The study proposes a method of locating leaks in water distribution networks using Bayesian classification. By injecting and propagating digital faults to separate leakage characteristics, an accuracy of 94.6% and 93.76% is achieved in Hanoi and Modena networks, respectively, outperforming existing methods.
[2]	2023	Optimal sensor location for leak detection in water distribution networks, based on the EGAE clustering algorithm	The study proposes a pressure sensor design method based on EGAE clustering, optimizing the placement of sensors in water networks to improve leak localization and reduce errors compared to other approaches.

(Continued)

**Table 3 (continued)**

Item	Year	Title	Key findings
[3]	2024	Performance of low-cost fiber optic cables as leak detection sensors in water pipes in unsaturated soils	This paper presents a method for converting band-bounded signals into band-bound signals in water distribution networks, improving sensor placement and accurate leakage localization using graphical sampling.
[4]	2023	Frequency-Based Leakage Signature Investigation Using Acoustic Sensors in Urban Water Distribution Networks	The study evaluates low-cost hydrophones to detect leaks in water networks, using acoustic analysis. Although real-world conditions present challenges, hydrophones showed potential to identify leaks in complex pipelines.
[5]	2024	Hybrid wireless sensor network based on TDR-MI for the detection and location of leaks in underground water pipes using pressure residues and classifiers	This study proposes a hybrid network of wireless sensors based on magnetic induction and time-domain reflectometry (TDR) to detect and locate leaks in underground pipes in real time, improving accuracy and reducing inspection time.
[6]	2023	“Efficiency enhancement of leakage detection and localization methods using leakage gradient and most affected sensors”	Water leaks cause major economic and resource losses in distribution networks. This study proposes an efficient three-step strategy—model calibration, detection, and localization—validated in the L-Town benchmark, demonstrating higher efficiency and accuracy than conventional methods.
[7]	2025	A Two-Stage Leak Monitoring Framework for Water Distribution Networks Based on Acoustic Signals	This study presents a two-stage system based on acoustic signals and RCT-Net networks to detect and evaluate leaks in pipes, achieving high precision and robustness, and improving the management and sustainability of water distribution networks.
[8]	2025	Detection and localization of leaks in water pipes with an integrated AI technique	This study proposes a standalone leak detection and localization system using an acousto-optic sensor and a 1DCNN-enhanced AdaBoost model, achieving high accuracy and stability, with potential for real-time applications across various pipeline conditions.

(Continued)

**Table 3 (continued)**

Item	Year	Title	Key findings
[9]	2025	Low-model-dependent sensor placement method for water distribution networks using adaptive attributed graph clustering	This study proposes an efficient and adaptable method for the placement of sensors in water networks, based on the classification of nodes using graphs, improving leak detection and reducing dependence on complex hydraulic models.
[10]	2025	Network of hybrid wireless sensors based on TDR-MI for the detection and location of leaks in groundwater pipes using pressure residues and classifiers	The study proposes a hybrid network of sensors based on magnetic induction and TDR to detect and locate leaks in underground pipes, improving real-time accuracy and optimizing the system with statistical classification and K-means clustering.
[11]	2025	Method of Sensor Placement for Water Distribution Networks Based on Sampling of Graphic Signals Without Bandlimit	This paper presents a method for converting band-bounded signals into band-bound signals in water distribution networks, improving sensor placement and accurate leakage localization using graphical sampling.
[12]	2025	A novel approach based on graph signal processing and sampling theory to set pressure sensors in water distribution networks	The chapter addresses the importance of real-time monitoring of water quality using sensors and AI algorithms, highlighting its role in the efficient management of limited resources, optimizing the detection of contaminants and promoting sustainability and environmental protection.
[13]	2024	Graph of the pressure sensor placement strategy based on Laplace's regularization for the location of leaks in water distribution networks under common hydraulic and topological conditions	The study investigates the use of five types of fiber optic cables, including telecommunications cables, for passive leak detection in water distribution systems. Leaks alter temperature and soil deformation, and flexible cables with a compact structure proved to be the most efficient as detection sensors.
[14]	2024	Water leak detection and classification using multiple sensors	This study uses machine learning methods and acoustic measurements to detect and classify leaks in water distribution networks, achieving satisfactory results in the detection and classification of different types of leaks.

