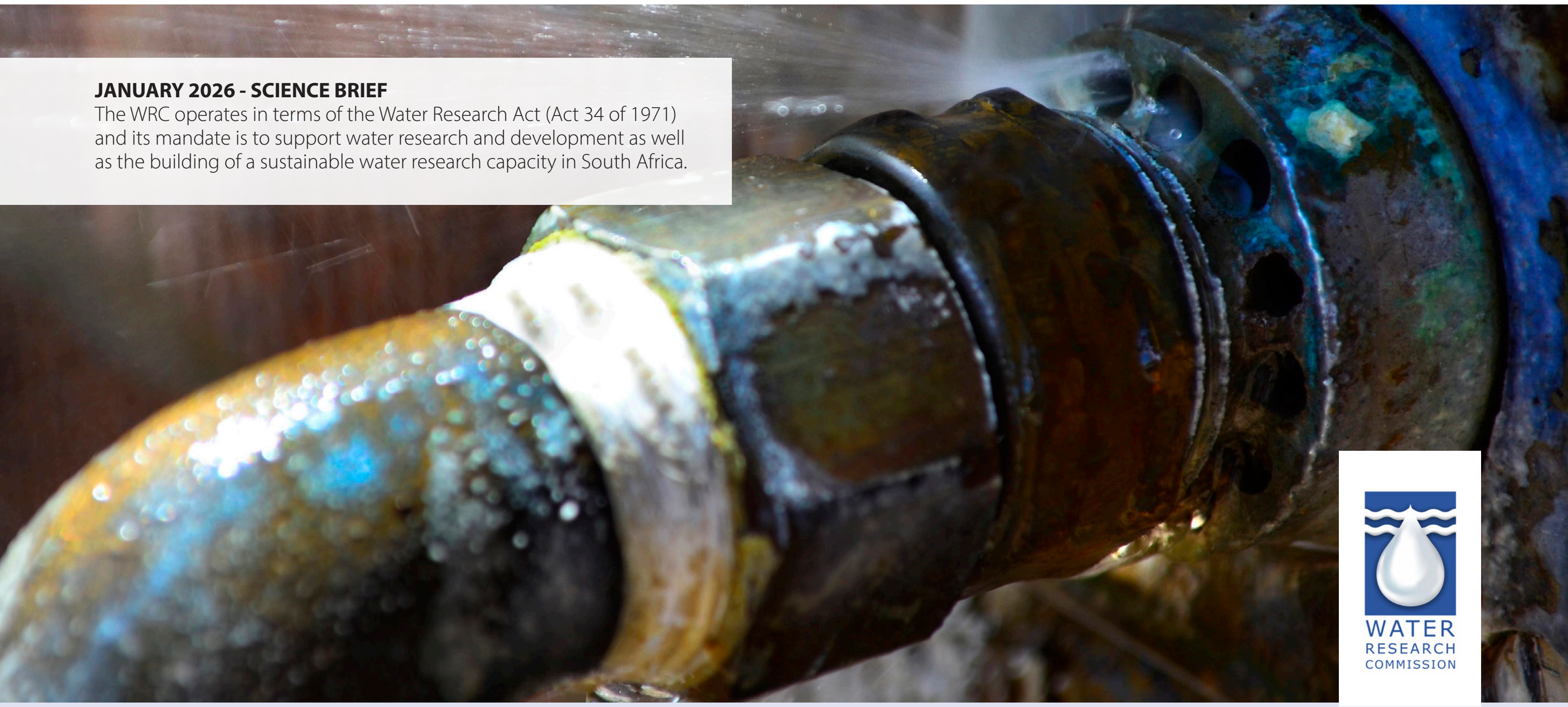

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The WRC operates in terms of the Water Research Act (Act 34 of 1971) and its mandate is to support water research and development as well as the building of a sustainable water research capacity in South Africa.

