نبراس
NPRAS
المنصة الوطنية لاستشراف البحث والابتكار للاستدامة
National Platform of R&I Analytics for Sustainability

وزارة البيئة والمياه والزراعة
Ministry of Environment Water & Agriculture

Water Innovation Trends

Smart Leakage Management


بسم الله الرحمن الرحيم

Foreword

Custodian of the Two Holy Mosques

King Salman bin Abdulaziz Al Saud

My primary goal is to be an exemplary and leading nation in all aspects, and I will work with you in achieving this endeavour.

His Royal Highness

Prince Mohammed bin Salman bin Abdulaziz Al Saud

"

Our ambition for Saudi Arabia is to become a global leader in research, development, and innovation with an annual investment equivalent to 2.5% of GDP in 2040. This will diversify and add 60 billion Saudi Riyals (US$ 16 billion] to the economy in 2040 while creating high-value jobs in science and technology.

"

Foreword

His Excellency Eng. Abdulrahman Abdulmohsen AlFadley

Minister of Environment, Water, and Agriculture

The Kingdom's leadership believes in the importance of research and innovation to build a knowledge economy and achieve true diversification of the state's resources, especially in the vital, priority sectors of environment, water, and agriculture. The Ministry of Environment, Water, and Agriculture aims to enable partners across the innovation ecosystem to stimulate and localize technologies to provide effective sustainability solutions within the Ministry's sectors.

His Excellency Eng. Mansour bin Hilal Al Mushaiti

Vice Minister of Environment, Water, and Agriculture

Innovation has been a fundamental pillar in the success of the water sector in the Kingdom. It laid the foundation for our journey towards sustainability and strengthened the Kingdom's global position in efficiently managing its water resources. This progress has been achieved through the support and empowerment of our wise leadership, the dedication of our passionate national talents, and our commitment to innovation and continuous improvement, in pursuit of our ambitious goals for a more sustainable future.

His Excellency Eng. Abdullah Ibrahim Al-Abdul-Karim

President of the Saudi Water Authority

In light of global challenges related to water and the growing demand, the water sector in Kingdom of Saudi Arabia today stands as a pillar of innovation—viewed not just as a strategic advantage but as a fundamental necessity.

From this perspective, the sector has adopted a forward-looking approach centered on innovation, considering it as a key driver toward achieving sustainability, enhancing operational efficiency, and enabling adaptability to future changes transforming challenges into promising opportunities.

This report aims to emphasize that innovation in the sector is not merely a theoretical luxury, but an institutional practice grounded in values and closely aligned with Kingdom's ambitious vision of becoming a pioneering, knowledge-based society. It represents a clear pathway to opportunities, empowering innovation, and fostering the uncovering growth of both national and global partnerships.

His Excellency Dr. Abdulaziz bin Muharib AlShaibani

Deputy Minister of Water

The Kingdom faces various water challenges in meeting the rising demand for water, as a result of the economic and social development, and the scarcity of natural water sources, this necessitates a collaborative effort to integrate effective water resource management to ensure sustainability, in alignment with the objectives of Saudi Vision 2030. Driven by the importance of innovation and modern technologies in enhancing water security, this report presents an overview of the key technological trends in the water sector, aiming to accelerate the adoption of innovative, integrated and effective solutions.

His Excellency Dr. Abdulaziz bin Malik Al-Malik

Deputy Minister for Research and Innovation

The adoption of technologies and innovation in the water sector represents a key pillar in achieving the Kingdom's water security objectives. The Ministry works to support the adoption of modern technologies through the development of the research and innovation ecosystem. This report aims to present key technological trends and identify solutions whose adoption will contribute to enhancing efficiency and sustainability in this vital sector.

About the report

The strategic direction of the sectoral innovation system requires continuous and extensive monitoring of the most important technology and innovation trends to enable stakeholders from various sectors to optimize their policies and plans to deal with an increasingly complex and competitive world, both technologically and economically. The Ministry of Environment, Water and Agriculture established the NPRAS Platform, a platform that enables the use of monitoring and technical survey tools and methodologies to guide the innovation system in the environment, water and agriculture sectors to focus on technologies and innovations with the greatest sectoral potential.

This report is part of a series of periodic sectoral reports issued by NPRAS Platform, dedicated to tracking and analyzing innovation trends in the sectors of environment, water, and agriculture. This report specifically focuses on the water sector by taking an in-depth look at one of the five technology priority groups with good potential across the value chain of the sector, providing insights into trends, developments, and opportunities that are shaping the future of the water sector.

This series aims to achieve several aspects:

1. **Raising stakeholder awareness** of emerging technologies, market dynamics, best practices, and global policies related to innovation in the environment, water, and agriculture sectors.

2. **Accelerating efforts** to localize and deploy water technologies by highlighting the most ready technologies that can enhance the efficiency and sustainability of the water sector.

3. **Enable strategic decision-making** by providing policymakers, industry leaders, and investors with data-driven insights to guide innovation initiatives.

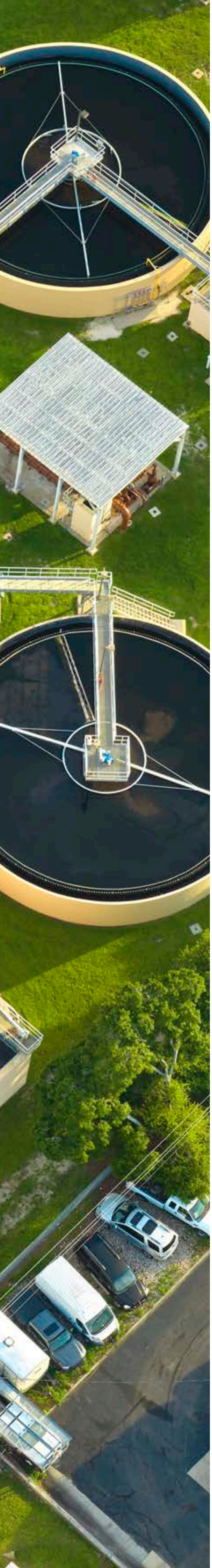


Table of Contents

Executive Summary

- To ensure the report scientific rigor and practical relevance of its findings, the report —published by the NPRAS Platform— has been reviewed by subject matter experts and industry professionals. The report begins with an overview of the challenges faced by the water sector and emphasizes the importance of one technology priority group: **Smart Leakage Management.** This technology priority group is included under the **Transmission & Storage and Distribution** phases of the water value chain (refer to page 20 and 21), it is the use of advanced technologies—such as IoT sensors, AI, and real-time monitoring systems—to detect, prevent, and respond to water leaks. Additionally, it reduces water loss, cuts costs, preserves infrastructure, and supports water management for sustainability and uninterrupted water supply.

- Building on this foundation, the report follows a rigorous, three-stage methodology aligned with global best practices—specifically the **OECD Framework for Anticipatory Governance** — ensuring that its insights are not only robust and in-depth but also actionable for driving innovation and policy development.

- The first stage in the OECD framework is systematic monitoring, where the NPRAS Platform tracks **10,000+ sources** (scientific publications, patents, industry reports, and news) with **100M+ data points**, updated twice daily to identify signals of high-interest technologies. The second stage is technology trend analysis, where technologies are evaluated for momentum, innovation maturity, and relevance to national water challenges. Moreover, redundancy is removed by clustering similar innovations. The final stage is technology assessment. Where rapidly evolving, high-impact technologies are selected and then examined in greater depth to assess their strategic significance and inform relevant policy decisions.

- Additionally, to prioritize RDI investments, the report examines key shifts across the water sector's social, economic, and political spheres. In Smart Leakage Management, six major trends are shaping 2024*

- The Business Case for Water Conservation

– Real-time Consumption Monitoring and Smart Meters

– Strategic Acquisitions and Partnerships

– Major Utility Investments in Infrastructure Upgrades

– Regulatory Penalties and Incentives for Leak Management

– Water Credit Systems

- The report will highlight the key technology segments within the smart leakage management landscape, detailing the most relevant technologies in each segment. A chart will assist in selecting the top technologies, with each one assessed based on Technology Readiness Levels (TRL), ease of implementation, and potential impact. The following five key selected technologies represent the top choices within each technology segment:

– Self-adapting digital twins from the Analytics & Simulation segment

– Free-swimming systems from the Control & Response segment

– Self-healing materials from the Materials & Coatings segment

– Self-reconfiguring network nodes from the Network Optimization & Infrastructure segment

– Pressure wave sensors from the Sensing & Detection segment

- In the following Technology Spotlight section, the report delves into detailed insights for each selected technology, highlighting key players, case studies, Market Readiness Level (MRL), Technology Readiness Level (TRL)*, and Expected Impact. Notable emerging solutions, such as real-time monitoring systems and digital twins, are explored in depth, supported by relevant case studies and trend analyses.

- The selection criteria used for scoring the five technologies are based on the technology chart described earlier. The three criteria are:

– Technology Readiness level (TRL)

– Potential Impact

– Increase in Signals

- In conclusion, the report incorporates insights gathered from interviews with innovation leaders in the private sector, providing an overview of key priorities. These insights collectively serve as a guiding framework for policymakers, industry leaders, and investors to foster innovation and advance sustainable water management in alignment with Vision 2030.

*Technology Readiness Levels (TRL) are defined in the glossary section.

*2024 refers to the complete calendar year.

Introduction

Technology and innovation are essential to achieving Saudi Arabia's national water sector goals, enhancing security, sustainability, and efficiency. Recognizing the need for transformative solutions, the Kingdom is accelerating the adoption of emerging technologies to address critical challenges and unlock new opportunities. Building on the previous Water Sector Innovation in Saudi Arabia report—which identified 20 technology groups—this edition hones in on one technology priority group with high-impact within that broader landscape. This focus area address both the challenge of water loss within distribution networks and the opportunity to recover and repurpose water, aiming to accelerate the adoption of transformative solutions in the sector. The report highlights six major technology sectoral trends shaping 2024, with a focus on water conservation as a critical priority. Currently, companies worldwide are increasingly aware of the financial risks associated with water-related challenges, driving greater investment in sustainable water management solutions.

One of the most significant developments is the rapid adoption of smart metering, which is expanding globally and is expected to reach a market value of $7.36 billion by 2031.

Governments are also stepping up their efforts, with major investments in water infrastructure—such as the $11.5 billion U.S. water infrastructure upgrade—to modernize and enhance utility systems. At the same time, stricter regulatory policies are being introduced, increasing penalties for water loss while incentivizing advanced leak management solutions.

Key technological innovations driving this transformation include real-time monitoring systems, AI-driven analytics, digital twin platforms, and self-adapting water networks. These advancements are revolutionizing the way water resources are managed, making systems more efficient and resilient.

In line with these global trends, Saudi National Water Strategy aims to significantly reduce reliance on non-renewable water sources. Another strategic goal is lowering water production costs by 2035, underscoring the Kingdom's strong commitment to sustainable and efficient water management. These initiatives reflect a growing global shift toward smarter, more efficient water management solutions that balance economic and environmental priorities.

This report is designed to provide structured insights into water innovation trends and emerging technologies in Saudi Arabia. It begins with an overview of key national challenges in the water sector, followed by an analysis of technological advancements and strategic opportunities.

The report is divided into sections that explore and highlights emerging technologies, their implementation feasibility, and potential impact. **Readers can navigate through expert analyses, case studies, and sectoral trends, ensuring a comprehensive yet accessible understanding of the innovations shaping Saudi Arabia's water future.** Each section is crafted to support policymakers, industry leaders, and stakeholders in making informed decisions that align with vision 2030's water sustainability goals.


60
40
°C
80
20
100
0
120
60
40
°C
80
100

Scope of the Report [1/3]

The focus of this report covers **"Smart Leakage Management",** exploring emerging trends and technologies within the technology priority group. The report evaluates its strategic relevance, technological readiness, and potential impact on the Kingdom's water sector, providing actionable insights to drive innovation and sustainability.

Target Audience:

This report is developed for the key stakeholders driving the transformation and sustainability of Saudi Arabia's water sector.

Leaders and Decision Makers

Senior officials and executives within Saudi ministries, authorities, and government-affiliated organizations who shape national strategies and lead sustainability initiatives across the Environment, Water, and Agriculture (EWA) sectors.

Policymakers

Government officials and advisors responsible for formulating water-related policies and regulations in line with Saudi Arabia's Vision 2030, national priorities, and regional development plans.

Investors

Public and private sector stakeholders—including sovereign funds, local investment firms, and strategic partners—committed to financing innovative, high-impact water technologies and infrastructure projects within the Kingdom.

Researchers and Scientists

Experts from Saudi universities, research centers (such as KAUST and KACST), and specialized institutes driving R&D to advance sustainable water solutions tailored to the Kingdom's unique environmental context.

Innovators and Entrepreneurs

Saudi-based startups, incubators, and technology developers creating localized, scalable innovations to address water scarcity, reuse, and efficiency challenges in alignment with national goals.

The report outlines key advancements in **Smart Leakage Management** and presents data on the economic and environmental impact of water loss, emphasizing the need for targeted investments and regulatory frameworks. These insights align with Saudi Arabia's efforts under Vision 2030, reinforcing the importance of technology adoption and strategic planning to enhance national water security.

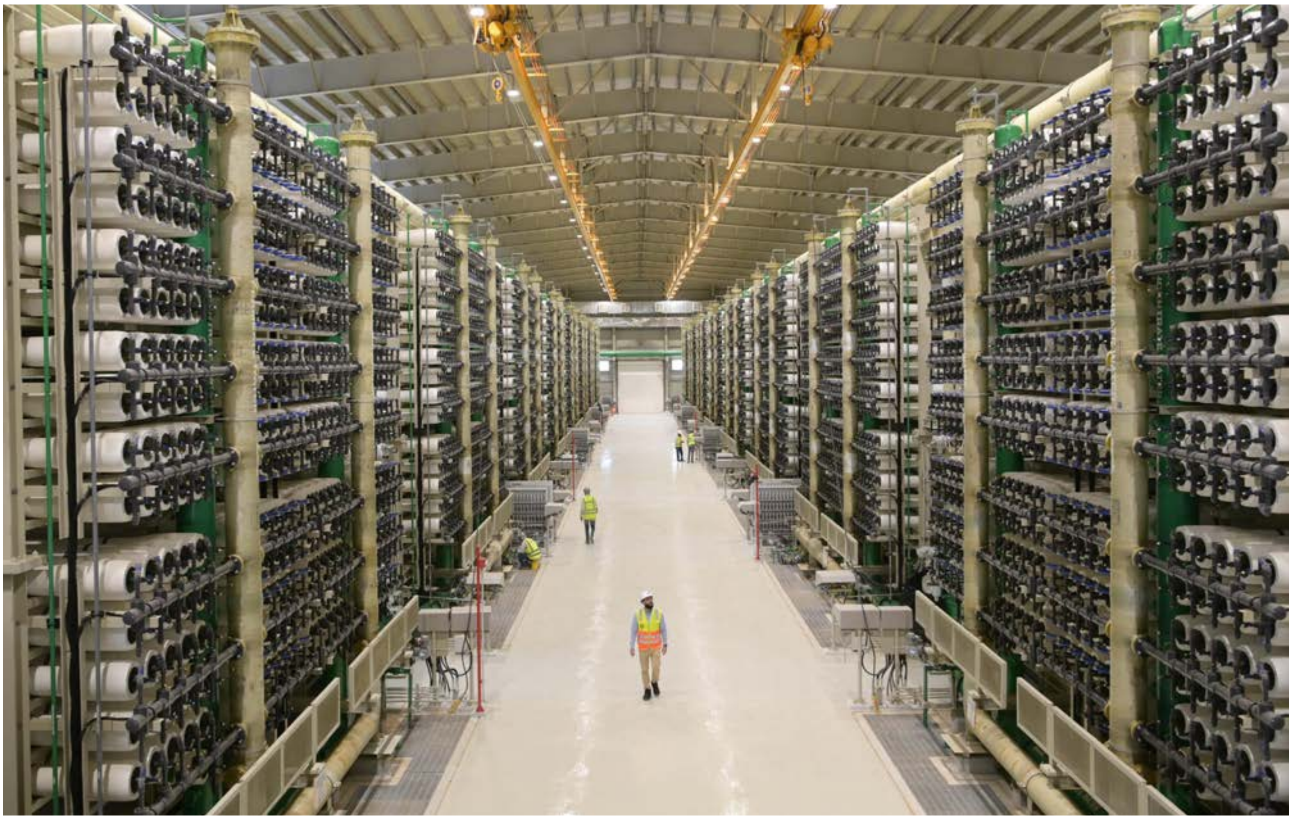
Saudi Arabia's water sector faces a series of interconnected challenges across its value chain, from supply and transmission to distribution, wastewater treatment, and demand management. The Kingdom's reliance on desalination and limited renewable water sources highlights the need for innovative solutions to optimize resource use, reduce costs, and enhance sustainability. Critical challenges include high energy demands for water production, significant distribution losses, insufficient wastewater reuse, and increasing urban and industrial water consumption. These issues require targeted technological interventions to achieve the sustainable water management goals outlined in Vision 2030.

This report provides a detailed analysis of one of the technology priority groups. It provides an in-depth analysis of Smart Leakage Management Technologies which fall under the **Transmission & Storage and Distribution phases.**

1

Smart Leakage Management

Mitigating water losses in transmission and distribution networks through intelligent detection and repair systems.



Scope of the Report [2/3]

Strategic Benefits and Alignment with National Goals

In alignment with the national goals, this report focuses on **Smart Leakage Management**, a significant technology priority group that plays a critical role in enhancing water efficiency, reducing losses, and promoting sustainability.

The selection is driven by the **impact it has on the sector and on the broader water ecosystem, ensuring a holistic approach** to water resource management where the following are strategic benefits and alignment with national goals for it:

Smart Leakage Management (Transmission & Storage, Distribution)

- **Urgency in Reducing Water Loss:** Saudi Arabia faces **high non-revenue water (NRW) losses**, making leakage detection and prevention a **top priority** to improve water conservation and supply efficiency.
- **Infrastructure Modernization:** With ongoing investments in water transmission and distribution networks, **smart technologies** such as self-adapting digital twins, pressure wave sensors, and self-reconfiguring network nodes can significantly enhance **operational efficiency.**

In the pursuit of sustainable water management, it is essential to address challenges. Smart Leakage Management is playing a transformative role in this effort. It is targeting different yet complementary aspects of the water cycle. The following sections explore how this technology contribute to enhancing water efficiency and reliability.