(Continued)

**Table 3 (continued)**

Item	Year	Title	Key findings
[15]	2024	Combining clustering and regularised neural network for burst detection and localization and flow/pressure sensor placement in water distribution networks	The study uses sensory data from a laboratory-scale water distribution system to detect and locate leaks using artificial neural networks. Using features such as autocorrelation and signal energy, the model achieved an accuracy of 86.5%, highlighting the value of AI in water management.
[16]	2023	Smart Water Networks: Systematic Review of Applications with High-Frequency Acoustic and Pressure Sensors in Real Water Distribution Systems	This study analyzes real cases of smart water networks with high-frequency sensors, identifying applications, benefits and challenges, and suggests standardizing their implementation to optimize the management and evaluation of water systems.
[17]	2023	Optimal Sensor Placement for Leak Location in Water Distribution Networks: A Feature Selection Method Combined with Graphical Signal Processing	The study proposes an Optimal Sensor Placement (OSP) method for water distribution networks, avoiding dependence on hydraulic models. It uses a heuristic algorithm and graph signal processing, achieving efficient monitoring and rapid selection of nodes with better comparative results.
[18]	2023	A two-phase approach to leak detection and localization in water distribution systems, using wavelet decomposition and machine learning	The paper presents a two-phase approach to leak detection and localization in water distribution systems, using wavelet analysis and machine learning. The first phase achieves 99% accuracy in detection, and the second phase locates leaks using sensors. It is validated in the “L-Town” system and is supported by a web application.
[19]	2023	Optimal Placement of Acoustic and Pressure Sensors for Leak Detection in Nagpur City Ramnagar GSR Water Distribution Network	The study proposes a method to determine the optimal locations of pressure and acoustic sensors in the Ramnagar GSR network, using DEMATEL and an entropy-based approach, optimizing the number of sensors.

(Continued)

**Table 3 (continued)**

Item	Year	Title	Key findings
[20]	2023	A recessed impedance sensor in pipes to monitor water leaks in distribution networks: design and validation	An impedance sensor is introduced to detect small water leaks (less than 1 L). Using longitudinal electrodes and real-time detection, it allows for early warning. It was experimentally validated, optimizing the electrode geometry and the detection frequency (2 MHz).
[21]	2022	Optimal multi-target, risk-based sensor placement for leak detection in a water distribution system	A method of optimal placement of sensors is proposed considering the risk of leakage in each node. Using multi-objective optimization and impact-based functions, a more effective and realistic scheme for limited networks is obtained.
[22]	2022	Evaluation of robust sensor location schemes for leak isolation in water distribution networks	This study proposes a robust scheme for the location of pressure sensors in RDA, optimized with genetic algorithms, considering noise and demand variation, and evaluated by simulation in a real network in Italy.
[23]	2022	A novel method of detecting and locating leaks in pipes based on the FBG pipe fitting sensor array and compressed detection theory	This study proposes a method of detecting leaks in pipes based on the theory of sensory compression, improving accuracy without further sensors, and achieves localization errors of only 2 m with $bCS = 0.5$ .
[24]	2022	Model-free sensor placement for water distribution networks using genetic algorithms and clustering	This paper proposes a model-free methodology for locating pressure sensors in RDA using genetic algorithms and distance metrics, validated in L-TOWN, without requiring hydraulic models.
[25]	2022	Sensor placement methodology with incremental updating: Application to the location of leaks in water networks	A methodology for the remapping of pressure sensors in large-scale water networks is presented, optimizing their location to improve fault isolation, using sequential algorithms and simulations with real leakage data.

(Continued)

**Table 3 (continued)**

Item	Year	Title	Key findings
[26]	2022	Methodology for the optimal placement of pressure sensors for leak detection in water distribution systems using the value of information	This study proposes a methodology to locate pressure sensors considering the Information Value (VOI), optimizing decisions about leaks in water networks. Outperformed traditional configurations in one European district evaluated.
[27]	2022	Optimal Sensor Placement for Sustainable Leakage Management in Water Distribution Networks in Developing Economies: A Hybrid Decision Support Framework	This study proposes a decision support framework for locating sensors in deficient water networks, combining sensitivity analysis and MCDM, allowing leakage management in a cost-effective way in resource-limited contexts.
[28]	2022	Improve leakage management to achieve sustainable water supply networks through green energy systems. Optimized case study	This study proposes a methodology for self-calibration of leaks in water networks, optimizing hydraulic and energy efficiency, with environmental and economic benefits, applied to a case in Manta, Ecuador.
[29]	2022	Positioning Methodology for Incremental Improvement Sensors: Application to Leak Location in Water Networks	A methodology for reassigning pressure sensors in water networks is presented, optimizing their location through a sequential algorithm. It is validated in two Spanish networks using simulations, real measurements and spatial interpolation.
[30]	2021	Robust Method of Hierarchical Optimization of Sensor Placement for Leak Detection in Water Distribution Systems	This study presents an improved hierarchical algorithm for the optimization of sensor placement in water distribution systems, improving leak detection and robustness to sensor failures.
[31]	2021	Leak Detection and Localization in Water Distribution Systems: A Model Invalidation Approach	This study proposes an optimization-based methodology to detect and locate leaks in water distribution systems using a priori information, modeling uncertainties with intervals, and refining locations through pressure and flow measurements.