THE USE OF THE INTERNET OF THINGS IN THE MANAGEMENT OF NON-REVENUE WATER IN THE WATER DISTRIBUTION NETWORK FOR RESILIENT SMART CITIES

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The water sector is under increasing pressure from global megatrends, including urbanisation, population growth, and climate change. South Africa faces a particularly critical challenge: approximately 50% of potable water is lost as non-revenue water (NRW). Detecting and localising leaks are crucial for reducing water loss in water distribution networks (WDN) and realising sustainable water usage. The global volume of NRW is estimated to be 126 billion cubic metres per year, and the cost/value of water lost amounts to R39 billion annually (Liemberger and Wyatt, 2019). This level of water loss is unsustainable and underscores the urgent need for modern technology-enabled management of WDN.

Globally, countries such as Singapore, South Korea, and Malta have achieved NRW levels of about 12% by legally mandating the adoption of smart technologies in their WDN. For example, South Korea's Gochang Water Works has deployed smart meters in 24 000 households using long-range automatic meter reading systems, thereby improving billing accuracy and enhancing leak response (Adedeji et al., 2022). Cases such as this one demonstrate that IoT-based solutions can substantially reduce NRW when scaled across a national water sector.

A WRC funded study investigated an in-depth scan and documentation of case studies on the deployment of emerging technologies and leak detection sensors; reviewed and identified the most relevant IoT solutions and leak detection sensors; and conducted laboratory-based and on-site testing of IoT solutions integrated with leak detection sensors.

A variety of integrated commercial sensors is currently available for detecting and managing leaks and pressure variations along water distribution networks, with notable small-scale deployments. Despite their apparent advantages, water companies in the Global South have not yet fully adopted technological innovations to manage water loss sustainably (Chan et al., 2018).

Water utilities face issues with NRW management, which accounts for huge revenue losses resulting from leaks, theft, intrusion, and other types of unaccounted water loss (Taha et al., 2020). However, with the development of IoT, utilities may now choose from a variety of tools to improve the operations and management of their water systems and minimize NRW. Water utilities can use either LoRa, Sigfox, or NB-IoT to link IoT devices to deploy a variety of sensors and devices that can track pressure and leaks across the entire WDN and monitor their systems in real time (Chettri & Bera, 2020). IoT solutions can aid in significant NRW reduction via flow sensors, which provide instant data on water flow, leaks, and pressure; tracking of water usage in real time, enabling utilities to spot anomalies and leaks; acoustic sensors to locate water leaks and alert management; and pressure sensors to monitor pressure levels and locate low-pressure locations that might be a sign of leaks due to cracks, bursts, or intrusion (Shrikrishna et al., 2022; Chan et al., 2018).

The enablers of any IoT system consist of IoT devices (such as sensors, smart meters, actuators, controllers, cameras, alarms, and level meters) and communication services (including WiFi, LoRa, NB-IoT, 4G/5G, and Sigfox). In addition to enablers, there are enabling techniques and services; thus, IoT services, such as platform hosting, device management, device discovery, and data acquisition; and big data, artificial intelligence, and machine learning functionalities that aid in data storage, predictive insights, activity recognition, situation awareness, crowd dynamics, target modelling and detection, object tracking, and identification of suspicious and unusual behaviours. The last driver component of an IoT system is an application that helps detect anomalies, monitor asset conditions, environmental conditions, water quality, and facilitate leak detection, as well as network optimisation (Aiello et al., 2022; Alabi et al., 2019; Allam 2020).

In South Africa, the uptake of IoT for NRW management is still at an early stage, but there are significant developments: Several municipalities are testing advanced metering infrastructure (AMI) and digital water meters. The UtiliMeter device, introduced by MICROmega, integrates prepaid, post-paid, flat-rate, and flow-restricting options while enabling prompt responses to leaks and tampering.
Conventional vs. smart methods**:** While traditional leak detection methods (e.g., ground microphones) remain dominant, smart metering and automated leak detection pilots are proving to be more accurate and scalable.