Addressing Key Challenges Across the Water Value Chain

- **Smart Leakage Management** focuses on reducing **transmission and distribution losses,** enhancing **network coverage,** and ensuring a **more reliable and uninterrupted water supply**. By minimizing water loss, it helps **optimize water availability** and reduces the pressure on supply sources.

5 technologies segments

were listed for Smart Leakage Management to further go in-depth of this edition

1 Analytics & Simulation

2 Materials & Coatings

3 Network Optimization & Infrastructure

4 Sensing & Detection

5 Control & Response

Scope of the Report [3/3]

Value Chain	Supply	Transmission & Storage	
Technology Priority Groups	Advanced reverse osmosis		
Challenges and Opportunities	Reduce production energy and major costs	Reduce transmission cost	
	Optimize environmental impact of desalination	Increase number of storage available days	
	Increase non-renewable water sources		
	Improve preservation of groundwater quality		

The process to gather intelligence on technologies and compile the report consists of a three-staged approach – following established practices such as the [OECD Framework for Anticipatory Governance of Emerging Technologies.]

Distribution	Wastewater Treatment & Reuse	Demand	
Smart leakage management	Wastewater Treatment & Reuse	Innovative irrigation	Innovative water consumption in homes
Improve network coverage	Improve wastewater network	Reduce urban water consumption levels (LCD)	
Reduce distribution losses	Improve wastewater treatment	Reduce industrial water consumption levels	
Ensure uninterrupted and reliable water supply	Increase use of treated wastewater	Reduce use of non-renew able water sources (agri. water consumption)	

Systematic Monitoring

The NPRAS Platform tracks 10,000+ sources (scientific publications, patents, industry reports, and news) with 100M+ data points, updated twice daily to identify signals of high-interest technologies.

Technology Trend Analysis

Technologies are assessed based on the speed of change, frequency of mentions, funding trends, and innovation milestones to gauge their development momentum.

Strategic Technology Assessment

High-impact technologies undergoing rapid evolution are selected for deeper analysis to determine strategic relevance and policy implications.

*"Innovation in the Water Sector in Saudi Arabia - Technology Adoption Roadmap" 2024

Methodology

Specifically, the content of this report is based on a three-stage process for analyzing technology signals.

1. Signal Collection & Technology Identification

Considering established practices, such as the Framework for Anticipatory Governance of Emerging Technologies (OECD 2024), the first analysis step involved the systematic collection and evaluation of signals to identify relevant technologies. To achieve this, the team employed a scanning method that combines the advantages of human expertise and machine intelligence, utilizing a signals database that contains over 100 million data points (e.g., patents, industry reports, scientific publications, etc.). Over the past five years, about 9,600 signals related to Smart Leakage Management were sourced. Using Retrieval-Augmented Generation (RAG) AI and human expert validation, a longlist of 109 distinct technologies mentioned in Smart Leakage Management was compiled for in-depth analysis.

2. Technology Assessment & Landscape Creation

In the second step, a comprehensive technology landscape was created from the longlist of the technologies mentioned in the signals. First, all technologies were eliminated that can no longer be considered as emerging, i.e., which have already entered mainstream adoption in relevant markets – e.g., "Smart Water Meters". In addition, conceptual overlap among the technologies was minimized by subsuming similar or idiosyncratic technologies (e.g.,, "Robotic Sensors", "Free-Swimming", and "Untethered Systems"). Finally, the technologies were clustered into technology segments based on the purpose of use and functional characteristics. Finally, all technologies included in the landscape were evaluated on maturity level, impact potential, and ease of implementation following the criteria outlined in the MEWA Water Technology Adoption Roadmap.

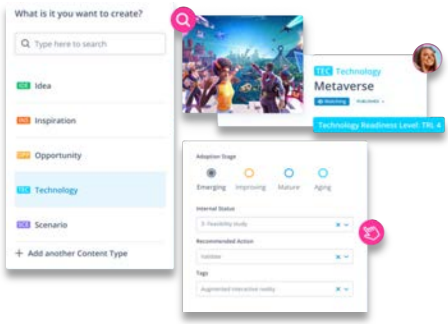
3. Detail Analysis & Spotlight Selection

In the final step, the signals for each technology were examined in detail. Based on this, technology descriptions covering information such as global key players, current state of adoption, development outlook, and relevant case studies were created. In this report, one technologies in each of the identified segments were selected to be presented as a spotlight in this report. The selection was done by an assessment of the combination of three criteria (technology maturity, impact potential in Saudi Arbia, and the growth in the number and impact of signals throughout 2024). The rationale of this approach was to select highly-promising technologies with considerable advancements made in the past year.

The analyses leading to this report were conducted during the first iteration of MEWA's NPRAS Platform— an AI-enhanced Innovation Operating System that enables the systematic scouting of technology signals, the continuous tracking of emerging technologies and innovation efforts, and the creation and continuous updating of comprehensive technology databases across various fields of innovation.

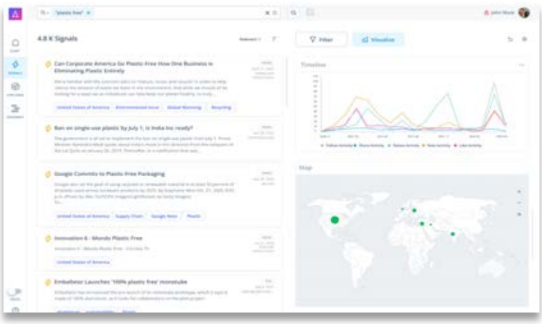
Technology Radar

In an interactive, visual radar view, emerging technologies can be analyzed and their relevance, maturity level (TRL), and application potential assessed. The Technology Radar helps identify new developments early, strategically prioritize innovation fields, and continuously monitor technology trends.



Collaborative Evaluation

The platform enables a structured, collaborative evaluation of emerging technologies. The involvement of various experts minimizes subjective assessments and facilitates the efficient identification of innovation opportunities and risk evaluation.



Automated Monitoring

The platform's scouting function utilizes AI-powered analytics to continuously capture technological developments from various sources such as scientific publications, patents, industry reports, and news. Through intelligent filters and algorithms, relevant signals are identified, categorized, and updated in real time.

03

TECHNOLOGY PRIORITY GROUPS

Water Sector Challenges and Opportunities

The water sector vision statement states:

> A sustainable water sector that develops and preserves water resources, protects the environment, provides a secure supply and high-quality services, and efficiency contributes to economic and social development

Value Chain	**Supply**	**Transmission & Storage**	
Technology Priority Groups	Advanced reverse osmosis		
Challenges and Opportunities	Reduce production energy and major costs	Reduce transmission cost	
	Optimize environmental impact of desalination	Increase number of storage available days	
	Increase non-renewable water sources		
	Improve preservation of groundwater quality		

Value chain source:“Innovation in the Water Sector in Saudi Arabia - Technology Adoption Roadmap“ 2024

Investing in research, development, and innovation within the water sector is essential to overcoming both global and national challenges. Achieving sustainable water management requires a strategic focus on technologies that address country-specific priorities, while also fostering collaboration across public and private sectors. To succeed, ongoing monitoring of national and global trends, technological advancements, and evolving needs is critical. By aligning policies and innovation efforts, Saudi Arabia can drive impactful change across the water value chain. As outlined by RDIA, the national goal is to reduce reliance on non-renewable water sources and decrease water production costs by the year 2035.

Distribution	Wastewater Treatment & Reuse	Demand	
Smart leakage management	Wastewater Treatment & Reuse	Innovative irrigation	Innovative water consumption in homes
Improve network coverage	Improve wastewater network	Reduce urban water consumption levels (LCD)	
Reduce distribution losses	Improve wastewater treatment	Reduce industrial water consumption levels	
Ensure uninterrupted and reliable water supply	Increase use of treated wastewater	Reduce use of non-renew able water sources (agri. water consumption)	

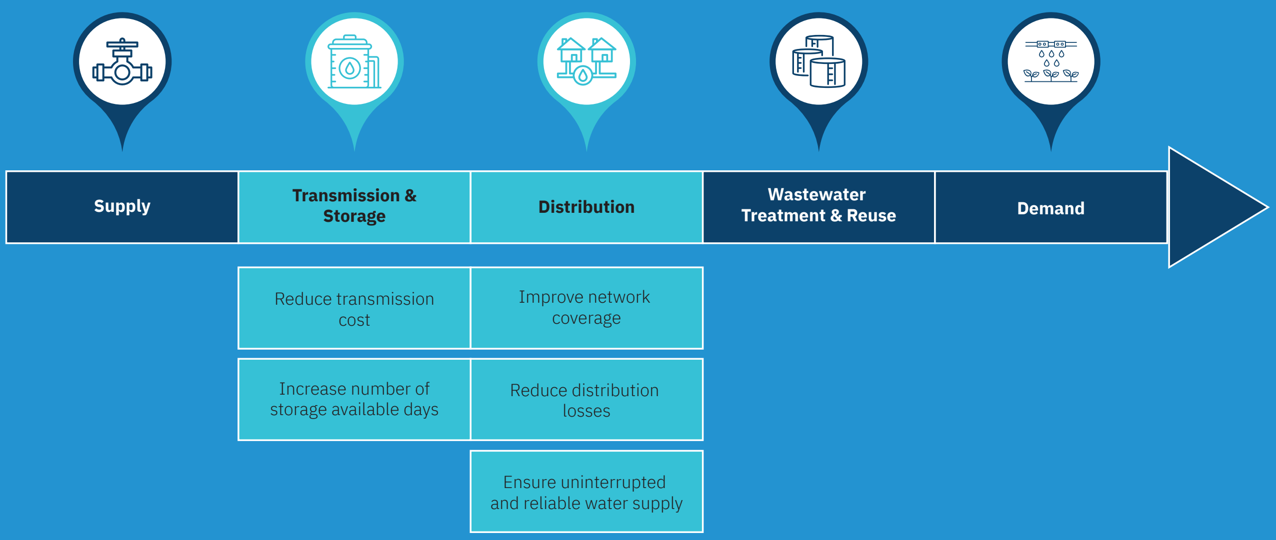
Technology Priority Group focus for this edition

TECHNOLOGY PRIORITY GROUP FOCUS

3.1 SMART LEAKAGE MANAGEMENT

The “Smart Leakage Management" addresses the challenges of the “Transmission and Storage” and the “Distribution” phase. By leveraging solutions such as advanced sensors, real-time monitoring, and automated control systems, this technology priority group can reduce water loss and lower associated costs.

Source: https://iotbusinessnews.com/2024/10/23/25252-smart-water-metering-market-size-worth-7-36-billion-globally-by-2031/



Smart Leakage Management

Smart leakage management refers to the integration of advanced technologies, such as Internet of Things (IoT) devices and artificial intelligence (AI), into water systems to detect, monitor, and prevent leaks in real time. This proactive approach enhances efficiency, reduces waste, and safeguards infrastructure. By utilizing sensors and AI algorithms, smart systems can identify leaks promptly, allowing for immediate intervention before they escalate into significant issues, minimizing water damage and associated repair costs.

Implementing smart leak detection systems leads to substantial financial benefits by reducing expenses related to extensive repairs and water loss, emphasizing the importance of preventive measures. Continuous monitoring helps maintain the integrity of buildings and infrastructure, preventing water accumulation and potential structural damage, contributing to overall safety and longevity. Additionally, smart leakage management promotes efficient water usage by detecting and addressing leaks promptly, conserving this vital resource and supporting global sustainability efforts. The integration of IoT devices also allows for the collection and analysis of data on water flow, pressure, and consumption

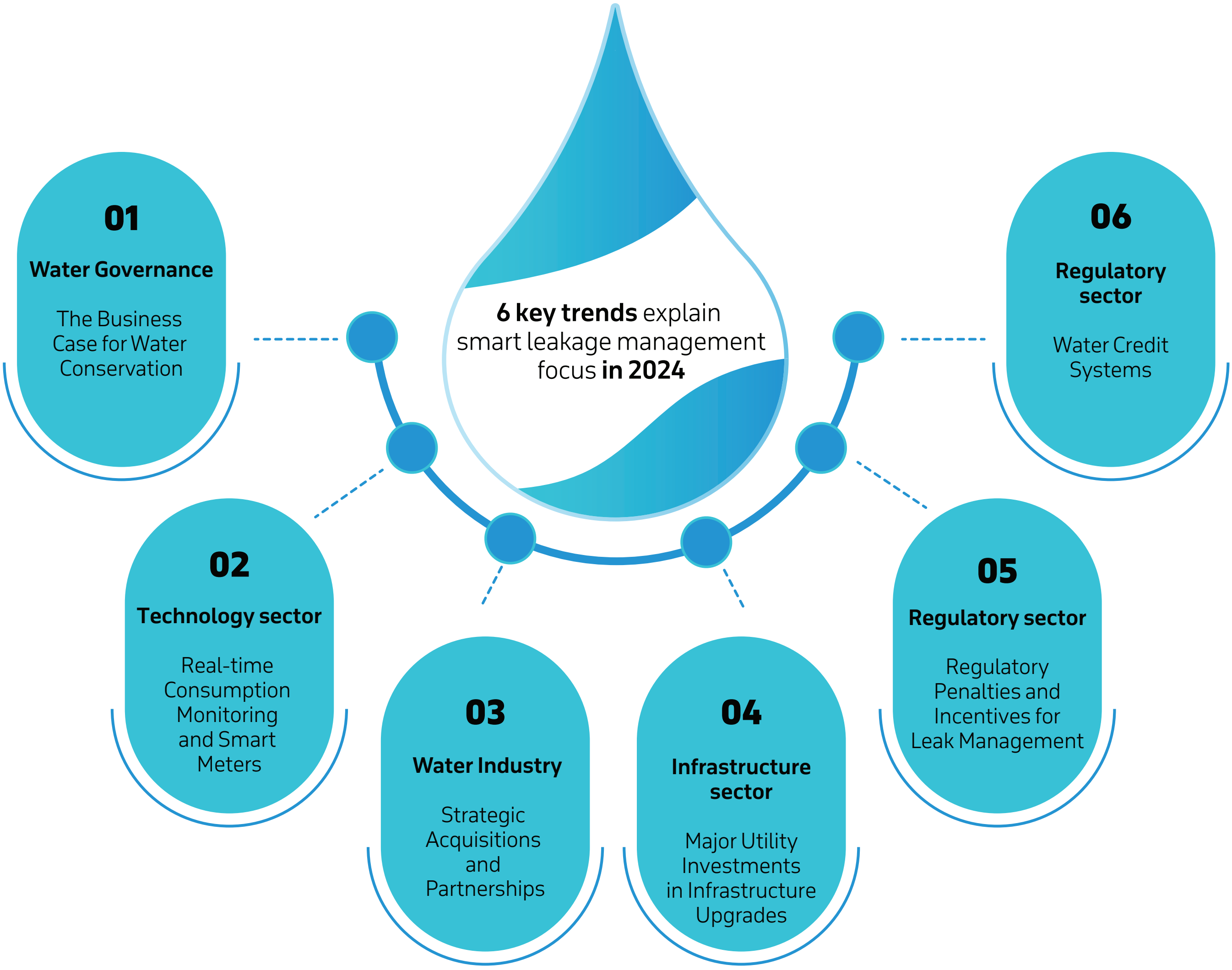
patterns, enabling informed decision-making, predictive maintenance, and optimization of water management strategies.

Incorporating smart leakage management systems is a forward-thinking approach that not only protects assets and reduces costs but also contributes to environmental sustainability and resource efficiency.

Sectoral Trends [1/3]

To identify technological opportunities and prioritize RDI investments. **a clear understanding of the broader sectoral context** is essential. Analyzing current trends in the water sector reveals shifts across social. economic. and political spheres. shaping the landscape in which emerging technologies take root. Navigating this evolving environment is key to anticipating and preparing for future developments.

In the context of Smart Leakage Management. **six key trends stood out in 2024** either accelerating ongoing advancements or introducing new directions for change. Building on the technology landscape outlined above. this section highlights the most notable trends observed. The six trends in Smart Leakage Management span the sectors of governance. industry. technology. regulation. and infrastructure.



Sectoral Trends [2/3]

THE BUSINESS CASE FOR WATER CONSERVATION

Gaining in traction among consumers and utilities

Signals from 2023 indicate that water conservation has gained significant recognition among homeowners, corporations, and utilities worldwide, driven by a growing expectation of tangible financial benefits. In the corporate sector, for instance, the **CDP Global Water Report 2023** highlights that approximately **20% of the 3,163 large companies surveyed worldwide** reported significant water-related supply chain issues, marking an increase from 16% in 2021. These risks collectively threaten at least **US$77 billion** in annual business value at risk. Additionally, there has been a **23% increase in the number of companies disclosing water-related data through CDP compared to the previous year, with 118 global brands** implementing financial incentives for Chief Procurement Officers to address water-related issues. In addition, both AWWA* and WEF* have picked up the topic, portraying smart water technologies as key lever toward sustainable, affordable, and resilient water supply.

National Signal

The National Water Efficiency and Conservation Center (MAEE) launched the "A Habit That Achieves Sustainability" campaign to promote water conservation behaviors across households. This initiative aims to instill daily practices that reduce water waste.
MAEE" launches "A habit that achieves sustainability.
According to the General Authority for Statistics' latest Water Accounts report, water reuse consumption increased by 12 percent to 555 million m^3, signaling progress in recycling initiatives.

REAL-TIME CONSUMPTION MONITORING AND SMART METERS

Accelerating Adoption and Expanding Global Market Presence

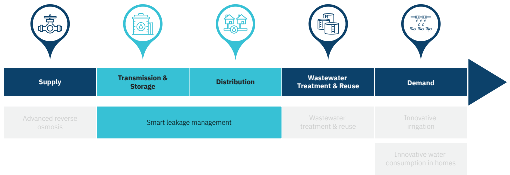
In 2024, the adoption of real-time consumption monitoring through smart meters has accelerated, shifting from early adopters to the early majority. This growth is particularly strong in **North America, Europe, and Asia-Pacific, with Germany, Italy, Spain, the UK, China, Japan, and India** emerging as key markets. The global smart water metering market, valued at **$3.8 billion in 2023,** is projected to reach **$7.36 billion by 2031,** reflecting a **CAGR of 9.9%.** Increasing adoption is expected to enhance early leak detection, improve leakage management, and reduce non-revenue water in private homes.