(Continued)

**Table 3 (continued)**

Item	Year	Title	Key findings
[32]	2020	Placement of pressure sensors in water distribution networks for leak detection using a hybrid approach of information and entropy	This study proposes a hybrid optimization framework based on Information Value and Transinformation Entropy to identify leaks in water distribution networks, improving accuracy and reducing computational load.
[33]	2019	Leak Detection in a Real Water Distribution Network Based on Search Space Reduction	This paper presents a multi-objective approach to the placement of sensors in water distribution networks, optimizing the detection and localization of leaks in the presence of uncertainties and variability.
[34]	2019	Location of multi-objective sensors for the detection and location of leaks in water distribution networks	This article presents a method based on optimization and reduction of search space to detect and locate leaks in water distribution networks, improving accuracy and reducing economic impacts.
[35]	2018	Sensor Location for Classifier-Based Leak Localization in Water Distribution Networks by Selecting Hybrid Features	This paper presents a hybrid approach to the placement of pressure sensors in water distribution networks, using a genetic algorithm to determine the optimal location and improve leak localization.
[36]	2018	Optimal joint implementation of flow and pressure sensors for the identification of leaks in water distribution networks	This study proposes a sequential optimization methodology with NSGA-II to locate pressure and flow sensors in water networks, improving the accuracy in the identification of leakage zones.
[37]	2018	Optimizing the Performance of a Leak Detection System in Water Distribution Networks	This paper proposes a robust leak detection scheme in water networks, using an autoregressive model with evolutionary optimization to improve performance in real distribution systems.
[38]	2018	Optimal sensor location based on compressed detection for the location of leaks in water distribution networks	This paper proposes an optimization strategy for placing sensors in water networks, based on compressed detection and a bee colony algorithm, maximizing diagnostic capacity with budget constraints.

(Continued)

**Table 3 (continued)**

Item	Year	Title	Key findings
[39]	2018	A Graph Partitioning Algorithm for Leak Detection in Water Distribution Networks	This paper presents a method for detecting leaks in urban water distribution networks by means of water balance and minimum flow measurements, using graph partitioning and MILP programming.
[40]	2018	Locating Leaks in Water Distribution Networks Using Fisher Discriminant Analysis	This paper proposes the use of Fisher's Discriminant Analysis (ADF) for the location of leaks in water distribution networks, also considering the optimal location of the sensors.
[41]	2017	Planning model for the optimal implementation of leak sensors in a water pipe network	This study proposes a model based on the k-median problem to plan the optimal installation of leak sensors in water pipe networks, maximizing efficiency and reducing costs.
[42]	2017	Detection and localization of leaks in water pipes using vibration sensors and modified ML prefilters	This paper presents an improved method for detecting and locating leaks in water pipes using vibration sensors and generalized cross-correlation, achieving greater accuracy through a modified maximum likelihood prefilter.
[43]	2017	Risk-Based Sensor Placement Methods for Break/Leak Detection in Water Distribution Systems	This study formulates the optimal placement of sensors in water networks as a risk-based optimization problem, considering probability of detection, impact and exposure, with application in Harrogate.
[44]	2017	Optimal placement and evaluation of pressure sensors for leak detection by means of a relaxed insulation index: Application to the water network in Barcelona	This article proposes a methodology for the placement of sensors to improve the location of leaks in water distribution networks, considering practical aspects such as topology and acceptable distances, validated in real networks in Barcelona.
[45]	2017	Sampling design for leak detection in water distribution networks	This study presents a sampling design method to optimize the placement of sensors in water distribution systems, improving leak detection through a multi-objective approach.