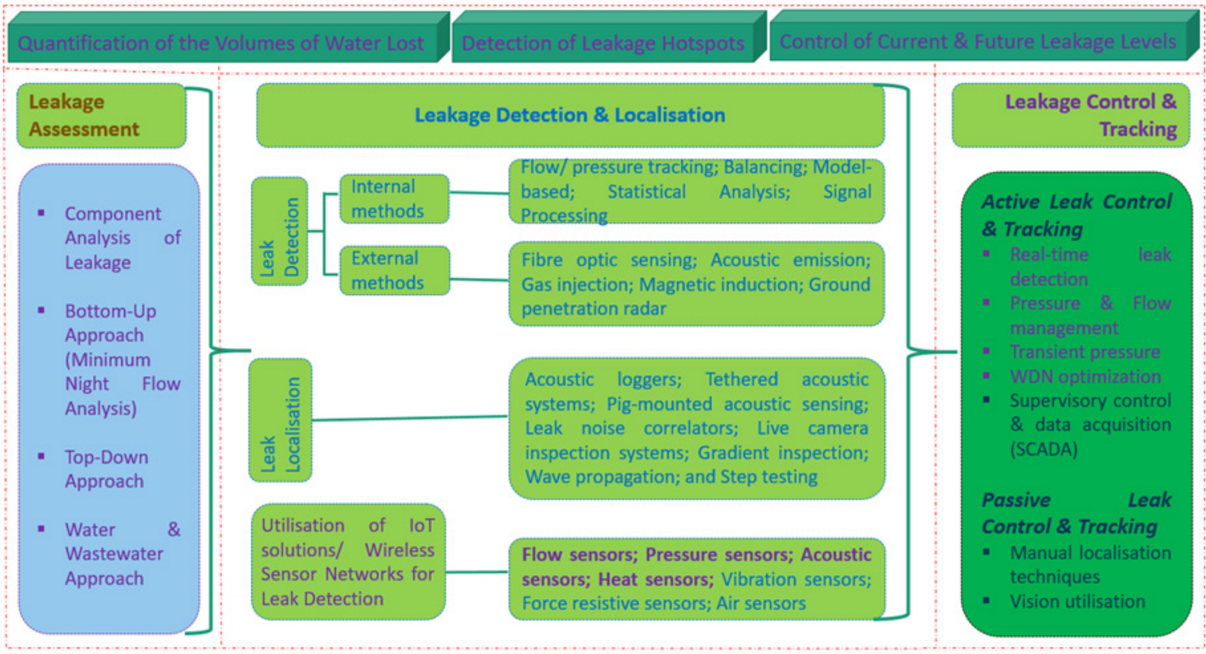
Various leak detection approaches have been proposed, such as pipeline fault detection methods (pulse echo methodology, acoustic techniques, vibration analysis, negative pressure waves, support vector machines, interferometric fibre sensors, filter diagonalization methods, pressure-based methods, externally and internally based methods, data-driven methods, and current and proposed intelligent methods. Further detailed insights and perspectives on the topical focus of these studies are presented in Table 1 and Figure 1.

Table 1. Summary of literature reviews about leakage detection and localisation methods

Focus	Classification	Remark
Pressure-based leakage detection method	Pressure-flow deviation method; pressure residual vector method; negative pressure wave method; inverse-transient analysis method; inverse resonance method; transient damping method; and transient steady state method.	Hydraulic leak detection has the important advantage of being less costly and has a faster response compared to other leak-detection approaches.
Leakage detection and localisation	Externally and internally-based methods; leak localisation; utilisation of wireless sensor networks.	The practical application of these techniques for large-scale WDNs is still a major concern.
Leakage detection	Current technologies and intelligent methodologies	Higher leakage localisation accuracy is still a difficult task
Transient-based leak detection methods	Direct transient analysis, frequency domain techniques; inverse-transient analysis, and transient leak detection	A comprehensive review of transient-based methods of field testing is needed.
Pipeline fault detection methods	Blockage detection techniques and leakage detection techniques	Acoustic reflectometry is found to be most suitable

Burst/leakage detection and location	Hardware-based methods and software-based methods	Higher detection accuracy and Timelier
Data-driven approaches for burst detection	Classification method, prediction-classification method, and statistical method	A more comprehensive performance evaluation needed
Steady-state leakage detection strategies	Hybrid leak detection techniques, hardware-based methods, and software-based methods	The hybrid technique provides better accuracy in leak detection and fewer false alarms.