National Signal

Saudi Arabia is advancing its smart water meter market, leveraging IoT and data analytics for real-time monitoring, leak detection, and efficient consumption. Driven by Vision 2030 and urbanization trends, the market is set for strong growth in 2024. Robust Growth Projected for Smart Water Meter Market

*AWWA: American Water Works Association – a nonprofit organization dedicated to improving water quality and supply through science, policy, and education.

*WEF: World Economic Forum – an international organization for public-private cooperation, known for engaging political, business, academic, and other leaders to shape global, regional, and industry agendas.



STRATEGIC ACQUISITIONS AND PARTNERSHIPS

Growing integration of smart leak detection in water networks

In 2024, the global water industry witnessed a number of major strategic acquisitions and partnerships between corporates in innovators in the area of smart leakage management, including Diehl Metering acquiring PREVENTIO GmbH (Germany), Bradford White acquiring FloLogic (an American company headquartered in **Ambler, Pennsylvania**), ABB acquiring Real Tech (ABB is a multinational corporation headquartered in Zurich, Switzerland), and Xylem acquiring majority stakes in Idrica (Xylem Inc., a leading American water technology provider, is headquartered in **Washington, D.C., USA**.).

National Signal

The National Water Company (NWC) and SICWT have partnered to launch an incubator for advancing water sector innovations. This initiative supports business acceleration, research, and new technologies, aligning with NWC's strategic goals. NWC and SICWT Agree to Establish Incubator

Sectoral Trends [3/3]

MAJOR UTILITY INVESTMENTS IN INFRASTRUCTURE UPGRADES

Facilitating the integration of smart leakage management

In 2024, substantial investments in water infrastructure upgrades have been initiated globally to address aging systems and enhance efficiency. Examples include the allocation of $11.5 billion for water infrastructure upgrades by the US government in FY2024, the **£100 billion** investment plan 2025-2030 by UK Water Companies, and the **$4 billion** investment plan of Karachi Water and Sewerage Corporation (KWSC) backed among others by the European Investment Bank (EIB) and the World Bank.

National Signal

Saudi Arabia's National Water Company (NWC) is investing SAR 11.6 billion ($3.2 billion) in water and sanitation projects across Aseer, Qassim, and Al Baha. These efforts align with Vision 2030, aiming to modernize water distribution and wastewater treatment for a more sustainable future. NWC Announces Projects Worth SAR 11.6 Billion

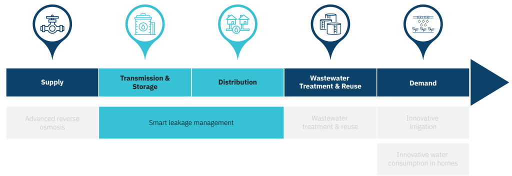
REGULATORY PENALTIES AND INCENTIVES FOR LEAK MANAGEMENT

Underscoring the growing regulatory emphasis for water conservation

In 2024, regulatory bodies intensified penalties and introduced incentives to enhance leak management in water utilities. In the UK, Ofwat mandated that water companies in England and Wales return £158 million to customers after failing to meet targets for reducing sewage spills and leaks. In the U.S., the Environmental Protection Agency adjusted its civil penalty policies to account, increasing fines for violations, including those related to water management. Overall, such policies should encourage utilities to adopt technologies for prevention and rapid response to minimize water loss.

National Signal

The **National Water Strategy** developed by MEWA provides a unified framework for the country's water sector. It integrates policies, regulations, and practices at the national level to address key challenges and restructure the sector. National Water Strategy Emphasizes Water Loss Reduction



WATER CREDIT SYSTEMS

Emerging a market-based mechanism promoting water conservation

Throughout 2024, Water Credit Systems continued to gain traction as a market-based policy mechanism promoting water conservation. These systems incentivize utilities and consumers to invest in technologies that reduce water usage, such as smart leak detection and efficient irrigation systems. For instance, in the United States, the Bureau of Reclamation's Water SMART program reported its support in over 2,300 projects with $3.23 billion in funding. In the private sector, several insurance companies have begun offering discounts to policyholders who install smart water monitoring devices.

National Signal

The National Water Company (NWC) is introducing an initiative aligning with the principles of water credit systems. The incentive-based program is designed to reward citizens for reducing their water usage. Participants who achieve reductions are awarded points to be redeemed for various benefits, including discounts on water bills and offers from partner brands.

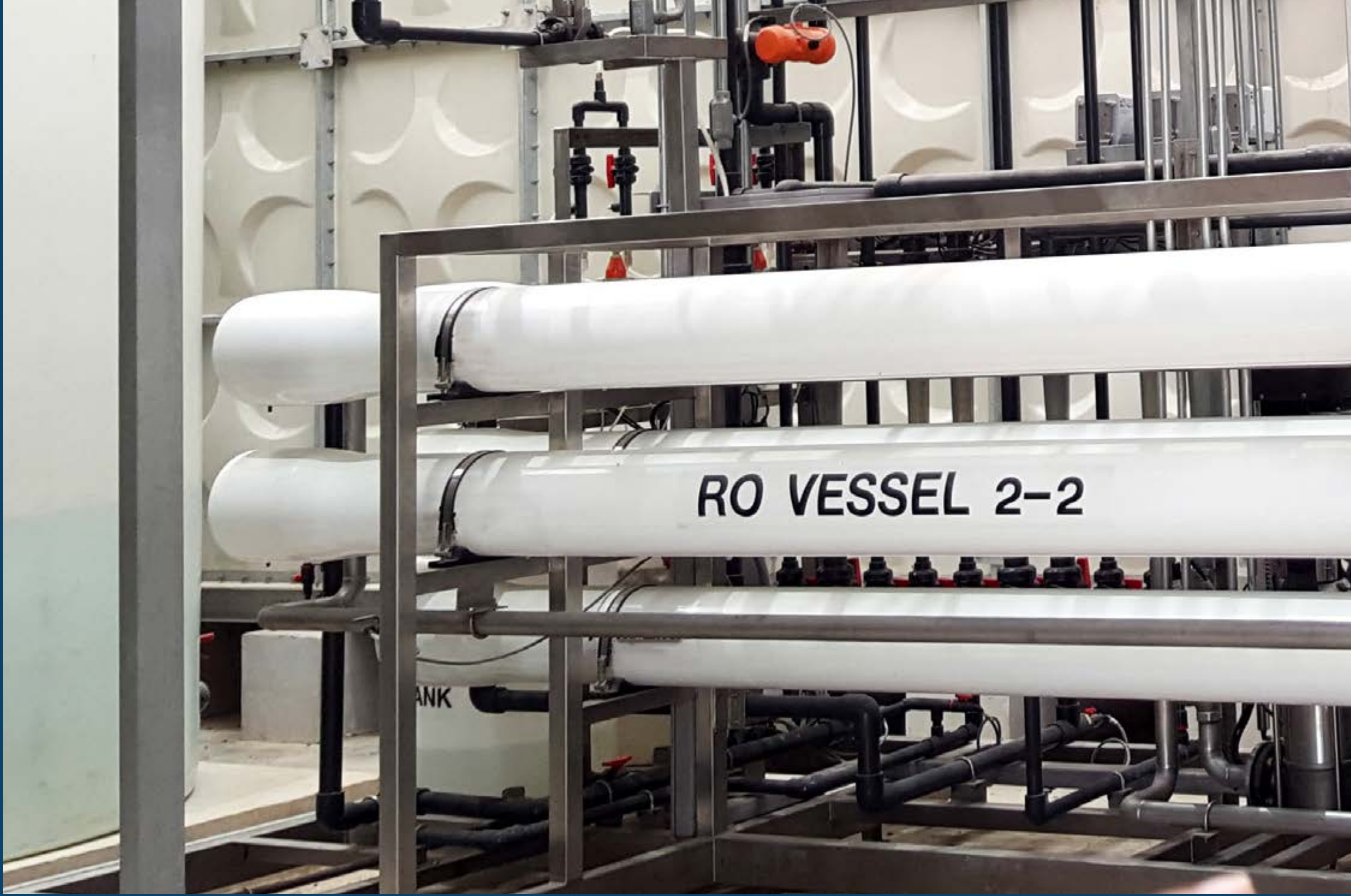
Designing an Incentive Program that Motivates Citizens to Reduce their Water Consumption

From Sectoral Trends to Technological Advancements

The evolving landscape of water management is being shaped by key sectoral trends, including increased emphasis on conservation, the rise of real-time monitoring, strategic partnerships, and regulatory shifts. These trends indicate a growing demand for intelligent solutions e.g., free-swimming system and pressure wave sensors that can enhance efficiency, reduce water loss, and support sustainability efforts.

As utilities, governments, and industries adapt to these changes, technology plays a pivotal role in enabling this transformation. The integration of Smart Water Management Technologies is not just a response to these sectoral shifts but a fundamental driver of progress. Advanced innovations, including AI-driven leak detection, IoT-enabled smart meters, and predictive analytics, are accelerating the transition towards a more resilient and efficient water infrastructure.

To meet the ambitious goals of national and global water strategies, stakeholders must leverage a combination of cutting-edge technologies designed to enhance leak prevention, detection, and mitigation. The following section explores these high-potential technologies, mapping their impact and feasibility in addressing the challenges posed by water management today. The next section explores specific technologies enabling smart leakage management.



Smart Water Management Technologies Driving Efficiency and Sustainability

To meet the ambitious goals of the National Water Strategy—including reducing wasted water by **15%** and achieving **100%** continuity of water supply—a smart combination of various new technologies is required. In this effort, RDI stakeholders benefit from a holistic understanding of the technology landscape, ensuring they can effectively leverage emerging innovations. Aligned with this vision, the RDI Water National Mission Statement, announced during SIW*, sets even more transformative objectives, **"By 2035, it aims to decrease the withdrawal of non-renewable water and reduce the cost of water production"** reinforcing the Kingdom's commitment to sustainable and efficient water management.

The chart of the technologies in the following next slides provides a **comprehensive overview of key technologies** that can address the challenges of Smart Leakage Management. The visualization intends to **extend the scope of awareness, inform RDI planning** and **inspire deeper investigation** into selected technology fields.

*SIW: Sustainability Innovation Weeks

The chart comprises **32 high-potential innovative technologies within the smart leakage management family,** spanning short-term gains to long-term vision and ranging from exploratory research to market-ready solutions. It maps promising approaches for **leak prevention, detection, and mitigation.** Beyond technology maturity, the chart also evaluates **impact and ease of implementation,** balancing **high-impact technologies** with **quick-win solutions** that require minimal adaptation. This ensures a strategic mix of effective and feasible technologies for sustainable water management.

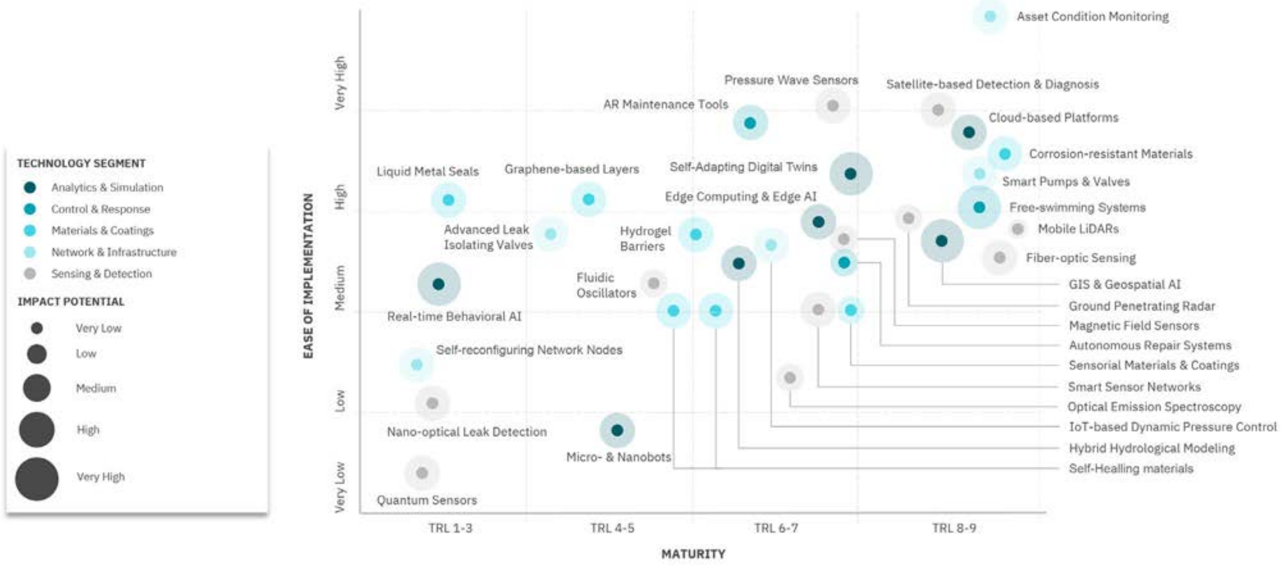
Technology Segments in Smart Leakage Management

ANALYTICS & SIMULATION	MATERIALS & COATINGS	NETWORK OPTIMIZATION & INFRASTUCTURE
Cloud-Based Platforms (TRL 8-9)	Corrosion-resistant Materials (TRL 8-9)	Asset Condition Monitoring (TRL 8-9)
GIS & Geospatial AI (TRL 8-9)	Hydrogel Barriers (TRL 6-7)	Smart Pumps & Valves (TRL 8-9)
Edge Computing & Edge AI (TRL 6-7)	Sensorial Materials & Coatings (TRL 6-7)	IoT-based Dynamic Pressure Control (TRL 6-7)
Hybrid Hydrological Modeling (TRL 6-7)	Self-healing Materials (TRL 4-5)	Advanced Leak-Isolating Valves (TRL 4-5)
Self-Adapting Digital Twins (TRL 6-7)	Graphene-Based Layers (TRL 4-5)	Self-Reconfiguring Network Nodes (TRL 1-3)
Real-Time Behavioral AI (TRL 1-3)	Liquid Metal Seals (TRL 1-3)	

The definitions of the listed technologies are in the glossary section

SENSING & DETECTION	CONTROL & RESPONSE
Fiber Optic Sensing (TRL 8-9)	Free-swimming Systems (TRL 8-9)
Ground Penetrating Radar (GPR) (TRL 8-9)	Remote-controlled Pipe Robots (TRL 8-9)
Mobile LiDARs (TRL 8-9)	AR Tools for Pipeline Maintenance (TRL 6-7)
Satellite-based Detection & Diagnosis (TRL 8-9)	Autonomous Repair Systems (TRL 6-7)
Magnetic Field Sensors (TRL 6-7)	Micro - and Nanobots (TRL 4-5)
Optical Emission Spectroscopy (TRL 6-7)	
Pressure Wave Sensors (TRL 6-7)	
Smart Sensor Networks (TRL 6-7)	
Fluidic Oscillators (TRL 4-5)	
Nano-optical Leak Detection (TRL 1-3)	
Quantum Sensors (TRL 1-3)	

Chart of the technologies [EASE OF IMPLEMENTATION vs MATURITY]



This section began by outlining six key sectoral trends influencing water sector innovation in 2024 and its role in transforming water management. It highlighted the challenges in smart leakage management emphasizing the need for advanced technologies. With regulatory incentives and infrastructure upgrades accelerating adoption, this section examines the smart leakage management emerging technologies and showcasing their level of ease of implementation compared to their maturity.

The following section starts to direct its focus to the five selected technologies, exploring and introducing an in-depth analysis of each one.

Ease of implementation, potential impact, and impact definitions are in the Glossary

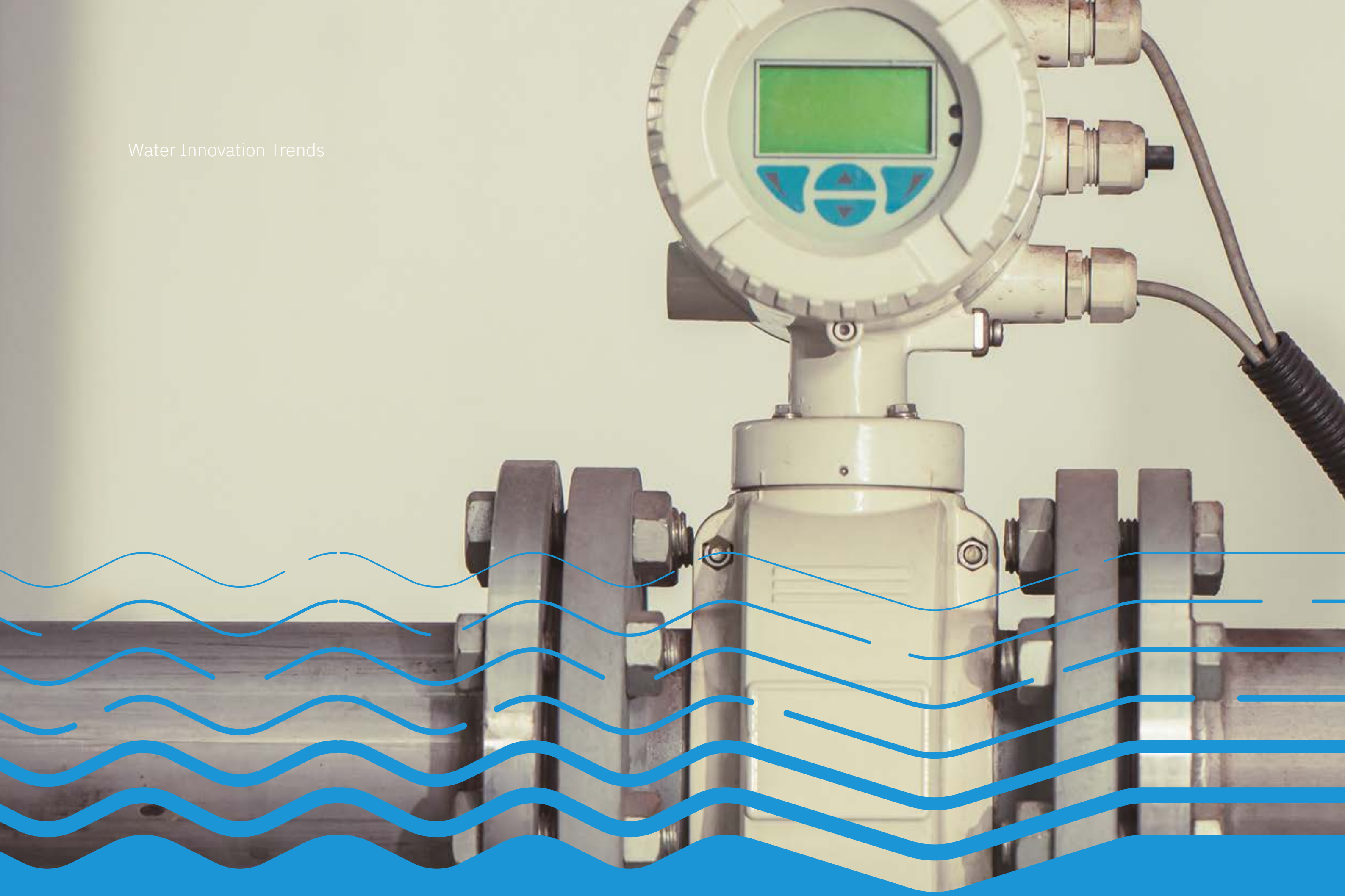
The chart presents Smart leakage management technologies, a key part of the Transmission and Distribution stage in the water value chain mentioned in the water sector challenges section.