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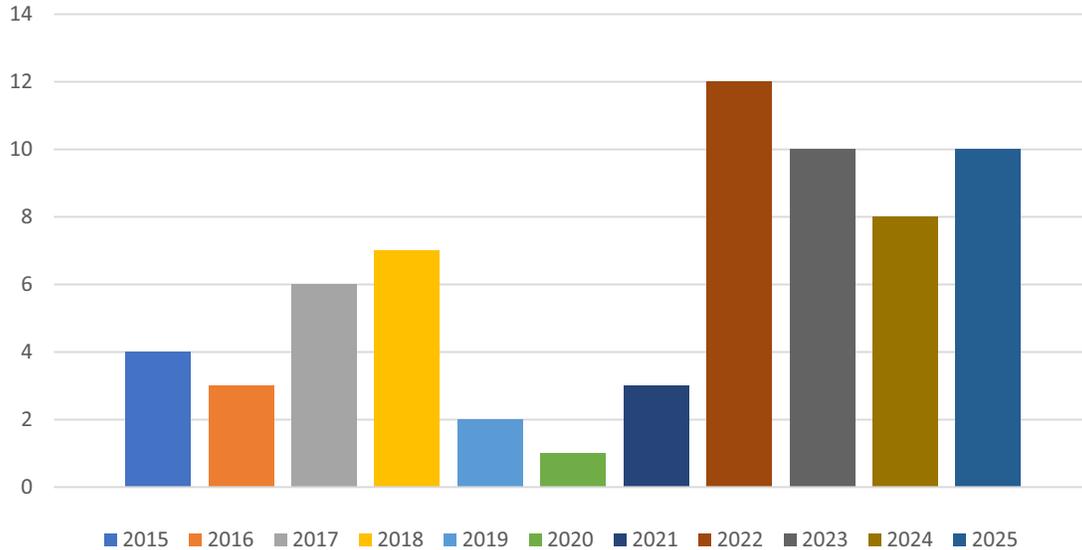
**Table 3 (continued)**

Item	Year	Title	Key findings
[46]	2016	Mobile sensor networks for the optimal detection and localization of leaks and backflows in municipal water networks	This study proposes a network of wireless mobile sensors to detect leaks in water systems, optimizing the location of sensors and beacons with budget constraints through a MINLP model and a disjoint strategy.
[47]	2015	Location of sensors for the detection of leaks in water distribution networks using the leak signature space	This paper proposes an integer optimization approach to position sensors and improve leak localization in water networks, minimizing the overlapping of leak signatures by AG or PSO.
[48]	2015	Optimal placement of pressure sensors in water distribution networks: minimization of uncertainty in the location of leaks	This paper presents an optimal strategy for placing sensors in water networks using pressure sensitivity analysis, comprehensive search, and a new metric to assess uncertainty in leak location.
[49]	2015	Optimal Location of Sensors for Leak Detection in Water Distribution Networks Using Evolutionary Algorithms	This study proposes to place sensors in water networks minimizing overlapping signatures using the LSS method and algorithms such as AG and PSO, thus improving the accuracy in the location of leaks.
[50]	2015	Locating Leaks in Water Distribution Networks Using Simulated Annealing and Graph Theory	This paper presents an optimization approach for leak localization in water distribution networks, based on pressure monitoring, graph theory, and simulated annealing.