Figure 1: Different leakage management and detection methods



To provide further insights into IoT-enabled WDN, the authors also reviewed the existing literature. They presented an analysis of various IoT technologies and their applications in WDN, as presented in Table 2. An effective WDN can be built through the effective usage and implementation of proper devices, components, and communication technologies.

Table 2: Roles of IoT technologies and innovations in various applications of WDN

Technology	Application 1	Application 2	Application 3	Application 4	Application 5	Application 6	Application 7
Bluetooth	EARNPIPE: Energy Aware Reconfigurable Sensor Node for water PIPEline monitoring Role: Sensor node communication	Water environment remote monitoring system Role: Network connection between the routing node and to monitoring service centre	Smart water meter via Smart App Role: Meters with EIM transmitting data to a Smartphone	Mobile Phone Wireless Bacteria Sensing System Role: Communication between the wireless bacteria sensor and to mobile phone app	Wireless water flow monitoring based on an Android smartphone Role: Wireless technology for the data transmission of water flow	Flows sensor to the mobile app network, Autonomous Water Monitoring, and Sampling System for Small-Sized ASV Role: Sensor probe to the vessel	Autonomous real-time water quality sensing Role: Multiple sensors nodes to the base station
LoRa	Campus water management system monitoring of the overhead tanks and ground-level reservoir Role: Network connection for the gateway to upload the data	Monitoring and control of the water distribution network Role: Connection to the overhead tank and underground tank updates to the gateway	Adige: An efficient smart-water network monitoring and control system Role: Connectivity between the sensors to the gateway	Smart water quality monitoring and metering Role: Connectivity between the sensors to the gateway and the gateways to the cloud	Water quality monitoring system Role: Sensor node to the IoT cloud communication	Smart water management system in urban areas Role: Transceiver for smart water meter data to the cloud-based server	Water quality monitoring system for soft-shell crab farming Role: Sensor node to the gateway communication
RFID	IoT Network for monitoring the water loss Role: Unique identifier	Bristol Is Open (BIO) platform for water quality monitoring Role: Network connectivity	Groundwater level measurement Role: Levelling package transmission of data	Water level detection with chipless RFID Role: Detector power transmitter	Water quality monitoring Role: Data transmitter	Smart water monitoring Role: Communication network	Water level monitoring Role: Data acquisition
Wi - Fi	Automatic water level checking at the dam gate with a moisture sensor and server monitors in Arduino Role: Arduino to the remote server	Water quality (TDS and pH) monitoring Role: Raspberry pi to the cloud	Smart water meter via Smart App Role: Meters with EIM transmitting data to smartphones	Real-time water quality monitoring and controlling system Role: Connectivity between Raspberry pi to the cloud server	Real-time monitoring of water quality in an IoT environment Role: The Wi-Fi module connects the embedded device to the internet	Critical water infrastructure monitoring and protection against cyber and physical attacks Role: Human intrusion detection via wireless signal reflection	Water quality monitoring system for water tanks Role: Sensor data (ESP 8266) to Raspberry pi
Zig Bee	Water quality monitoring system Role: Communication between the sensor node to the microcontroller	Real-time monitoring of water pressure distribution Role: Intra-cluster of nodes' communication	Smart sensors for real-time water quality monitoring Role: Sensor data transmission and reception from sensors to the microcontroller	Smart water quality monitoring Role: FPGA to monitoring modules	Water quality monitoring system Role: Network layer (connectivity) data transmission		

Key findings

The key findings from the study show that :