The technologies are categorized into five segments:

- Analytics & Simulation
- Control & Response
- Materials & Coatings
- Network & Infrastructure
- Sensing & Detection

Each technology is assessed based on Technology Readiness Levels (TRL), ease of implementation, and impact potential, with technologies distributed across TRLs, ranging from early development to near-commercialization (X-Axis) and ease of implementation (Y-Axis).

Higher TRL technologies with high ease of implementation and high impact indicate great potential and may be prioritized for near-term deployment. Lower TRL technologies with high potential impact require further R&D investments, funding and grants, and strategic collaborations to accelerate their development and integration.



SMART LEAKAGE MANAGEMENT

3.1.1 TECHNOLOGY SPOTLIGHT

The Smart Leakage Management Most Promising Technologies

The selection of technologies featured in this spotlight section was selected based on three key criteria, ensuring relevance, impact, and diversity in addressing smart leakage management:

New and Notable Developments

Technologies were evaluated based on recent advancements, considering both novelty—the likelihood of introducing unprecedented innovations—and impact, which measures their contribution to progressing toward market readiness.

Relevance to KSA's Challenges

Priority was given to technologies with the potential to address Saudi Arabia's unique smart leakage management challenges.

Diversity of Technologies

A balanced selection was maintained across different technology segments, ensuring representation in the spotlight. The selection also considers a mix of high-maturity technologies for near-term application and emerging innovations with long-term potential.

Refer to the Selection Criteria Scorecard in the Appendix section

Trending Smart Leakage Management technologies are aligned with Vision 2030

The selected smart leakage management technologies align with the key criteria of innovation, relevance, and diversity. They enhance predictive analytics and adaptive infrastructure, addressing water loss, resilience, and detection challenges while supporting Vision 2030. The selection balances mature solutions for immediate use with emerging innovations for long-term impact.

Technology Segments	Technology	Maturity	Vision 2030 Relevance
Analytics & Simulation	Self-adapting digital twins	TRL 6-7	Enable real-time monitoring and predictive analytics, optimizing smart leakage management efficiency and aligning with Vision 2030's sustainability and smart infrastructure goals.
Control & Response	Free-swimming systems	TRL 8-9	Utilize autonomous bioengineered microorganisms or robotic units to enhance smart leakage management, improving efficiency and sustainability in line with Vision 2030's environmental and technological advancements.
Materials & Coatings	Self-healing materials	TRL 4-5	Enhance infrastructure durability by autonomously repairing cracks in smart leakage management systems, reducing maintenance costs and supporting Vision 2030's commitment to sustainable and resilient water management.
Network Optimization & Infrastructure	Self-reconfiguring network nodes	TRL 1-3	Adapt dynamically to changing smart leakage management demands, enhancing system efficiency and resilience in alignment with Vision 2030's smart infrastructure and sustainability goals.
Sensing & Detection	Pressure wave sensors	TRL 6-7	Enable real-time leak detection and flow optimization in smart leakage management, improving efficiency and conservation efforts in support of Vision 2030's smart water management and sustainability objectives.

TECHNOLOGY SPOTLIGHT

A. Self-Adapting Digital Twins

Digital twin platforms for water networks create real-time virtual replicas, allowing utilities to monitor, simulate, and optimize performance while predicting leaks, failures, and inefficiencies.

Source: https://www.tu.berlin/en/communication/aktuelles/publikationen/tagesspiegelbeilage/tagesspiegel-beilage-oktober-2024/digital-twins

Self-adapting digital twins

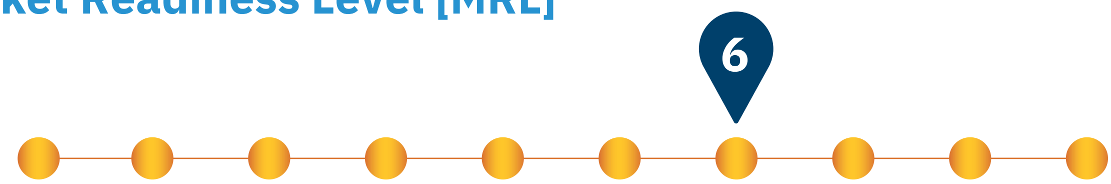
Digital twin platforms for water networks are designed to create real-time virtual replicas of water distribution systems. Integrating the technology with other tools, such as AI, Edge Computing, GIS, and Satellite Imaging, enables utilities to monitor, simulate, and optimize network performance. These platforms enhance decision-making by predicting leaks, failures, and inefficiencies before they occur. Self-adapting digital twins continuously evolve using live data to simulate performance, predict failures, and optimize operations, providing real-time insights and enabling proactive management of water networks.

Global developments in 2024 were characterized by highly-ambitious project kick-offs aiming to enhance the real-time monitoring of water systems in cities such as Houston, Fuzhou (receiving the IWA Project Innovation Award), and communities along the River Thames. The Naver project the is set to cover many cities in Saudi Arabia, developing digital twins platforms. Using this cutting-edge technology it will be applied through many integrated services such as flood simulations. This project fits Saudi Arabia's broader strategy to advance smart city infrastructure and improve urban management.

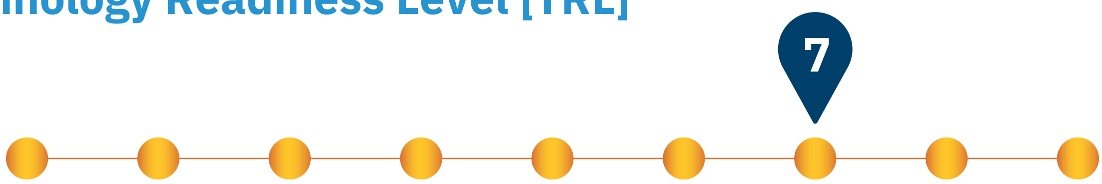
Technology and Market Maturity

Digital twin technology in water management has progressed to the stage where system prototypes are being demonstrated in operational environments **[TRL 7]**. Several utilities have implemented digital twin systems to monitor and manage their water distribution networks. The MRL for Digital Twin Platforms in water distribution is assessed at **[MRL 6]** indicating that the technology is market-ready, with pilot implementations underway and initial adoption by early users. Overall, the technology is expected to scale globally within the near future.

Market Readiness Level [MRL]



Technology Readiness Level [TRL]



Market Rediness Level (MRL) and Technology Readiness Level (TRL) descriptions are in the Glossary

Key Players

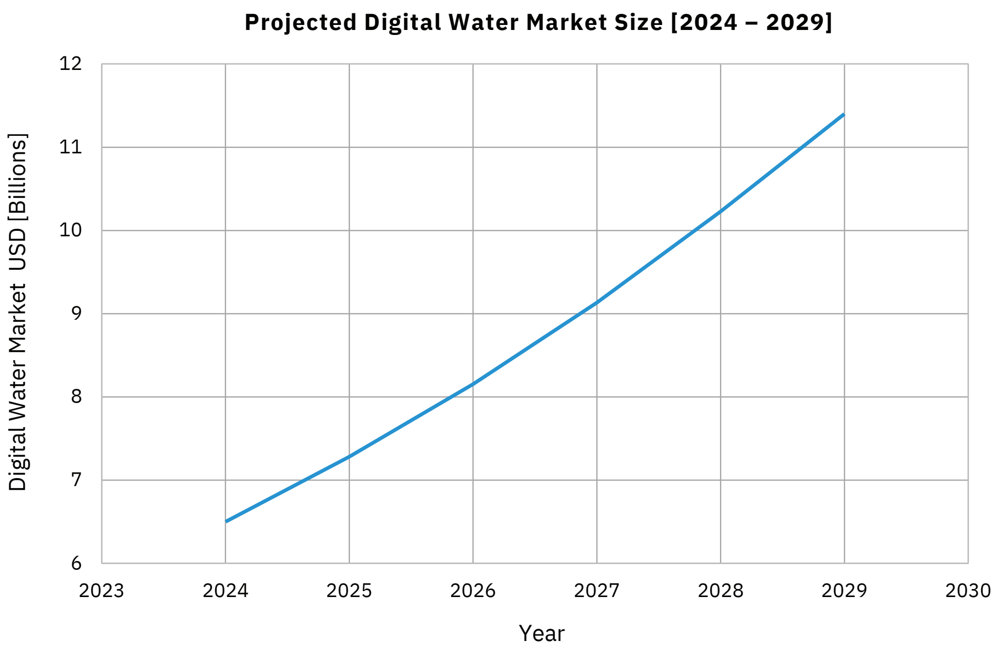
1. Autodesk
2. Bentley Systems
3. DHI Group
4. Idrica
5. SIEMENS
6. SenseTime
7. Thames Water
8. TU Berlin
9. Vassar Labs

Insights and statistics

By analyzing data, predicting issues such as leaks, and optimizing operations, Digital Twins can help enhance efficiency, reduce costs, and conserve energy as seen below.

Impact and Key Stats

- **Enhanced Operational Efficiency:** Digital twins provide real-time, detailed analyses, enabling utility staff to manage complex pumping and distribution operations more effectively. This leads to improved staff efficiency and optimal equipment operation. AWWA
- **Capital Planning and Risk Management:** Integrating hydraulic models within a digital twin allows utilities to simulate events like pipe failures and power outages, enhancing resilience and optimizing capital investments. Waterfm
- **Enhanced Leak Detection:** By tracking water quality, flow, and pressure, digital twins enable technicians to quickly identify leaks and predict future issues. Idexx Currents
- **Cost Savings:** Implementing digital twins can lead to significant cost reductions. For instance, a digital twin pump station in the Lushan Waterworks Water 4.0 testing facility (developed in collaboration with TU Berlin) resulted in a reduction of maintenance time by **up to 30%** and maintenance costs **by up to 25%.** WEF
- **Energy Efficiency:** Optimizing pump operations through digital twins can result in energy savings of **up to 15%,** as utilities can simulate and implement more efficient pumping strategies. IWA Network
- **Digital Water Market Expansion:** The broader digital water market, encompassing digital twin technologies, is anticipated to reach **USD 11.4 billion by 2029, up from USD 6.5 billion in 2024, with a CAGR of 12%.** MarketsandMarkets



Technology adoption

This focuses on the adoption of Digital Twins in water management, showcasing their growing global implementation, standardization efforts, and integration with advanced technologies such as IoT and GIS.

Current State

- **Growing Number of Project Initiation and Successes:** Digital twin technology is increasingly being integrated into water management systems worldwide, offering real-time monitoring and predictive capabilities to enhance efficiency and resilience. WEF
- **Standardization Efforts:** Industry organizations are working towards standardizing the definition and components of digital twins within the water sector. Bentley Blog
- **China in a Pioneering Role:** With **94 pilot** digital twin programs established in **48** locations across the country, China is actively preparing to take a leadership position in digital twin technologies for water governance and conservancy. Swissnex

Global Lessons Learned

- **Integration with Advanced Technologies:** The incorporation of Internet of Things (IoT) sensors and Geographic Information System (GIS) data into digital twin platforms is enhancing real-time monitoring and spatial analysis capabilities. This integration has been a key success factor in recent projects. Aquatech
- **Proactive Approach to Data Challenges:** Utilities like Anglian Water found that legacy data issues can hinder digital twin development. Assessing and improving data quality early in the project is crucial for success. IoT Insider
- **Scalable and Flexible Technology:** Platforms that can evolve with technological advancements and adapt to utilities growing needs are key for ensuring long-term viability. Info-Tech Research Group

Outlook

This outlines the future of Digital twins in water management, emphasizing advancements such as AI-driven optimization and integration with smart city networks.

Key Signals of Change

- **Integration of High-Resolution Earth Observations:** Vassar Labs has advanced digital twin technology by incorporating high-resolution Earth data enabling detailed simulations of the water cycle. Vassar Labs
- **Enhanced Real-Time Monitoring and Predictive Analytics:** The American Water Works Association (AWWA) reports successful implementations of digital twins that leverage static and live data streams, such as SCADA and IoT data, to accurately describe system performance. AWWA
- **Standardization Efforts by AWWA and SWAN:** The American Water Works Association (AWWA) and the Smart Water Networks Forum (SWAN) have collaborated to standardize the definition and components of digital twins within the water sector. Engineering & Construction

Future Trajectory

- **Advanced AI and Automation Will Drive Digital Twin Evolution:** Over the next decade, digital twins will likely become more self-learning and autonomous, using AI to optimize water networks in real-time. Predictive models will continue to improve, allowing for faster, more accurate leak detection with minimal human intervention. Idrica , LG Sonic
- **Integration with Broader Smart City and Utility Networks:** At some point, we expect digital twins to connect seamlessly with smart cities, integrating with energy grids, weather forecasting, and transportation systems. Smart Water Magazine
- **Automated Repair and Maintenance Becoming Reality:** Future developments will likely move beyond leak detection to leak prevention and automated repairs, reducing water loss. Robotics and self-repairing materials may be integrated into pipeline networks, further enhancing digital twin capabilities. Building Smart International

Case Study

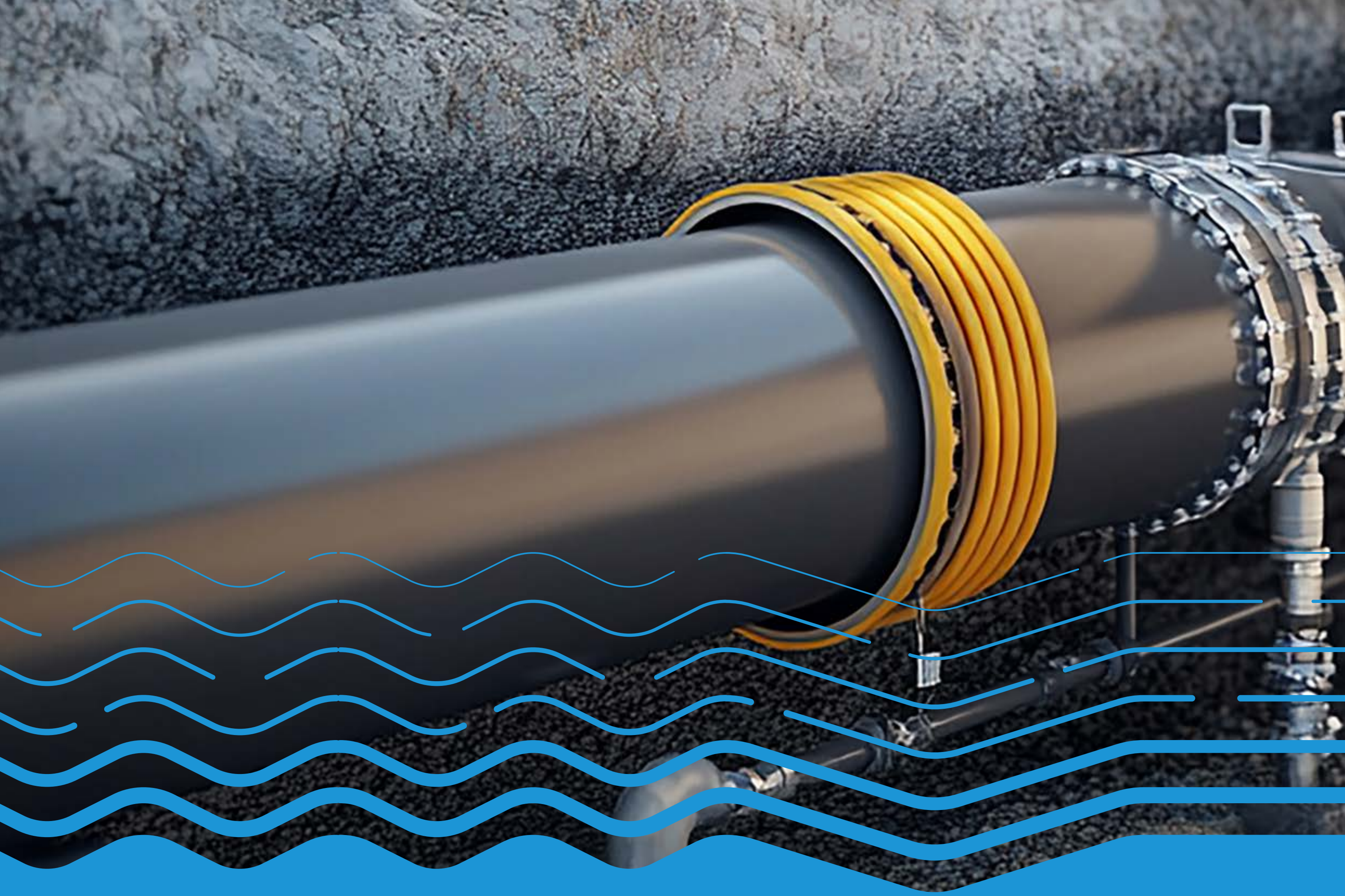
Self-adapting digital twins: 3D Model Cities - National Case Study

Starting in 2024, five major Saudi Arabian cities (Riyadh, Medina, Jeddah, Dammam, and Mecca) have embarked on a significant five-year partnership with Naver, a leading South Korean internet and technology company to develop digital twin platforms to transform urban planning, including water management. Singapore and Shanghai both have complete digital twins that work to improve energy consumption, traffic flow and even help plan developments. 5 Real World Examples of Digital Twins — PALAMIR The adoption of digital twins has already proven successful in other global cities. Singapore and Shanghai, for example, have fully developed digital twins that help optimize energy consumption, traffic flow, and urban development planning. These cases highlight the potential for Saudi Arabia's initiative to drive more efficient, data-driven decision-making

This initiative, secured through a $100 million contract in October 2023, aims to create highly accurate 3D models of these cities with a precision of up to 10 centimeters. The project also involves collaboration with Korean partners, including Korea Water Resources Corporation (K-Water) and Korea Land and Geospatial Informatix Corporation (LX), to integrate critical services and enable knowledge

transfer in alignment with Saudi Arabia's broader strategy to advance smart city infrastructure and through cutting-edge technology.