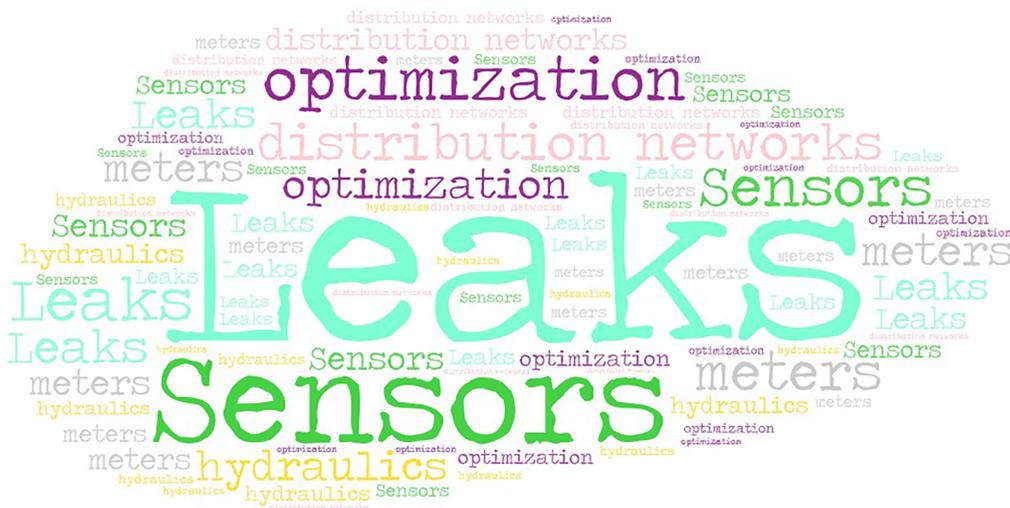
Fig. 2 illustrates the temporal distribution of scientific publications analyzed in this review. The trend shows a progressive increase in research output, with modest activity between 2015 and 2019, followed by an exponential rise beginning in 2021. The peak in 2022 (12 publications) marks a turning point in the consolidation of smart sensor technologies and AI-driven models for leak detection in water distribution networks. The sustained high output from 2023 to 2025 confirms a shift toward digital transformation and data-centric approaches, indicating growing global attention and research maturity in intelligent water management systems.

Fig. 3 presents the keyword frequency network generated from the 50 selected studies. The most prominent terms—“*Leaks*”, “*Sensors*”, “*Optimization*”, and “*Distribution Networks*”—indicate the dominant research focus on sensor-based monitoring, leak detection, and network optimization in water distribution systems. The frequent appearance of terms such as “*Hydraulics*” and “*Meters*” further emphasizes the integration of hydraulic modeling and sensor instrumentation as central components of modern water management research. The visualization confirms that the intersection

between **sensing technologies** and **optimization strategies** has become the main axis of scientific development in this domain over the last decade.



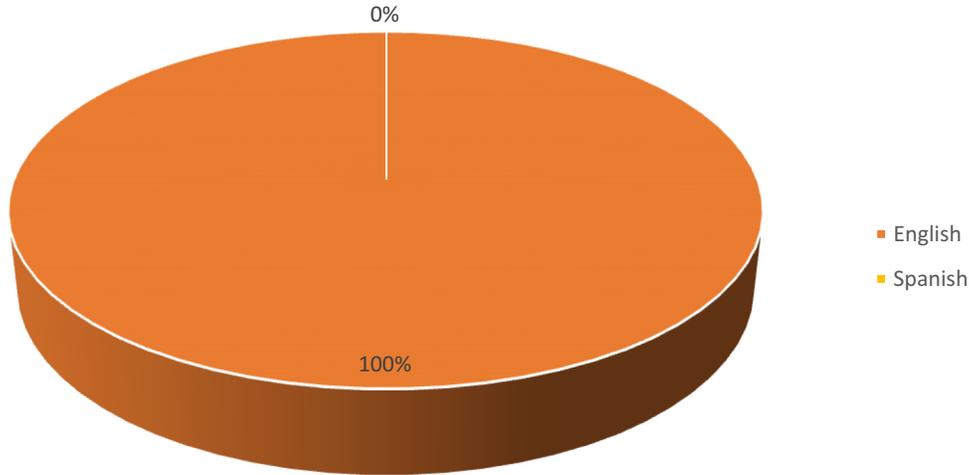
**Figure 2:** Publication trends by year from 2015 to 2025



**Figure 3:** Increased keyword trend

Fig. 4 shows that 100% of the selected studies were published in English, while no Spanish-language research met the inclusion criteria for this systematic review. This finding highlights the predominance of English as the global language of scientific communication, particularly in engineering and applied science disciplines. The absence of studies in Spanish suggests a limited regional contribution or reduced visibility of Latin American research within major indexed databases such as Scopus, ScienceDirect, and Web of Science. Consequently, future efforts should aim to strengthen

the publication and indexing of research in other languages, especially from developing regions, to promote greater inclusivity and knowledge transfer in the field of intelligent water management.



**Figure 4:** Number and percentage by publication language

Table 4 shows a comparative analysis that shows a marked technological evolution in the last ten years. Acoustic sensors ([14,19,35]) have historically been the first choice due to their low cost and ease of installation; however, they present limitations in urban environments with high background noise and variable hydraulic conditions, which generates relatively high margins of error ( $\pm 6\%$ ).