- South Africa's NRW level, at approximately 50%, is significantly higher than the global best practice of around 12%. While the adoption of IoT technology for water management is currently limited to pilot studies and a few municipalities, there are considerable opportunities for its broader application. IoT can enable real-time leak detection, optimise pressure management, and improve billing systems, leading to better decision-making and protecting revenue.
- Although digital technologies are being introduced in the water sector in the Global North, full-scale practical applications remain unreported. Several issues must be addressed to ensure a smooth transition, including security, data quality and uncertainty, scalability, sustainability, and energy solutions for smart sensing equipment.
- The urban water sector faces challenges in delivering consistent, high-quality access while controlling operational costs. To gather and analyse data more effectively, water utilities need to employ smart water solutions and emerging technologies. By deploying IoT devices and data analytics tools, utilities can enhance asset management, transform workforce operations, reduce non-revenue water, improve customer service, and cut costs. This leads to a clearer understanding of the system and better optimization of operations and teams, ensuring reliable service delivery.
- Various integrated commercial sensors for detecting and managing leaks and pressure variations along water distribution networks are available, with some small-scale deployments.
- Practically, utility managers can adopt these technologies with minimal additional infrastructure, leveraging existing pipeline sensor installations for early detection of leaks. This approach opens a clear path to implementation, offering a timely and effective tool to improve water resource management and sustainability in real-world water distribution networks.
- The IoT is considered a tool for monitoring and automation that allows for precise control over water resource data, thereby proactively innovating and resolving water scarcity problems, as well as addressing ageing water infrastructure. Additionally, the IoT can integrate analytics and intelligence to enable control and automation features in a water distribution system.
- Moreover, sensing systems, communication technologies, networking capabilities, and computing with storage and visualisation make the IoT an efficient platform for intelligent monitoring systems. Some of the main applications of IoT-enabled monitoring systems include the inspection of pipes (e.g., for corrosion and cracks), predictive maintenance, real-time analysis of sensor data to identify leaks and cracks, and software leverage to help utilities and consumers track their water usage patterns for improved water management.
- A systematic review identified LoRa as the ideal IoT protocol for water networks due to its ultra-low power requirements, long range (2–5 km in urban areas, 5-15 km in rural areas), deep indoor penetration, and bi-directional communication. A pilot study validated an acoustic leak detection method that processes sensor signals and compares them to a baseline. This technique outperformed traditional methods, demonstrating that IoT-enabled sensors provide earlier and more reliable leak alerts (Shrikrishna et al., 2022).

In summary

IoT adoption offers South Africa a clear path to reducing NRW, improving service delivery, and enhancing long-term resilience in municipal water systems. By leveraging pilot studies, scaling proven technologies, and learning from international benchmarks, the water sector can transition from fragmented efforts to a systematic, technology-driven approach to water management for sustainable urban futures.

It is recommended that all infrastructure sectors, including the water industry, undergo technological advancement at the customer level, recognising that the water sector can no longer remain isolated from these advancements. Adoption and implementation of emerging technologies are imperative.

The Internet of Things (IoT) serves as a powerful tool for monitoring and automation, enabling precise control over water resource data. This approach facilitates proactive innovation in addressing water scarcity and ageing infrastructure challenges.

By integrating analytics and intelligence, IoT enhances control and automation within Water Distribution Networks (WDNs). By combining sensing systems, communication technologies, networking, computing, and visualisation, the IoT provides an efficient platform for intelligent monitoring.

Water utilities can deploy IoT devices connected via LoRa, Sigfox, or NB-IoT to monitor pressure, flow rate, velocity, and leaks across the WDN in real time. These solutions contribute to significant non-revenue water (NRW) reduction by delivering instant data on flow, leaks, and pressure. Acoustic sensors identify leak locations and alert management, while pressure sensors detect low-pressure zones signalling potential leaks from cracks, bursts, or intrusion.

Furthermore, building capacity within municipalities for data analysis and digital network management is a crucial next step. The study team strongly recommends embracing IoT adoption in the water sector. Deploying IoT-based Smart Water Network Management systems is viable for addressing persistent challenges in water provision services and building resilient, smart cities.

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