This initiative is expected to optimize city infrastructure, improve sustainability, and enhance public services. The digital twins will facilitate proactive leak detection, traffic management, and emergency response planning. By 2030, these digital twins are intended to serve as foundational tools for sustainable, AI-driven smart cities, showcasing a revolutionary approach to city management.



TECHNOLOGY SPOTLIGHT

B. Free-swimming Systems

Free-swimming, untethered systems are autonomous devices equipped with sensors that travel through pipelines to detect leaks, gas pockets, and structural anomalies. This technology provides a solution for inspecting pipelines, particularly in large-diameter or hard-to-access networks.

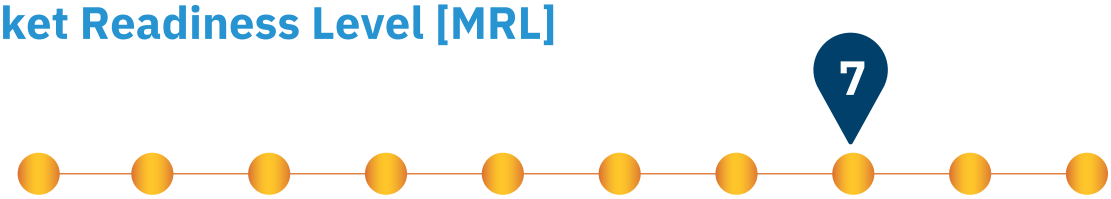
Free-swimming systems

Free-swimming, untethered systems are autonomous in-pipe inspection technologies used for leak detection and structural assessments in water pipelines. Equipped with acoustic, pressure, temperature, and magnetometric sensors, they identify leaks, gas pockets, and anomalies with high accuracy. These devices can travel long distances in pipes, navigating bends and valves without disrupting service. Unlike tethered systems, they move freely with water flow, making them ideal for large-diameter pipelines. GIS mapping enhances leak localization, enabling precise repairs. Utilities in Qatar, Scotland, Norway, and Canada — comprising diverse infrastructure conditions — have adopted solutions like SmartBall and PipeDiver to reduce water loss and extend infrastructure lifespan. As technology advances, AI and real-time analytics will further optimize leak detection and pipeline monitoring. In terms of limitations, there are challenges and limitation of free-swimming systems. For example, free-swimming devices have limited performance when it comes to complex, high-pressure pipelines.

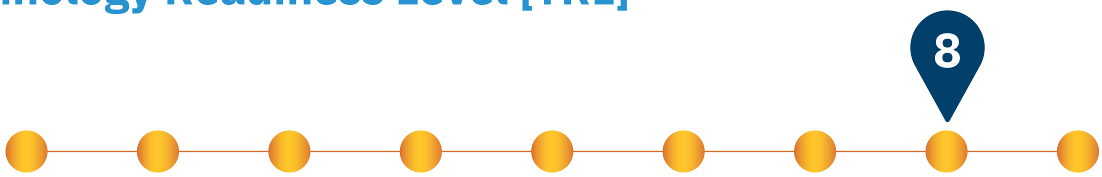
Technology and Market Maturity

Free-swimming and untethered systems for pipeline inspection have achieved a Technology Readiness Level **[TRL 8]**, indicating that they are complete and qualified through testing and demonstration. For instance, the SmartBall® by Xylem's Pure Technologies is a commercially available solution that has been successfully deployed in various pipeline networks. Recent advancements in 2024 have focused on enhancing sensor accuracy, battery life, and data analytics capabilities, further solidifying their technological maturity. In terms of Market Readiness Level **[MRL 7]** these systems are at Level **7**, reflecting a mature market with established products and growing adoption.

Market Readiness Level [MRL]



Technology Readiness Level [TRL]



Market Readiness Level (MRL) and Technology Readiness Level (TRL) descriptions are in the Glossary

Key Players

1. Acwa Robotics
2. Aqua Analytics
3. INSIGHT Water Technologies
4. Massachusetts Institute of Technology
5. Rosen Group
6. Xylem Inc. [Pure Technologies]
7. University of Sheffield

Insights and statistics

By detecting leaks early and without disruption, free-swimming systems enhance water conservation, reduce operational costs, and improve infrastructure resilience, as seen below.

Impact and Key Stats

- **Early Leak Detection:** By promptly identifying leaks, free-swimming systems facilitate timely repairs, addressing the 20–30% of water lost annually in supply systems and preventing minor issues from escalating into major failures. PMC
- **Extensive Pipeline Coverage:** Free-swimming systems can survey over 60 km of pipeline in a single deployment (at a flow rate of 1 m/s) without service disruption. They can navigate complex networks, including tight bends and inline valves, while operating effectively under low-flow conditions and across various pipe materials. IWA
- **Minimal Operator Intervention:** Moving with the water flow, free-swimming devices require fewer access points and less manual intervention compared to robotic crawlers or tethered sensors. IWA
- **Non-Disruptive Inspection:** Operating within live pipelines, these systems eliminate the need for shutdowns, excavation, or service interruptions, unlike some tethered or external detection methods. IWA
- **GIS and Digital Mapping Integration:** By capturing precise location data (within 1-2 m), the technology supports digital twin models and asset management strategies for long-term infrastructure planning. PMC
- **High Accuracy in Large-Diameter Pipelines:** Free-swimming systems are ideal for large transmission mains (wider than 20-30 cm in diameter), where external sensors and leak noise correlators often struggle due to distance limitations. Pacific Northwest National Laboratory

Technology adoption

Free-swimming systems are increasingly adopted globally, with advancements in sensor design and widespread municipal use driving improved pipeline management and water conservation.

Current State

- **Growing Adoption by Utilities:** The SmartBall technology has become a trusted solution globally, with utilities inspecting over 15,700 km of pipelines and identifying more than 4,450 leaks since its deployment in 2005. Xylem
- **Advancements in Sensor Design:** Research efforts have led to the development of optimized sensor designs (e.g., aerodynamic and hydrodynamic improvements) to ensure better stability, reduced noise interference, and enhanced leak detection accuracy in real-world conditions. ARFMTS
- **Expanding Municipal Adoption:** Utilities such as Scottish Water, City of Calgary, Oslo, and Qatar use free-swimming devices like SmartBall to inspect large-diameter water mains, preventing failures and reducing water loss.

Global Lessons Learned

- **Pipeline Design and Accessibility:** Lessons from deployments show the importance of strategic access points for insertion and retrieval, as retrofitting pipelines with these capabilities enhances the efficiency and feasibility of inspections. IWA
- **Integration of Multiple Technologies:** Free-swimming systems are not a standalone solution but valuable complements to other leak detection tools like tethered systems, imaging and sensing technologies, and software-based analytics. Together, these technologies allow utilities to cross-verify findings and collect more comprehensive data. Water
- **Addressing Regional Challenges:** Deployments in regions with aging infrastructure highlight the need for sensor designs that account for varying pipe materials, diameters, and flow conditions. ARFMTS

Outlook

Future developments in free-swimming systems will focus on precision, miniaturization, multi-sensor capabilities, IoT integration, and durability for diverse environments.

Key Signals of Change

- **Emergence of Self-Healing Pipeline Technologies:** Innovative solutions like Twin Balls Technology are being developed to detect leaks and instantly heal them within pipelines. This approach involves using smart balls that detect leaks through acoustic data and release healing agents to seal the leaks on the spot. ARFMTS
- **Advancements in Sensor Design:** Research focusing on improving sensor stability, reducing noise interference, and optimizing hydrodynamics for more accurate and efficient leak detection has proposed and tested new mobility modules, some inspired by ovoid and torpedo shapes. ARFMTS
- **New Benchmark in Precision and Efficiency:** The deployment of free-swimming systems in Oslo highlights their ability to detect leaks as small as 0.01 ℓ/m, demonstrating unparalleled precision and reliability in real-world conditions. MechChem

Future Trajectory

- **Miniaturization and Multi-Sensor Capabilities:** Future developments will likely focus on creating smaller, multi-functional sensors that can detect leaks, structural weaknesses, and contaminants simultaneously, making inspections more comprehensive. Pipelines 2024: Condition Assessment
- **Interoperability with IoT and Cloud Platforms:** Future systems will seamlessly integrate with cloud-based IoT platforms, enabling remote monitoring and real-time decision-making for utilities managing large pipeline networks. INSIGHT Water Technologies
- **Design for Harsh Environments:** The oil and gas sector has developed tools for high-pressure, high-temperature conditions. Applying these designs to water systems can improve durability and performance in challenging pipeline environments. NDT

Case Study

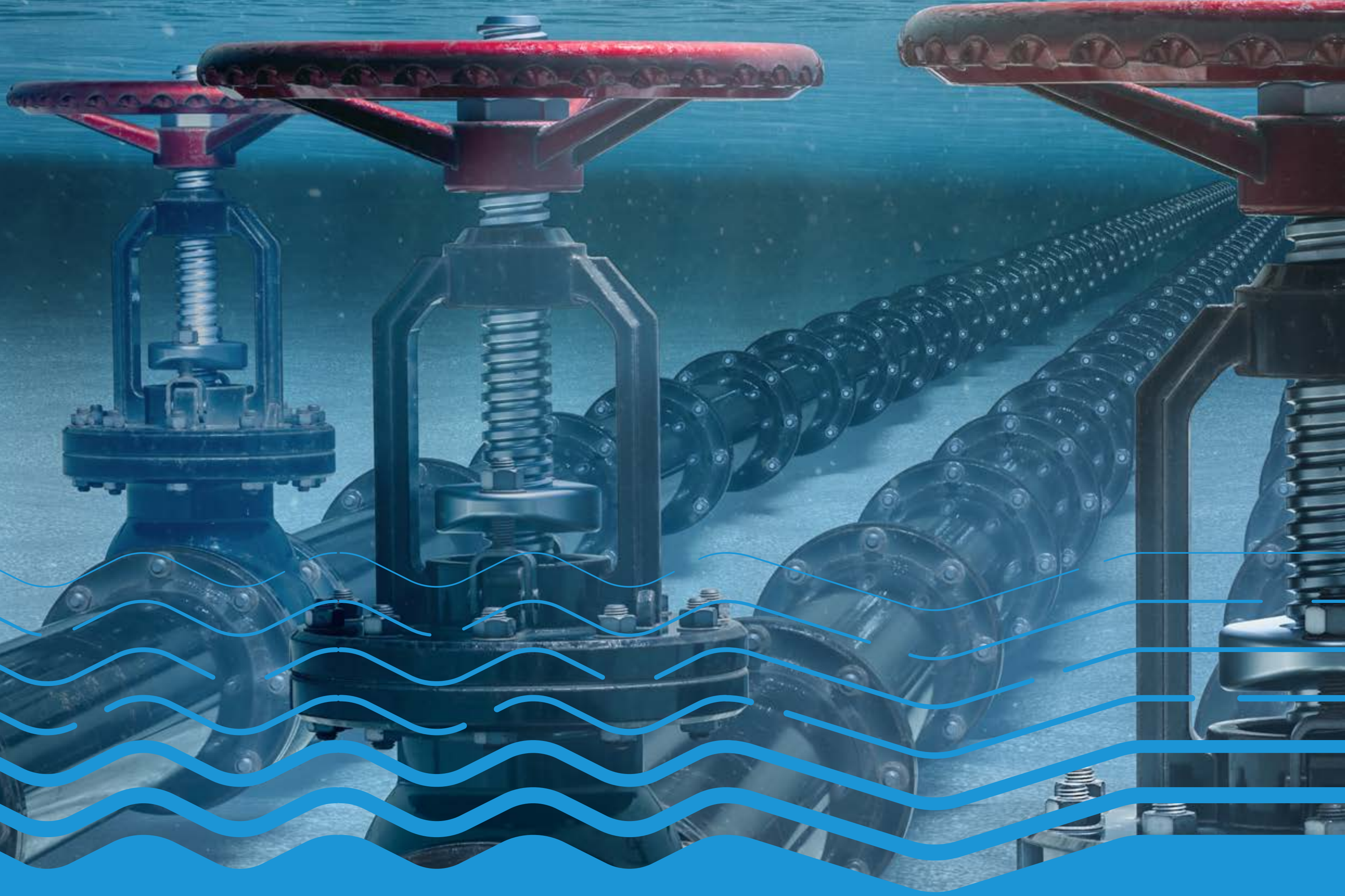
Free-swimming systems: AI-powered Autonomous Robotic Inspection for Water Pipeline Infrastructure

ACWA Robotics, a French startup, aims to address the significant issue of water loss in distribution networks, where utilities worldwide lose approximately 32 billion cubic meters of clean water annually due to deteriorating infrastructure. The company's goal is to provide water utilities with precise, real-time data on pipeline conditions to proactively manage and maintain water supply systems, thereby reducing water loss and optimizing infrastructure investments.

To achieve this, ACWA Robotics developed the Clean Water Pathfinder, an autonomous robot designed to navigate inside active water pipelines without disrupting service. Equipped with advanced sensors, including high-definition cameras and ultrasound instruments, the robot assesses pipe thickness, monitors corrosion, and detects leaks. Its AI-powered navigation system allows it to move through pipes of varying diameters, handling curves up to 90 degrees, and operate in pipes ranging from 200 to 1,000 millimeters in diameter. In October 2024, ACWA Robotics successfully conducted the first mission of

the Pathfinder robot in the Dunkirk water network, in partnership with SUEZ and Agence de l'Eau.

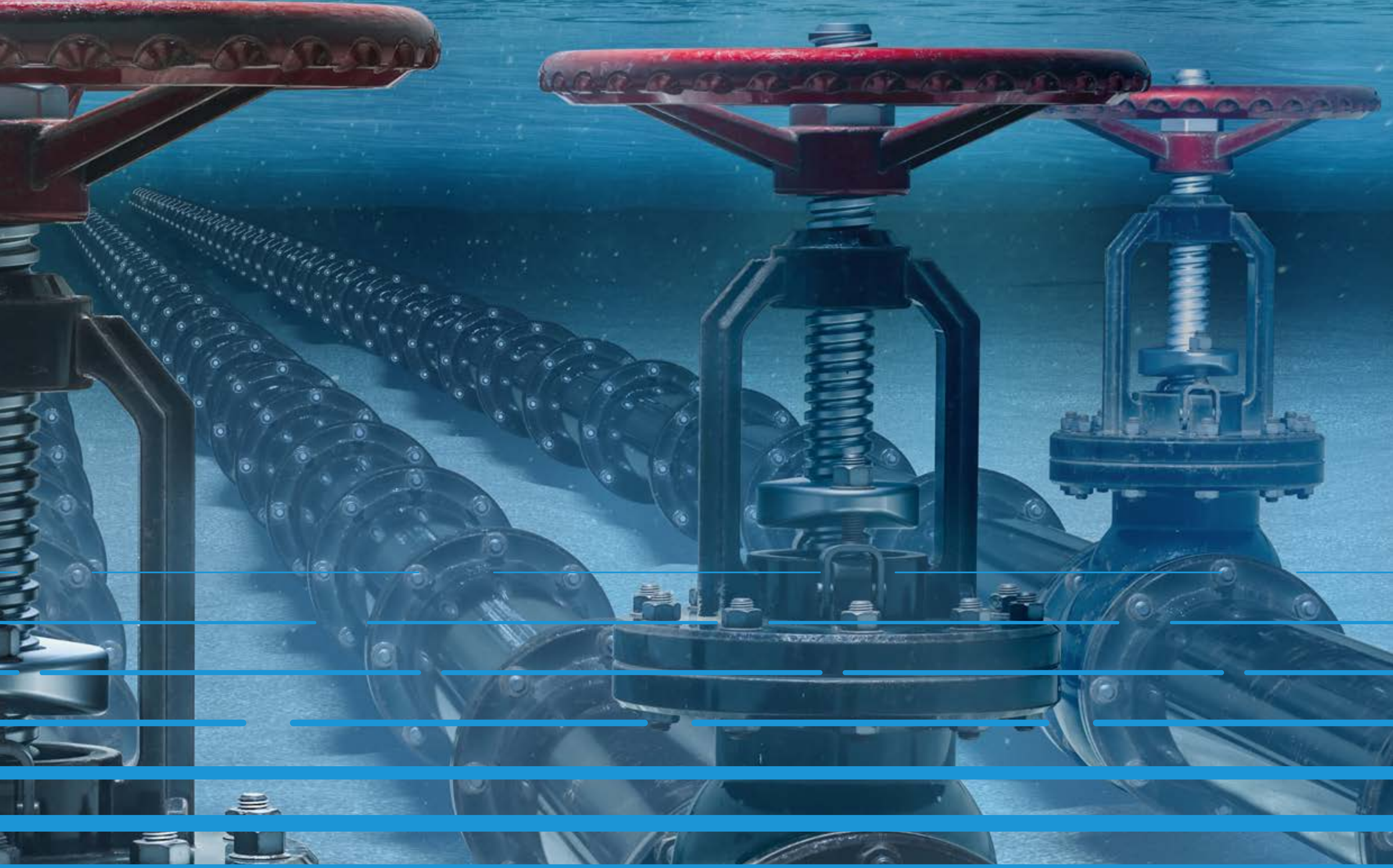
The deployment of the Clean Water Pathfinder enables utilities to gain comprehensive insights into their pipeline infrastructure, facilitating proactive maintenance and reducing water loss. By providing detailed assessments without the need for service interruptions or excavations, the robot helps optimize maintenance efforts and extend the lifespan of existing infrastructure. In 2023, the technology received the CES Best of Innovation in Smart Cities Award.