**Table 4:** Typology of sensors and technologies applied to urban drinking water networks

Technology category	Main sensors used	Example of applications	Level of accuracy	Typical margin of error	Key advantages	Key limitations	References
Acoustic	Piezoelectrics, hydrophones, accelerometers	Vibration and sound detection in pressurized pipes	High	$\pm 2\% - 6\%$	Simple installation, low cost, compatible with existing networks, effective for metallic pipes	Limited performance in plastic or buried pipelines, affected by background noise	[14]
Pressure	Nodal sensors, multi-parameter transducers	Real-time leak localization, pressure and flow optimization	High	$\pm 2\% - 5\%$	High temporal resolution, robust data for hydraulic modeling, useful for transient analysis	Requires network calibration, sensitive to pressure fluctuations and boundary conditions	[2]
Fiber Optics	FBG sensors, Brillouin and Raman-based cables	Passive leak detection in unsaturated or buried soils	Very High	$\pm 1\% - 2\%$	Immune to electromagnetic interference, long-distance monitoring, high spatial precision	High cost of installation and maintenance, complex data interpretation	[3,23]

(Continued)

**Table 4 (continued)**

Technology category	Main sensors used	Example of applications	Level of accuracy	Typical margin of error	Key advantages	Key limitations	References
Hybrids	Acoustic–Optical, TDR–MI integrated networks	Real-time localization of complex or multi-source leaks	Very High	±1%–3%	Combines multiple sensing modalities, enhances redundancy and reliability, adaptable to varied conditions	Requires complex data fusion algorithms, higher energy demand, difficult field calibration	[10]
Artificial Intelligence (AI)	CNNs, Bayesian Classifiers, Wavelet+ML models	Multi-objective prediction, leak classification, and optimization	Very High (>95%)	±1%–5%	Self-learning capability, predictive analysis, adaptable to different pipe materials and conditions	Requires large datasets, high computational demand, limited transparency (“black-box”)	[15,18]

On the other hand, pressure sensors ([2,10,14]) offer advantages in terms of network coverage and real-time detection, being widely used in optimal placement strategies. However, they rely on accurate hydraulic calibration and can lose efficiency in networks with incomplete records.

Fiber optics ([3,23]) represent a disruptive advance: it provides passive leak detection with very high accuracy (±1%–2%), even in unsaturated soils. Its main limitation lies in the high installation costs and the need for specialized equipment, which restricts its application to pilot projects or contexts with high investment.

Hybrid systems ([10]) integrate acoustic, pressure, and optical signals, achieving real-time detection and localization with reduced margins of error (±1%–3%). These models respond to the need for robustness in dense urban contexts, although with high infrastructure and data processing requirements.

Finally, solutions based on Artificial Intelligence (AI) ([15,18]) are consolidated as the most promising trend, exceeding 95% accuracy thanks to the use of neural networks, Bayesian classifiers and wavelet algorithms. AI not only improves detection, but also leak classification and resource optimization, although it relies on large volumes of training data and advanced computational capabilities.

Table 5 shows that the implementation cost is directly proportional to the level of technological sophistication and precision achieved. Low-cost sensors (<USD 2000), such as hydrophones and conventional pressure nodes, remain widely used in experimental and early-stage applications due to their affordability and ease of deployment ([4,18]). However, their performance deteriorates in networks with high ambient noise, variable pressure, or complex hydraulic layouts, which limits scalability and data reliability in large-scale urban systems.

In the mid-cost range (USD 2000–5000), advanced acoustic and optimized nodal sensors provide a better cost-benefit balance, achieving accuracy improvements of up to 20% compared to conventional setups ([2,41]). These technologies are recommended for medium-sized utilities, where operational robustness is needed with controlled investment, although they depend on support algorithms to refine leak localization and reduce false positives.

**Table 5:** Approximate implementation costs

Investment level	Estimated range (USD)	Associated technologies	Remarks	References
<b>Low</b>	<2000	Basic hydrophones, conventional pressure sensors	Easy installation, noise sensitive	[4,29]
<b>Middle</b>	2000–5000	Advanced acoustic sensors, optimized nodal	Good balance between cost and accuracy	[2,41]
<b>High</b>	5000–15,000	Fiber Optics, Hybrids, SWN	High precision; require calibration and IoT connectivity	[23,39]
<b>Very high</b>	>15,000	Hybrid IoT networks, complex algorithms (NSGA-II, Wavelet+ML)	Oriented to pilot projects or large cities	[18,34]

High-cost technologies (USD 5000–15,000)—notably fiber-optic and hybrid TDR–MI systems—offer superior precision and real-time data acquisition, with margins of error below  $\pm 2\%$  ([23,39]). Yet, their deployment requires specialized infrastructure, calibration expertise, and advanced data analytics, making them inaccessible for most utilities in developing economies.