TECHNOLOGY SPOTLIGHT

C. Self-healing Materials

Self-healing materials are innovative substances capable of autonomously repairing damage, such as cracks or leaks, in water pipelines and infrastructure.



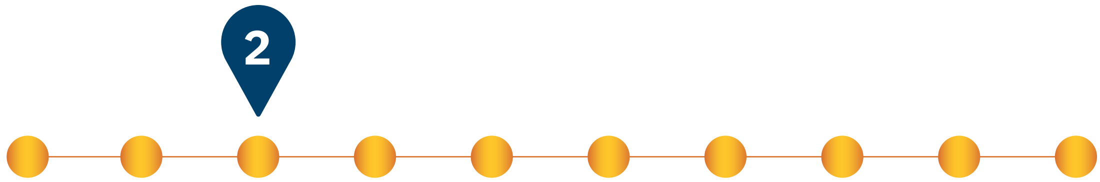
Self-healing materials

Self-healing materials are innovative substances designed to autonomously repair damage, such as cracks and leaks, in water pipelines. They work by incorporating microcapsules or nanomaterials filled with healing agents within the pipeline structure. When damage occurs, these capsules rupture, releasing the agents to seal the cracks and restore structural integrity without human intervention. This technology significantly reduces maintenance costs, minimizes water loss, and extends the lifespan of critical infrastructure. Most recently, pilot applications of the technology have been initiated such as the "No-dig" technology by Northumbria Water and OriginTech. Towards the mid-2030s, experts expect that nanotechnology-enhanced self-healing pipes are set to revolutionize water management systems, offering more sustainable, efficient solutions for leak prevention.

Technology and Market Maturity

Self-healing materials for water pipelines are currently at a Technology Readiness Level **[TRL 5]** indicating that while laboratory validation has been achieved and first field tests are ongoing, further development is necessary for real-world application. The Market Readiness Level **[MRL 2]** as while the general need in the market for advanced leak mitigation technologies is evident, ongoing research and demonstration projects are essential to address scalability, cost, and regulatory challenges, Self-healing materials are still in early research stages and are currently high-cost for mass deployment.

Market Readiness Level [MRL]



Technology Readiness Level [TRL]

Market Rediness Level (MRL) and Technology Readiness Level (TRL) descriptions are in the Glossary

Key Players

1 Autonomic Materials System Group [University of Illinois Urbana-Champaign]

2 Urban Research Group [Clemson University]

3 National Energy Technology Laboratory (NETL)

4 Northumbrian Water

5 RMIT University

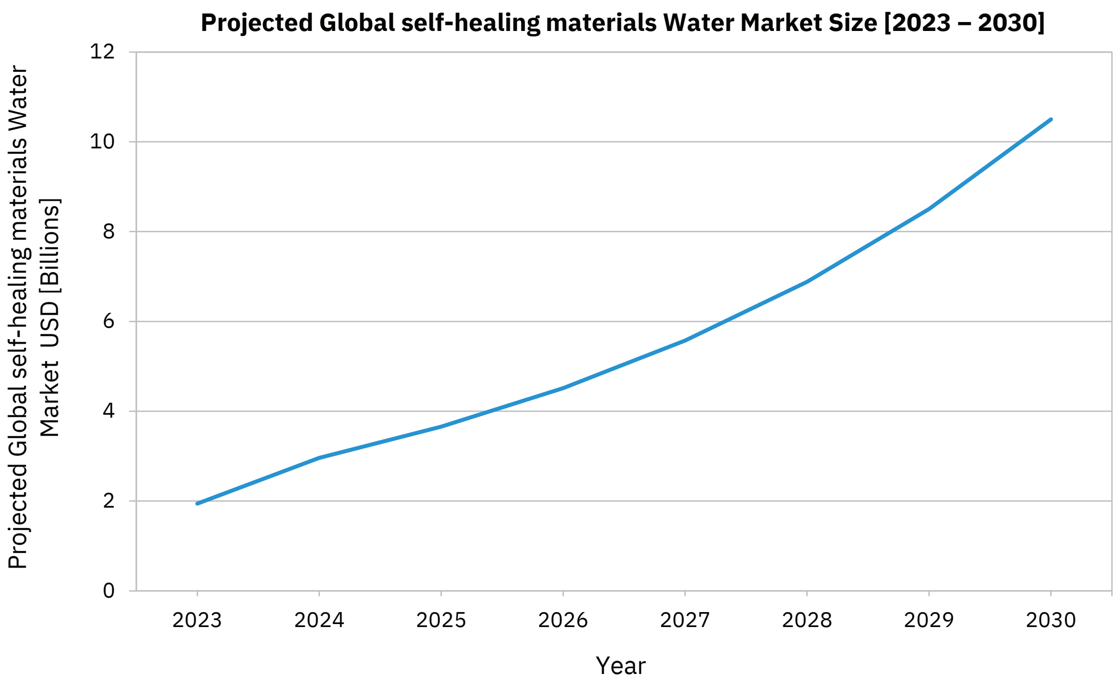
6 University of South Australia

Insights and statistics

Self-healing materials in water infrastructure have the potential to significantly reduce maintenance costs, minimize water loss, and extend the lifespan of critical infrastructure.

Impact and Key Stats

- **Maintenance Cost Savings:** Implementing self-healing technologies in concrete structures, including sewer pipes, could save economies like Australia's more than **$1 billion** in repair costs by extending the lifespan of infrastructure. University of South Australia
- **Reduced Disruption:** Traditional pipeline repairs often require extensive excavations, leading to traffic congestion and disturbances to local businesses. Self-healing materials minimize these disruptions by autonomously addressing leaks, ensuring smoother daily operations for communities. Smart Infrastructure & Construction
- **Market Growth:** The global self-healing materials market was valued at approximately **$1.94 billion** in 2023 and is projected to grow at a compound annual growth rate of **23.5%** from 2024 to 2030, indicating substantial economic potential. Grandview Research
- **Environmental Sustainability:** Self-healing materials can reduce the environmental impact of water infrastructure by decreasing the frequency of repairs and replacements, leading to lower resource consumption and waste generation. Advanced Science
- **Infrastructure Longevity:** These materials enhance the durability of water distribution systems by preventing minor damages from escalating, thereby extending the lifespan of the infrastructure. Envisioning



Technology adoption

While still in rather early stages, research on self-healing materials in water pipelines is steadily progressing, with several notable developments.in the past year.

Current State

- **Ongoing Experimentation and Diversity of Solutions:** As it is typical for a mid-TRL technology, there is a broad bandwidth of approaches and solutions developed in ongoing research project. Such developments include self-healing cold spray coating for pipelines, the integration of polymeric networks in water pipeline design, and the development of ultrafast self-healing materials based on piezo-ionic elastomers.
- **Commercialization Efforts:** While self-healing materials offer promising benefits, their market adoption in water pipelines is currently limited, with ongoing efforts to address scalability and cost-effectiveness for broader use. Advanced Science

Global Lessons Learned

- **Material Compatibility and Performance:** Ensuring that self-healing materials are compatible with existing pipeline materials is crucial. For instance, Australian engineers developed a zinc and polyurethane coating to prevent fatberg formation in sewer pipes, demonstrating the importance of selecting materials that can withstand specific environmental conditions. The Guardian
- **Design and Fabrication Strategies:** Innovative design approaches, such as embedding microcapsules or developing intrinsic self-healing polymers, are critical for creating effective self-repairing materials. A comprehensive review of self-healing composites emphasizes the importance of tailored fabrication techniques to enhance material longevity. Materials

Outlook

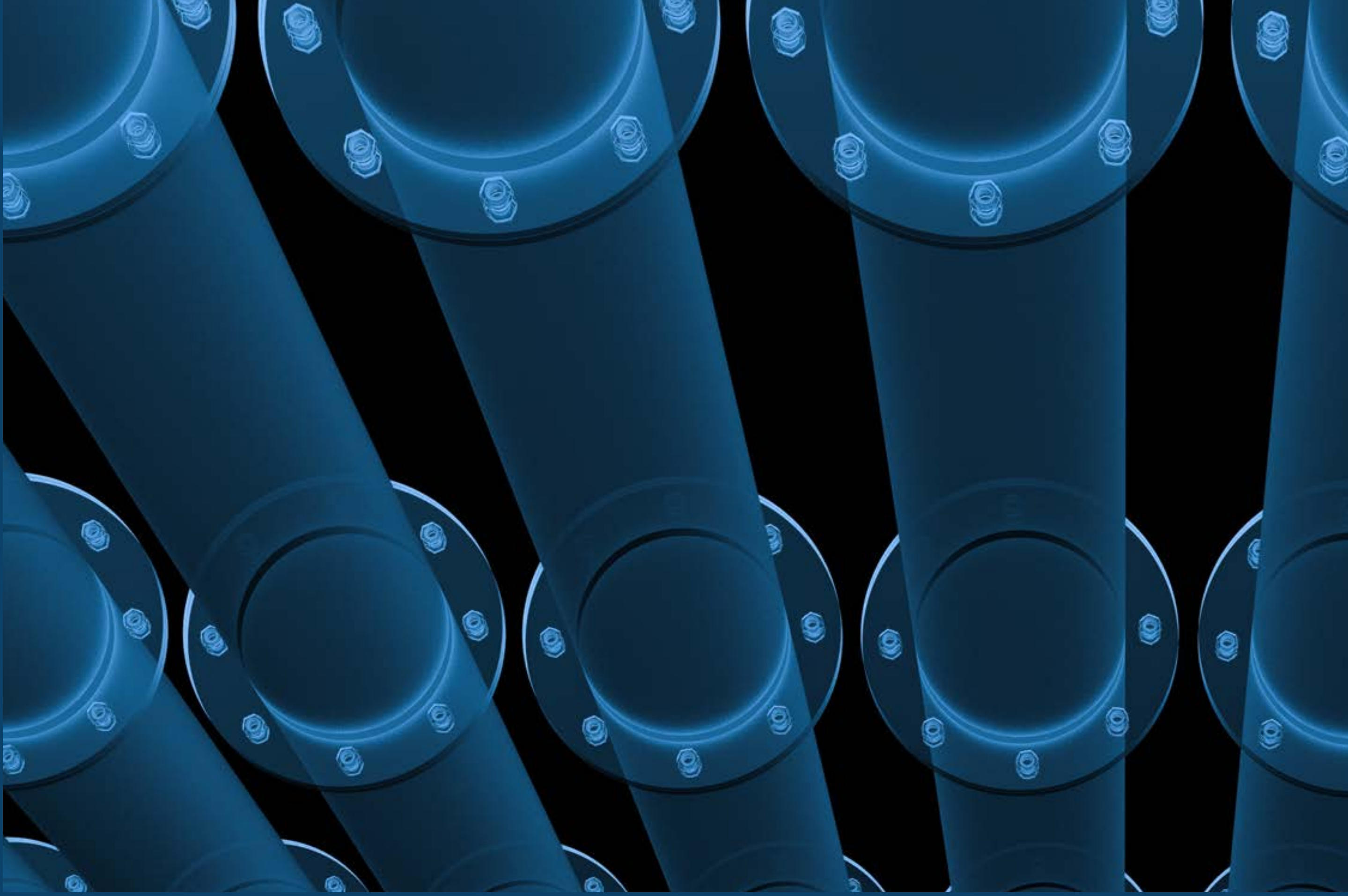
Recent advancements in self-healing materials indicate a future where water pipeline infrastructure is more resilient, sustainable, and cost-efficient in maintenance.

Key Signals of Change

- **Northumbrian Water's 'No-Dig' Self-Healing Pipe Technology:** Northumbrian Water successfully trialed an innovative 'No-Dig' technology in Newcastle, allowing water pipes to self-repair without excavation. This advancement aims to expedite leak repairs, minimize disruptions, and conserve water. Water Magazine
- **Advancements in Self-Healing Polymers for Wet Environments:** Research has progressed in creating self-healing polymers specifically designed for wet conditions, such as water pipelines. These materials autonomously repair damage in moist environments, enhancing infrastructure durability. Advances in Polymer Technologies

Future Trajectory

- **Gradual Integration in Water Infrastructures:** Starting in the 2030s, self-healing materials will likely be integrated primarily into new water pipeline projects, rather than retrofitting existing infrastructure. High costs, technical limitations, and compatibility issues with older systems will likely slow widespread adoption in legacy networks. Advanced Science
- **Focus on Hybrid Systems Combining Sensors and Self-Healing Materials:** The future of self-healing pipelines will likely involve hybrid technologies, where self-healing materials work in tandem with smart sensors. These systems will detect early-stage leaks, trigger localized healing mechanisms, and provide real-time data for predictive maintenance. Smart Infrastructure & Construction



Case Study

Self-healing materials: "No-Dig" Self-healing Pipeline Technology

Northumbrian Water faced the persistent challenge of detecting and repairing leaks within its extensive pipeline network. Traditional methods often required disruptive and costly excavations, leading to inconveniences for customers and increased operational expenses. The company sought an innovative solution to address leaks more efficiently while minimizing environmental and social impacts.

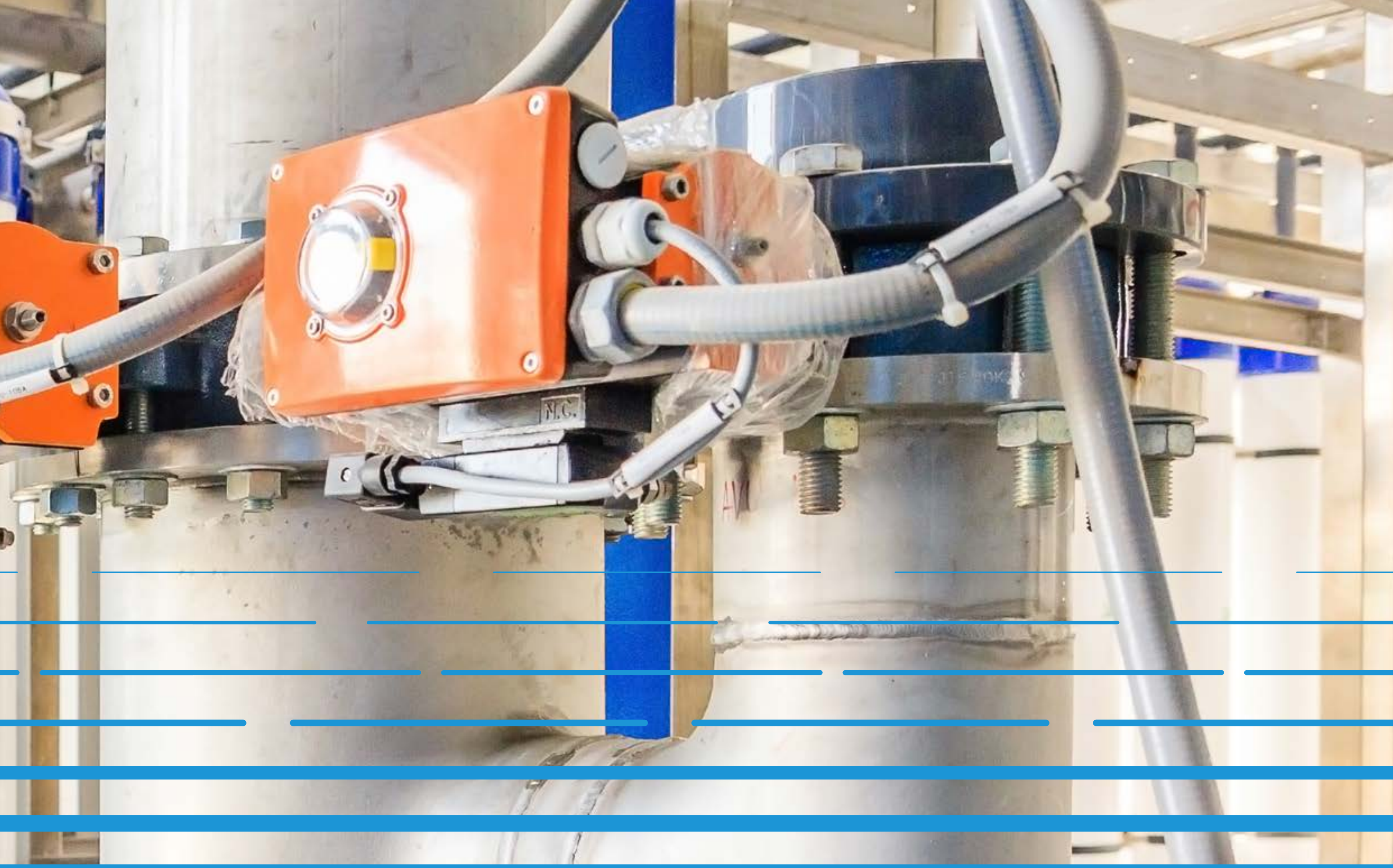
In collaboration with Origin Tech, Northumbrian Water developed the "No-Dig" technology—a pioneering approach that allows water pipes to self-heal without the need for excavation. This chemical-free solution comprises water, gel, and minerals, which are injected into the leaking pipes. The mixture travels through the pipeline, identifies the leak, and seals it from the outside, effectively plugging the hole. Initial trials started during the company's Innovation Festival in 2021, with further developments and field tests carried out in subsequent years.

The implementation of the No-Dig technology has yielded significant benefits. It has expedited leak repairs, reduced the need for disruptive excavations, and conserved water resources. By avoiding road closures and minimizing disturbances to customers, the technology has enhanced customer satisfaction. Additionally, the environmentally friendly composition of the solution aligns with sustainability goals. Following successful trials, Northumbrian Water plans to integrate this method into its standard leak repair processes, aiming for widespread deployment across the region by the end of the year

TECHNOLOGY SPOTLIGHT

D. Self-Reconfiguring Network Nodes

Intelligent nodes that autonomously reconfigure connections in the water network to adapt to demand and reduce vulnerabilities.



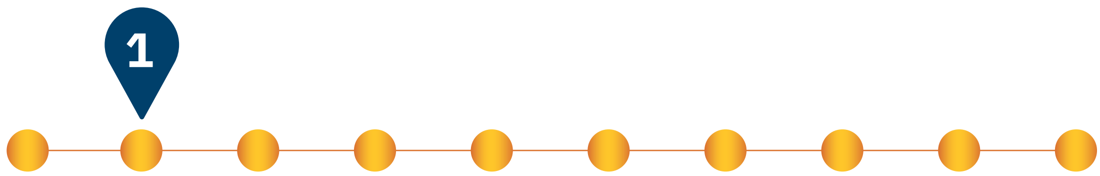
Self-reconfiguring network nodes

Self-reconfiguring network nodes are an early-stage technology envisioned to shape smart water leakage management in the future. These intelligent nodes would autonomously adapt and reconfigure water network connections based on real-time data inputs, such as pressure fluctuations, flow rates, and demand patterns. Utilizing advanced algorithms and predictive analytics, they could detect potential vulnerabilities before leaks occur, dynamically rerouting water to maintain system integrity. As of 2025, Self-reconfiguring network nodes remains conceptual with no full-scale pilots. However, In the future their integration with AI and digital twin models could enable fully self-optimizing water distribution systems, significantly enhancing resilience, minimizing water loss, and reducing manual intervention for leak detection and repair.

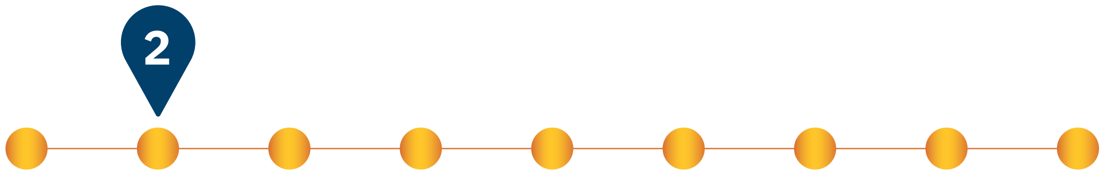
Technology and Market Maturity

Self-Reconfiguring Network Nodes are at an early conceptual stage **[TRL 2].** The idea revolves around integrating intelligent nodes with real-time reconfiguration capabilities into water distribution systems, leveraging predictive analytics and advanced algorithms. Theoretical foundations have been formulated, drawing on advancements in smart networks, IoT, and AI from other infrastructure domains (e.g., energy grids, telecommunications). While there is a recognized need for advanced leakage management solutions, especially in water-scarce regions like Saudi Arabia, this specific technology has not yet been defined with clear use cases, business models, or value propositions **[MRL 1]**

Market Readiness Level [MRL]



Technology Readiness Level [TRL]



Market Rediness Level (MRL) and Technology Readiness Level (TRL) descriptions are in the Glossary

Key Players

1. Aalborg University
2. CITEC Centre of Excellence, Bielefeld University
3. Grundfos
4. Imperial College London
5. UC Berkeley
6. University of Exeter
7. Virginia Commonwealth University, CCI Center for Cyber-Physical Systems

Insights and statistics

In the long-term, self-reconfiguring network nodes in water infrastructure could significantly enhancing resilience, minimizing water loss, and reducing manual intervention for leak detection and repair.

Impact and Key Stats

- **Dynamic Adaptation to Environmental Conditions:** Research on self-configuring localization systems highlights the importance of autonomous adaptation to environmental conditions. Implementing self-reconfiguring nodes could enable water networks to adjust to changing conditions, enhancing resilience and operational efficiency. ACM Transactions on Embedded Computer Systems
- **Proactive Leak Mitigation Through Autonomous Reconfiguration:** Self-Reconfiguring Network Nodes could dynamically adjust water flow and pressure in real-time based on detected anomalies, proactively mitigating leak risks before they escalate. This would shift the paradigm from reactive leak repairs to continuous, autonomous system optimization. Engineering Proceedings
- **Support for Smart City Integration and Data-Driven Governance:** As part of broader smart water grids, these nodes could integrate seamlessly with IoT platforms and digital twins, providing real-time data for municipal water management. This would enhance data-driven decision-making, improve regulatory compliance, and support sustainability initiatives in urban planning. Journal of Hydroinformatics
- **Energy Efficiency through Self-Adjustment:** Protocols that account for environmental factors, such as water currents, have achieved significant energy savings. Incorporating self-reconfiguring nodes that adjust to such factors could lead to substantial energy efficiency in water distribution. Sensors

Technology adoption

As of 2024, the technology Self-Reconfiguring Water Network Nodes is in its nascent stages, with research mainly focusing on first conceptualizations and adapting insights generated from adaptive network topologies in other grid types (e.g., energy).

Current State

- **Conceptualization of Adaptive Water Distribution Networks:** Research has introduced the idea of dynamically reconfigurable topologies in water networks to optimize pressure control and enhance system resilience. This approach integrates the benefits of traditional District Metered Areas (DMAs) with large-scale looped networks, aiming to improve leakage management and operational flexibility. Journal of Hydroinformatics
- **Distributed Optimization for Network Control:** Recent studies have proposed new control models utilizing distributed nonconvex optimization to enhance pressure and water quality operations in water distribution networks. These models aim to improve operational efficiency and robustness, which are essential for the development of self-reconfiguring capabilities. Water Resources Management
- **Physics-Informed Graph Neural Networks:** Innovations in machine learning, such as physics-informed graph neural networks, have been applied to water distribution systems for efficient hydraulic state estimation. These models offer faster emulation times and high accuracy, contributing to the foundational knowledge necessary for developing intelligent, self-reconfiguring nodes. Proceedings of the AAAI Conference on Artificial Intelligence 2024

Global Lessons Learned

- **Integration of Adaptive Control Mechanisms:** Implementing adaptive control strategies can enhance the efficiency of water distribution systems. Research indicates that IoT-based adaptive control schemes outperform traditional methods, suggesting a need for further exploration in this area. IEEE
- **Robust Adaptive Optimization for Demand Prediction:** Employing robust multi-step water demand prediction approaches within smart water management frameworks can improve system resilience. Further research in this area supports the development of nodes capable of autonomously adjusting to fluctuating demands. Nature: Scientific Reports
- **Application of Machine Learning Techniques:** Machine learning applications in smart water distribution systems can enhance predictive maintenance and operational efficiency. Identifying challenges and future directions in this domain is essential for advancing self-reconfiguring capabilities. Artificial Intelligence Review

Outlook

Self-Reconfiguring Network Nodes are expected to evolve from conceptual models to pilot-stage technologies by the mid-2030, building on recent developments in network simulation, digital twin, and machine learning technologies.

Key Signals of Change

- **Smart Water Infrastructures Laboratory: Reconfigurable Test-Beds for Control and Management of Water Infrastructures:** This paper discusses the development of a smart water infrastructures laboratory designed as a modular system that can be configured to represent specific water distribution and waste collection networks. It enables experimental research in control and management of water infrastructures in a realistic environment. Water
- **Dynamically Adaptive Networks for Integrating Optimal Pressure Management and Self-Cleaning Controls:** This research investigates the integration of optimal pressure management and self-cleaning controls in dynamically adaptive water distribution networks. It formulates a bi-objective design problem to optimize the placement and operation of control valves, providing important groundwork for network self-reconfiguration. Annual Reviews in Control

Future Trajectory

- **Gradual Transition from Concept to Prototype:** Self-Reconfiguring Water Network Nodes will progress from conceptual models to functional prototypes deployed in controlled pilot environments by the early 2030s. These pilots will likely focus on specific, high-risk urban areas where water loss is critical, rather than full-scale network implementations. Journal of Hydroinformatics
- **Integration with Digital Twins and Predictive Analytics:** The development of digital twins for water networks will become a key enabler for testing and optimizing self-reconfiguring node algorithms, allowing utilities to simulate reconfiguration strategies without risking real-world infrastructure failures. Artificial Intelligence Review
- **Limited Autonomous Functionality with Human-in-the-Loop:** Full autonomy in reconfiguring water networks will most likely not be achieved by the mid-2030s. Instead, systems may operate with a “human-in-the-loop” model, where self-reconfiguring nodes suggest optimal configurations but require human validation for implementation in critical infrastructure. IAPP

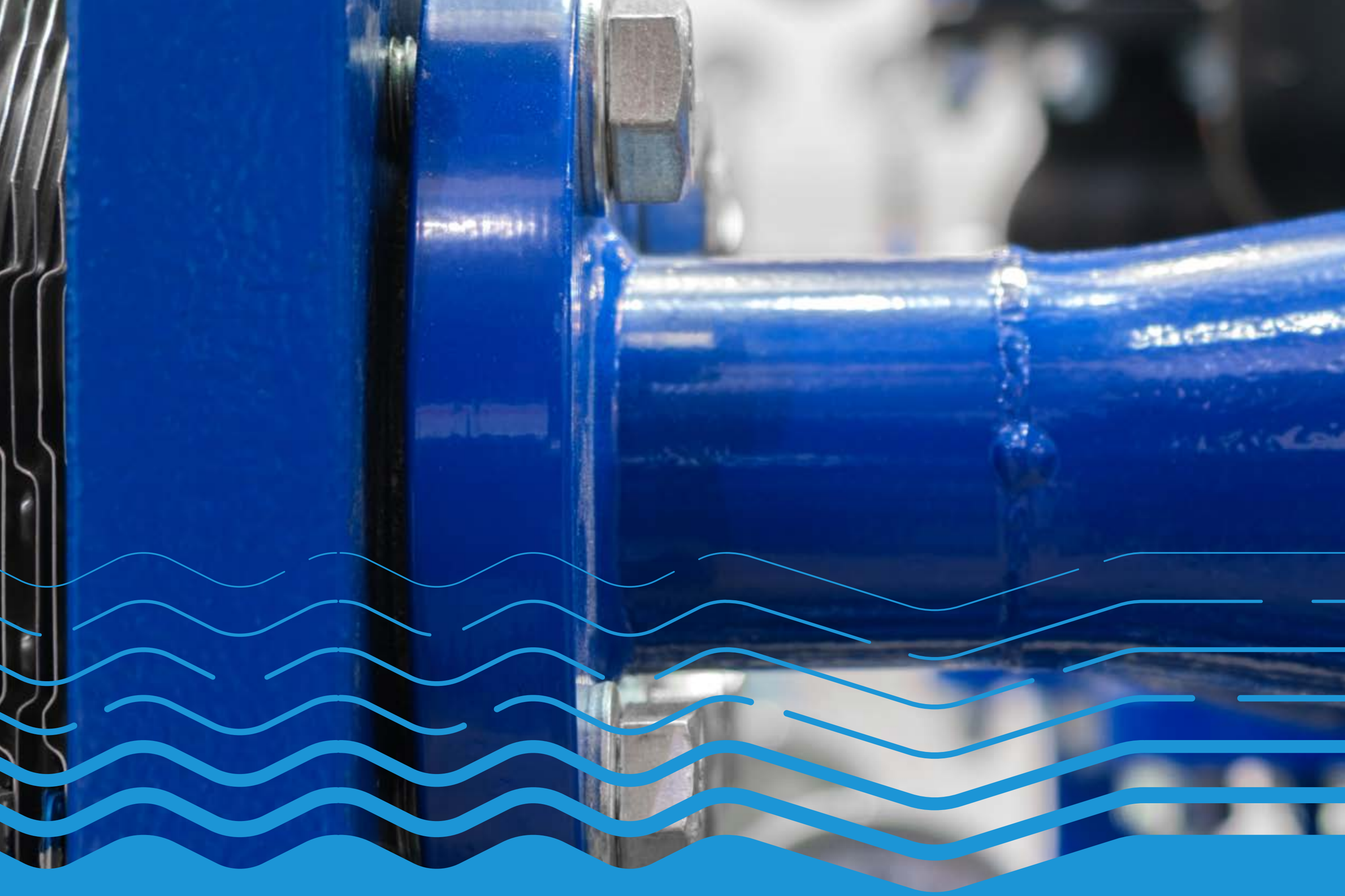
Case Study

Self-reconfiguring network nodes: Autonomous Water Network Optimization and Self-Reconfiguring Infrastructure Simulation

The Smart Water Infrastructures Laboratory (SWIL), a collaboration between Aalborg University and Grundfos, aims to revolutionize the management and control of water infrastructures by developing intelligent, adaptive systems. The laboratory focuses on creating robust, user-friendly solutions that cater to both industry professionals and consumers. A critical objective is to provide a platform for testing emerging technologies which promise to enhance water distribution efficiency through autonomous network optimization.

SWIL employs a modular, reconfigurable design that allows researchers to emulate a wide range of water infrastructures, including water distribution networks, wastewater systems, and district heating grids. This flexibility is pivotal for experimenting with self-reconfiguring network nodes, as it enables the simulation of dynamic network topologies to autonomously adjust flow paths and pressure zones. The laboratory integrates real-time monitoring systems, advanced control algorithms, and data acquisition platforms to evaluate how these self-reconfiguring technologies respond to varying demand conditions, leak scenarios, and operational stress.

The potential of SWIL lies in its ability to serve as a realistic testbed for emerging smart water technologies. By enabling controlled experiments, SWIL helps validate the operational feasibility, efficiency gains, and resilience improvements offered by such technologies. This research can accelerate the transition of self-reconfiguring nodes from theoretical models to practical applications, ultimately contributing to reduced water losses, optimized energy consumption, and enhanced network reliability in real-world infrastructures.



TECHNOLOGY SPOTLIGHT

E. Pressure Wave Sensors

Pressure wave sensors are advanced devices that monitor pressure waves in real-time and use high-resolution analytics to detect the smallest deviations caused by leaks.


80
60
100
40
120
20
140
C
0
160
1,5

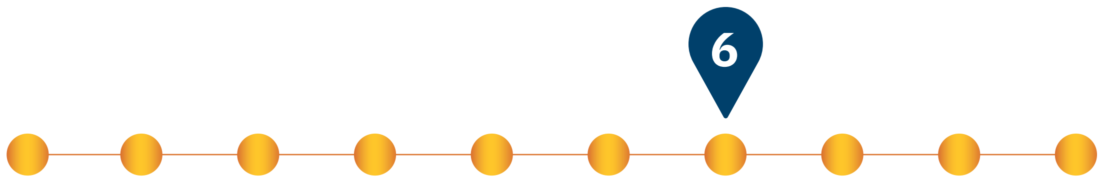
Pressure wave sensors

Pressure wave systems are advanced leak detection technologies that monitor transient pressure waves in pipelines to identify and locate leaks in real time. Using high-resolution sensors and negative-pressure wave analysis, these systems enable early detection, reducing water loss and infrastructure damage. They are crucial for municipal water networks, industrial facilities, and smart city projects, with adoption seen in Singapore's water utilities and European urban networks. The technology improves operational efficiency, but challenges include integration with legacy infrastructure and high data processing demands. Future developments will enhance AI-driven analytics, IoT connectivity, and predictive maintenance, making pressure wave systems a key tool in the push for resilient, efficient, and sustainable water management worldwide. Pressure wave sensors provide real-time, cost-effective leak detection and are well-suited for Saudi water networks, complementing existing National Water Company efforts like acoustic leak detection projects.

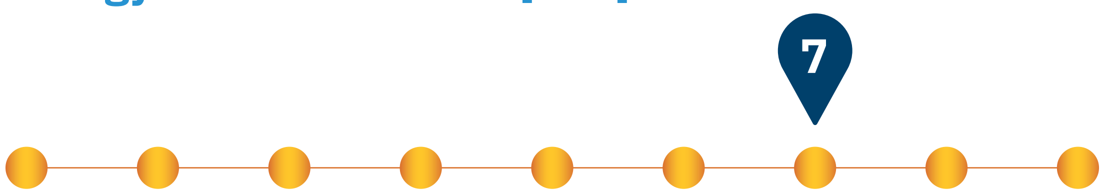
Technology and Market Maturity

Pressure wave systems are in the early commercialization to growth phase **[MRL 6]** with increasing adoption in urban water utilities and industrial applications. The technology is well-established in high-precision leak detection **[TRL 7]** but continues to evolve with AI-driven analytics and IoT integration. While pilot programs and deployments are expanding in regions like Europe, Singapore, and North America, challenges remain in scalability, cost, and integration with legacy infrastructure, limiting widespread adoption.

Market Readiness Level [MRL]



Technology Readiness Level [TRL]



Market Rediness Level (MRL) and Technology Readiness Level (TRL) descriptions are in the Glossary

Key Players

1. Atmos International
2. Beyond Limits
3. Echologics
4. Hitachi
5. NAI Company
6. Phyn
7. Siemens Energy
8. Visenti

Insights and statistics

Pressure wave systems enable faster leak detection, reduced water loss, lower repair costs, extended infrastructure lifespan, and improved sustainability in water management.

Impact and Key Stats

- **Long-Distance Monitoring Capability:** Negative pressure waves (NPW) can travel over 36 km in liquid pipelines with minimal attenuation, making them an ideal choice for long-distance water transmission networks. Measurement
- **High Sensitivity for Leak Detection:** Pressure wave systems can detect leaks as small as 5% of the nominal liquid flow rate, ensuring early intervention before water losses become significant. This is critical for water utilities managing aging infrastructure, as even small leaks can contribute to millions of liters of lost water annually. ASGMT
- **Rapid Leak Identification:** The ability to analyze negative pressure waves within milliseconds allows for near-instantaneous leak detection and response. Modern systems employ high-speed scan rates of up to 1 ms, ensuring no pressure anomalies go undetected. Applied Sciences
- **Accurate Leak Localization:** Pressure wave systems use pulse time delay analysis and cross-correlation algorithms to precisely locate leaks along pipelines. With error margins as low as **0.97%–1.46%,** these systems significantly reduce the need for costly excavation and exploratory digging. Sensors
- **Adaptability to Different Fluids:** Pressure wave systems can accurately detect leaks in a wide range of fluids. This adaptability ensures that different pipeline types—whether potable water, irrigation networks, wastewater, or desalination plants—can benefit from a unified, scalable leak detection approach. Sustainability
- **Integration with SCADA Using Minimal Data Packets:** Instead of transmitting continuous raw data, pressure wave systems send small, time-stamped event packets (100 bytes per 20-120 seconds) to central stations, ensuring faster processing with minimal bandwidth use. IEEE Control Systems Magazine

Technology adoption

As of 2024, the global adoption of pressure wave sensors for water leakage management is characterized by a solidified recognition of pressure wave sensors as a valuable tool in efficient water resource management.