At the top end, very high-cost systems (>USD 15,000) integrating hybrid IoT sensor networks and complex algorithms (e.g., NSGA-II, Wavelet+ML) are primarily used in pilot projects and smart city testbeds ([18,34]). These solutions enable predictive water management and long-term sustainability, but they depend on high computational capacity and regulatory support for data governance and cybersecurity.

From a strategic perspective, this review identifies as the most urgent research challenge the validation of low-cost AI-based solutions capable of replicating the precision of high-end systems at a fraction of the cost. Bridging this economic and technological gap is crucial for achieving equitable access to smart water management in developing regions. Therefore, future efforts should focus on open-source AI frameworks, energy-efficient sensors, and cloud–edge integration, ensuring that digital water technologies are both scalable and inclusive.

Table 6 summarizes the most influential studies identified in this Systematic Literature Review (SLR), confirming a clear transition toward smart and data-driven methodologies for leak management in urban water networks. The research by [7] demonstrates that integrating acoustic sensors with Convolutional Neural Networks (CNNs) can achieve accuracy rates above 95%, even under low-flow leak conditions. This result highlights the transformative potential of Artificial Intelligence (AI) to enhance conventional detection systems, marking a significant qualitative leap in operational efficiency and early event recognition.

Similarly, the contribution by [21] which applies multi-objective optimization algorithms for sensor placement—shows that the number of required pressure sensors can be reduced by up to 40% without compromising accuracy. This outcome is particularly relevant for utilities in developing economies, where installation and maintenance costs remain critical barriers to large-scale implementation.

**Table 6:** Featured studies and key findings

Applied technology	Methodology	Main results	References
Acoustic Sensors + AI	CNN Neural Network	>95% accuracy on small leaks	[7]
Pressure sensors	Multi-objective optimization	40% reduction in the number of sensors required	[21]
Acoustic-optical hybrid	AdaBoost + 1DCNN	High stability in urban conditions	[8]
Model-free sensors	Genetic algorithms	Efficient monitoring in calibration-free networks	[24]
Optimal placement	Value of Information (VOI)	Early detection (<1 h) in urban networks	[26]

Furthermore, Ref. [8] validates a hybrid acoustic–optical system combined with AdaBoost and 1D-CNN algorithms, achieving high stability and robustness in dense urban settings characterized by variable flow regimes and noise interference. This represents a crucial step toward resilient hybrid systems adaptable to complex real-world networks.

A disruptive advance is introduced by [24], which proposes model-free leak detection methods—eliminating the dependency on calibrated hydraulic models. This innovation extends the applicability of smart detection systems to networks lacking complete or accurate hydraulic data, a common limitation in many emerging cities.

Finally, Ref. [26] introduces an approach based on the Value of Information (VOI), optimizing the placement of pressure sensors to enable ultra-early leak detection (<1 h). This capability is particularly strategic in high-density urban environments, where invisible leaks account for substantial non-revenue water (NRW) losses.

Overall, these findings align with the urgent research priority of developing affordable and adaptive AI-based solutions capable of achieving high accuracy with minimal infrastructure investment. Future efforts should therefore focus on cost-effective AI frameworks, open data architectures, and real-time hybrid sensing, ensuring scalability, transparency, and inclusivity in smart water management.

### *Implications and Future Lines*

#### **Practical and institutional implications**

The findings of this review show that the incorporation of smart technologies in urban drinking water networks has a direct impact on the efficiency, sustainability and resilience of the systems. The integration of pressure, acoustic, fiber optic and artificial intelligence sensors reduces unaccounted losses, optimizes the use of water resources and reduces operating costs in the medium term. From an institutional perspective, the results offer a framework of reference for the modernization of infrastructures, facilitating decision-making aimed at prioritizing technological investments, the design of more efficient water management policies and the adaptation of regulatory frameworks that promote the digitalization of water services. For operators and local governments, this knowledge

allows them to structure evidence-based strategies, aimed at reducing physical losses and improving the sustainability of supply in urban environments.

### **Academic and scientific implications**

In the academic field, the review provides a synthesis of technological trends that consolidates the field of research in smart water networks. Methodologies for optimal sensor placement, the application of machine learning algorithms and experimental validation in urban conditions are areas of growing scientific interest. Likewise, the comparative analysis of costs and margins of error between technologies helps to define objective criteria for selecting tools based on the scale and complexity of each network.

### **Future lines of research**

**Validation in real conditions:** Evaluate emerging technologies in diverse urban environments (cities with different population density, topography and age of networks).

**Application in contexts with limited resources:** Develop low-cost and high-efficiency solutions for intermediate or rural cities, where investments are restricted.

**Integration of hydraulic and predictive models:** Combine platforms such as EPANET with AI algorithms and digital twin models for dynamic and preventive resource management.

**Technological interoperability:** Design schemes that allow the integration of heterogeneous sensors (acoustic, pressure, fibre optic) under the same management system.

**Socio-environmental assessment:** Analyze the impacts of these technologies in terms of environmental sustainability, equity in access to water, and contribution to SDGs 6 and 11.

## **4 Conclusions**

This systematic literature review demonstrates that the integration of smart sensors and artificial intelligence (AI) has redefined the detection, localization, and prevention of leaks in urban water distribution networks. The evidence compiled from 50 peer-reviewed studies (2015–2025) confirms a technological transition from traditional pressure- and acoustic-based methods toward hybrid and AI-driven frameworks capable of achieving precision levels above 95%, even under variable hydraulic and environmental conditions.

The effectiveness and precision of these intelligent systems are closely linked to the type of sensor and the computational model applied. Fiber-optic and hybrid networks (TDR–MI, acoustic–optical) provide exceptional accuracy ( $\pm 1\%$ – $3\%$ ), yet their deployment costs and technical demands restrict their large-scale adoption in developing regions. Conversely, low-cost acoustic and nodal sensors remain operationally valuable but require integration with machine learning algorithms to compensate for limitations in noisy or complex systems. This highlights the critical balance between cost, accuracy, and scalability, which must guide future innovations in digital water infrastructure.

The analysis also reveals that AI-enabled data fusion and predictive analytics are the most promising directions for the next decade. Machine learning and deep learning techniques—such as CNNs, Bayesian classifiers, and hybrid wavelet–ML models—demonstrate not only superior performance but also the potential for real-time and autonomous water management. However, achieving equitable access to these technologies depends on reducing their economic barriers through open-source platforms, low-cost AI models, and interoperable IoT architectures.

In summary, the findings emphasize that the transformative potential of AI in water network management lies in its ability to optimize resource use, minimize non-revenue water (NRW), and enable predictive maintenance under sustainable and inclusive frameworks. The next research frontier must focus on validating affordable, explainable, and energy-efficient intelligent systems, ensuring that advanced leak detection and monitoring technologies become accessible tools for all cities—particularly those in developing economies striving to meet the goals of SDG 6 (Clean Water and Sanitation) and SDG 11 (Sustainable Cities and Communities).

**Acknowledgement:** Not applicable.

**Funding Statement:** The authors received no specific funding for this study.

**Author Contributions:** The authors confirm contribution to the paper as follows: Conceptualization, Nancy Leticia Monzón de la Cruz, Arleth Joryeth Santos Cuba and Yvan Huaricallo; methodology, Nancy Leticia Monzón de la Cruz and Arleth Joryeth Santos Cuba; software, Arleth Joryeth Santos Cuba; validation, Nancy Leticia Monzón de la Cruz, Arleth Joryeth Santos Cuba and Yvan Huaricallo; formal analysis, Nancy Leticia Monzón de la Cruz and Arleth Joryeth Santos Cuba; investigation, Nancy Leticia Monzón de la Cruz and Arleth Joryeth Santos Cuba; resources, Yvan Huaricallo; data curation, Arleth Joryeth Santos Cuba; writing—original draft preparation, Nancy Leticia Monzón de la Cruz and Arleth Joryeth Santos Cuba; writing—review and editing, Yvan Huaricallo; visualization, Arleth Joryeth Santos Cuba; supervision, Yvan Huaricallo; project administration, Yvan Huaricallo; funding acquisition, Yvan Huaricallo. All authors reviewed the results and approved the final version of the manuscript.

**Availability of Data and Materials:** The data that support the findings of this study are available from the corresponding author, upon reasonable request.

**Ethics Approval:** Not applicable.

**Conflicts of Interest:** The authors declare no conflicts of interest to report regarding the present study.

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