Current State

- **Broad-scale Adoption in Singapore:** After successful trials, detecting **13 leaks** over a three-year period, the Public Utilities Board (PUB), Singapore's National Water Agency has started to stepwise deploy **1,200** sensors islandwide for leak monitoring since 2017. Smart Water Magazine
- **Advancements in Smart Home Leak Detection:** Recent developments have seen the incorporation of pressure wave analysis into smart home technologies, enabling the detection of hidden leaks within residential water systems. National Association of Home Builders
- **De Watergroep's Infrastructure Upgrade:** De Watergroep, a Belgian water utility, allocated **€17.8 million** to install **400** new flow and pressure wave sensors and replace 300 existing data loggers. This initiative aims to enhance leak detection and reduce water loss across their 34,000 km pipeline network. Asset Performance

Global Lessons Learned

- **Sensor Sensitivity vs. False Positives:** High-sensitivity pressure wave sensors can trigger false positives due to normal pressure fluctuations, leading to unnecessary alerts. Balancing sensitivity and specificity is crucial to minimize these occurrences. Laiier
- **Comprehensive Network Assessment:** A thorough assessment of the water distribution network is essential to identify vulnerable areas and optimize sensor placement for effective leak detection. This approach enhances the efficiency of pressure wave sensor deployment. Sensors
- **Synergies between Sensor Types:** Integrating various sensor types, such as pressure and acoustic sensors, enhances leak detection accuracy in water distribution systems by providing complementary data, leading to more reliable identification and localization of leaks. Water

Outlook

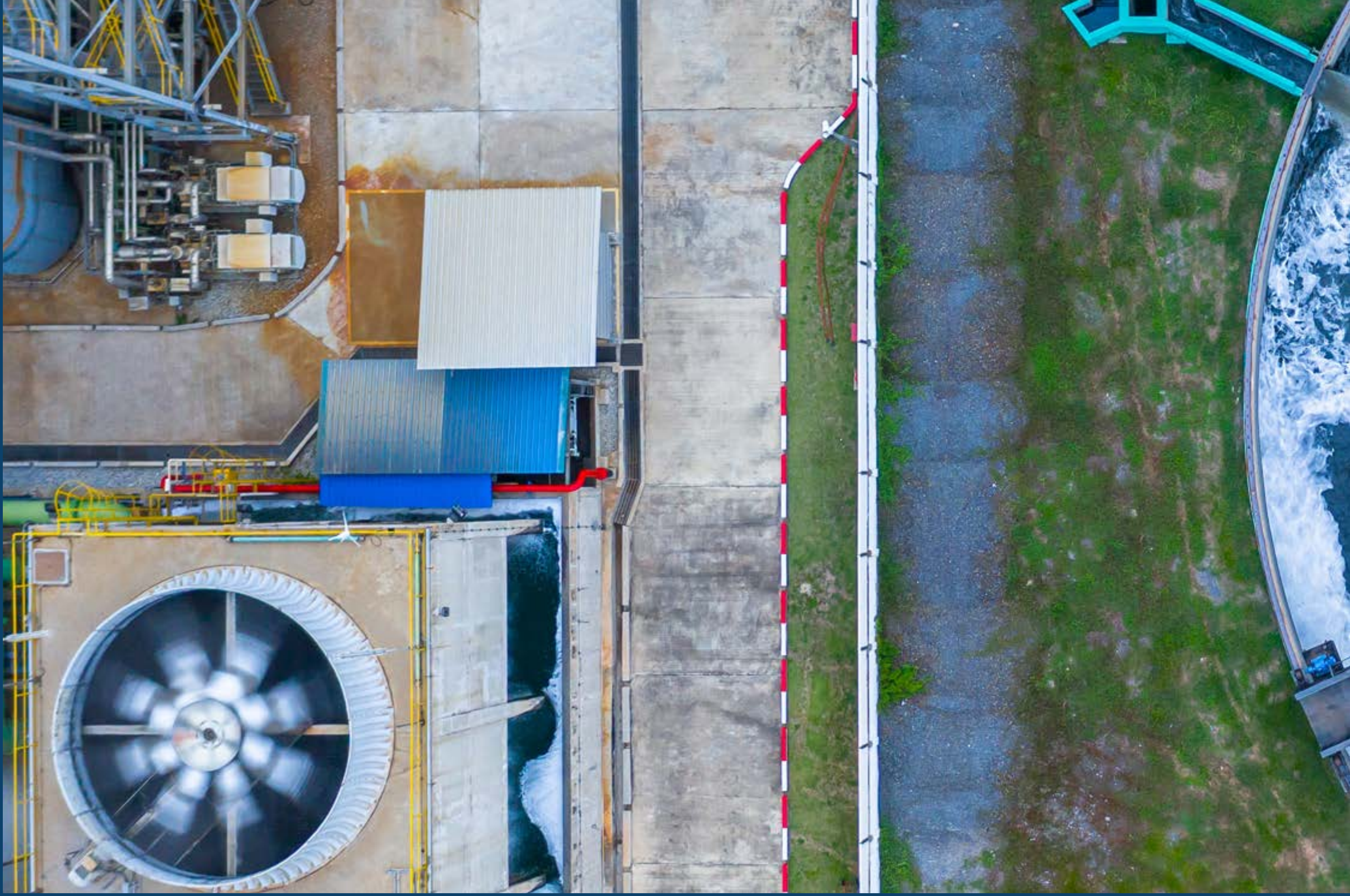
In the near future, pressure wave sensors are expected to evolve into highly integrated, multi-sensor systems with improved accuracy and real-time predictive capabilities.

Key Signals of Change

- **Iterative Leak Localization Techniques:** Recent studies propose methods using a minimal number of pressure sensors combined with physical simulations to iteratively pinpoint leak locations, optimizing sensor deployment and reducing costs. Systems & Control
- **Physics-Informed Machine Learning Models:** The application of machine learning models informed by physical laws has improved the estimation of irregular water demands, thereby enhancing the identification and localization of leaks. Water Research
- **Optimal Pressure Sensor Deployment:** Chinese researchers introduced a novel methodology for optimizing pressure sensor placement in water distribution networks, aiming to improve leak identification efficiency. Sensors

Future Trajectory

- **Hybrid Sensor Networks for Enhanced Leak Verification:** Hybrid sensor networks, combining pressure wave sensors with acoustic, thermal, and flow sensors, will likely become the industry standard for comprehensive leak detection, reducing false positives significantly. Water
- **Shift Toward Cloud-Based and Edge Computing Solutions:** Data from pressure wave sensors will increasingly be processed using edge computing devices for faster local analysis, with cloud-based platforms handling long-term data storage and advanced analytics. Sensors
- **Increased Miniaturization with Improved Sensitivity:** Recent developments point to pressure wave sensors becoming more compact and energy-efficient, allowing for easier deployment in residential and small-scale distribution systems without compromising detection sensitivity. Water



Case Study

Pressure Wave Sensors: Smart Water Leak Detection and Predictive Maintenance Using Pressure Wave Sensors

Singapore's Smart Water Initiative, led by the Public Utilities Board (PUB), aims to enhance water security and sustainability through the adoption of advanced technologies, including pressure wave sensors. Given Singapore's limited natural water resources and reliance on imported water, minimizing Non-Revenue Water (NRW)—water lost due to leaks, theft, or metering inaccuracies—is a critical national priority. The initiative's key objective is to detect and mitigate water leaks early, reducing water loss, ensuring supply reliability, and optimizing operational efficiency in the face of growing urban demand.

PUB has deployed over 300 sensor stations island-wide, monitoring parameters such as water quality, pressure, and flow in potable water pipelines. These sensors provide real-time data, enabling early detection of leaks and anomalies. The integration of pressure wave sensors allows for precise identification of leak locations by analyzing pressure transients within the network

The Smart Water Initiative has had a profound impact on Singapore's water management capabilities:

- Reduced Water Loss: PUB successfully reduced Singapore's NRW levels to around 5%, reducing the number of leaks recorded per 100km network length from 10 to 5.
- Faster Leak Response: Real-time data allows for the immediate detection of anomalies, reducing the time required to identify and repair leaks.
- Predictive Maintenance: The data supports predictive maintenance strategies, allowing PUB to anticipate potential failures before they occur, thus enhancing infrastructure resilience.

04

Leadership Insights

Innovating for a Sustainable Future: ENOWA on Water Technology Advancements

Water scarcity remains a pressing challenge worldwide, including in Saudi Arabia, due to population growth and climate change. The key water-related challenges are availability, cost, and energy use in water production and distribution. To address these challenges, innovative technologies are being developed to enhance efficiency and sustainability. One of the most promising advancements is brine valorization, which not only reduces water supply costs but also extracts valuable minerals from brine, such as sodium chloride. **"Brine valorization is not yet on everyone's radar, but we are tracking it very closely because it has the great potential to transform the cost and energy for water production."** In Saudi Arabia, a 1,000 m^3/day Brine Valorization Plant in Duba has been established to validate these technologies. The extracted brine salt is crucial for producing liquid PVC, a strategic material for the GCC region. Saudi Arabia's water innovation investments are primarily driven by the need to reduce energy consumption, lower water production costs, and minimize environmental impacts of desalination. Additionally, the country's industrial expansion aligns with Vision 2030, which seeks to establish Saudi Arabia as a high-tech economic powerhouse.

Dr. Nikolay Voutchkov
Executive Director for Water Innovation Center - ENOWA

Innovating for a Sustainable Future: ENOWA on Water Technology Advancements

To support this transformation, the government has established the Research, Development, and Innovation Authority (RDIA) to accelerate water innovation. Over the next 5 to 10 years, the Saudi water innovation market is expected to experience rapid growth, driven by technological advancements, sustainability goals, and increased investments. For Saudi Arabia to become a global leader in water innovation, one strategic action is ”to focus strategically on developing a 2030 roadmap for implementation of Saudi Water Innovation strategy in the field of desalination, **wastewater treatment and reuse** (Saudi Water Innovation Roadmap).” Other strategic action include establishing a centralized Innovation Hub with a steering committee to oversee and coordinate activities. Additionally, a strategic step that Saudi can take is encouraging entrepreneurship and startups through incubators, funding opportunities, and mentorship programs will help Saudi become a global leader. Another important strategic action is “Leveraging Digital Technologies by embracing digital transformation in water management through the use of **IoT, big data,** and AI. Implement **smart water management systems** that enhance efficiency, monitoring, and decision-making processes.”

Dr. Noura Chehab
Acting Head of Water Innovation Center- ENOWA

05

Appendix


20

Interviews – Questions for Private Sector Leader

Dr. Nikolay Voutchkov
(Executive Director for Water Innovation Center) – ENOWA

Dr. Noura Chehab
(Acting Head of Water Innovation Center) – ENOWA

1. What are the key water-related challenges, and how do technologies play a role in overcoming them?

The key water related challenges are: availability, costs and energy use to produce and convey water.

The world at large and KSA face water scarcity issues driven by population growth and global warming. New generation of water treatment and brine valorization technologies allow to significantly reduce cost of water supply by higher energy efficiency equipment. In addition, brine valorization technologies allow to extract valuable commercial minerals from brine which in turn can be sold commercially in order to offset the cost of water production.

2. What is not yet in everyone's radar and you are closely following?

A. Brine Valorization is not yet on everyone's radar but we are tracking it very closely because it has the great potential to transform the cost and energy for water production. We are following very closely brine valorization and have created a 1000 m3/day Brine Valorization Plant in Duba, Saudi Arabia to develop and validate the next generation of brine valorization technologies. The main product from the brine valorization facilities is sodium chloride, which can be now produced at costs lower than that of terrestrial salt sources. Brine salt is used for production of liquid PVC, which of strategic importance of all GCC countries.

B. New generation plastic materials allowing multiple use via 3-D printing and replacement of high-pressure stainless steel piping with plastic piping - currently, most of the desalination plant capital and operations costs are associated with abating the corrosive nature of desalinated water. A number of plastics specialty contractors are looking forward to develop plastic piping that can withstand high pressures and thereby to eliminate the need to use high-pressure stainless steel piping.

C. Generation of energy by harvesting of osmotic pressure differential of brine and fresh water sources - brine mining results in the generation of very high salinity streams that along with specialty membranes for pressure retarded osmosis can generate electricity at low cost in membrane systems with low salinity liquids.

D. Multifunctional membranes - existing membranes can only perform one function - produce fresh water from saline water. Multifunctional selective membranes can not only produce fresh water but to also select and harvest specific mineral from the source seawater stream and ultimately produce two commercial products - drinking water and particular mineral.

E. Utilization of brine in constructions- exploring the use of brine or salt as a replacement for cement in concrete could significantly reduce CO2 emissions associated with traditional cement production.

3. What drives investments in water innovation in Saudi Arabia?

The need to reduce the energy, fresh water production costs and environmental impacts of desalination - these are main investment drivers. In addition, another driver is the expected industrial growth of KSA as the country is striving to implement vision 2030 where Saudi Arabia would attain a high-tech economic status.

4. How do you see the market for water innovation evolving in the next 5-10 years?

We see the innovation market in KSA entering an accelerated growth to respond to the needs defined in mission 2030. KSA has created a special government entity (RDIA) to support this water innovation growth.

5. How can Saudi Arabia position itself as a global leader in water innovation?

To become a global leader in water innovation, Saudi Arabia has to focus strategically on the following:

A. Develop a 2030 roadmap for implementation of Saudi Water Innovation strategy in the field of desalination, wastewater treatment and reuse (Saudi Water Innovation Roadmap).

B. Create an innovation Hub governed by a steering committee to coordinate all activities associated with the implementation of the Saudi Water Innovation Roadmap

C. Significantly increase investment in water innovation to implement the Saudi Water Innovation Roadmap

D. Create Joint council with industry to implement the advanced technologies developed as a result of the implementation of the water innovation roadmap.

E. Encourage Entrepreneurship and Startups: Create an ecosystem that supports water-focused startups and entrepreneurs through incubators, funding opportunities, and mentorship programs. This will stimulate innovation and bring new ideas to the market.

F. Leverage Digital Technologies: Embrace digital transformation in water management through the use of IoT, big data, and AI. Implement smart water management systems that enhance efficiency, monitoring, and decision-making processes.

Detailed Methodology

Following established practices such as the OECD Framework for Anticipatory Governance of Emerging Technologies, the content of this report was produced based using systematic horizon scanning — a continuous exploration of technological developments and early signals that highlight which innovations or socio-technical dynamics are gaining strategic relevance, whether as opportunities or potential threats.

By identifying and analyzing weak signals, horizon scanning uncovers nascent areas of technological interest, pinpoints key drivers of change, and provides insights into how these forces might evolve into transformative opportunities or critical risks. This initial, yet ongoing, phase functions as a comprehensive 360-degree assessment of early-stage technology landscapes, ensuring that decision-makers remain agile and informed in an era of rapid innovation.

In an environment characterized by rapid technological advancements and new knowledge developed each day, information processing capacity is a key factor limiting the coverage of horizon scanning. To mitigate this challenge, MEWA deploys a scanning approach that combines the advantages of human expertise and machine intelligence, drawing on MEWA's NPRAS Platform database comprising over 10,000 source outlets (including scientific publications, patents, industry reports, and news) and over 100m datapoints which are updated twice daily.

Step #1 – Signal Collection & Technology Identification

Considering established practices, such as the Framework for Anticipatory Governance of Emerging Technologies (OECD 2024), the first analysis step involved the systematic collection and evaluation of signals to identify relevant technologies. To achieve this, the team employed a scanning method that combines the advantages of human expertise and machine intelligence, utilizing a signals database that contains over 100 million data points (e.g., patents, industry reports, scientific publications, etc.). Over the past five years, about 9,600 signals related to Smart Leakage Management were sourced. Using Retrieval-Augmented Generation (RAG) AI and human expert validation, a longlist of 109 distinct technologies mentioned in Smart Leakage Management was compiled for in-depth analysis.

Step #2 – Technology Assessment & Landscape Creation

In the second step, a comprehensive technology landscape was created from the longlist of the technologies mentioned in the signals. First, all technologies were eliminated that can no longer be considered as emerging, i.e., which have already entered mainstream adoption in relevant markets – e.g., "Smart Water Meters". In addition, conceptual overlap among the technologies was minimized by subsuming similar or idiosyncratic technologies (e.g.,, "Robotic Sensors", "Free-Swimming", and "Untethered Systems"). Finally, the technologies were clustered into technology segments based on the purpose of use and functional characteristics. Finally, all technologies included in the landscape were evaluated on maturity level, impact potential, and ease of implementation following the criteria outlined in the MEWA Water Technology Adoption Roadmap.

Selection Criteria Scorecard

	Terminology	TRL	Impact Potential	Increase in Signals
1	Self-Adapting Digital Twins	6-7	Very High	Very High
2	Free-swimming Systems	8-9	Very High	High
3	Self-healing Materials	4-5	High	Very High
4	Self-Reconfiguring Network Nodes	1-3	High	High
5	Pressure Wave Sensors	6-7	High	High
6	GIS & Geospatial AI	8-9	Very High	High
7	Real-Time Behavioral AI	1-3	Very High	High
8	Fiber Optic Sensing	8-9	High	High
9	Satellite-based Detection & Diagnosis	8-9	High	High
10	Hybrid Hydrological Modeling	6-7	High	High
11	Hydrogel Barriers	6-7	High	High
12	IoT-based Dynamic Pressure Control	6-7	High	High
13	Graphene-Based Layers	4-5	High	High
14	Micro - and Nanobots	4-5	High	High
15	Quantum Sensors	1-3	High	High
16	Cloud-Based Platforms	8-9	High	Medium
17	Corrosion-resistant Materials	8-9	High	Medium
18	Smart Pumps & Valves	8-9	High	Medium
19	Edge Computing & Edge AI	6-7	High	Medium

	Terminology	TRL	Impact Potential	Increase in Signals
20	Smart Sensor Networks	6-7	High	Medium
21	AR Tools for Pipeline Maintenance	6-7	High	Medium
22	Advanced Leak-Isolating Valves	4-5	High	Medium
23	Nano-optical Leak Detection	1-3	High	Medium
24	Liquid Metal Seals	1-3	High	Medium
25	Sensorial Materials & Coatings	6-7	Medium	High
26	Optical Emission Spectroscopy	6-7	Medium	High
27	Ground Penetrating Radar [GPR]	8-9	Medium	Medium
28	Magnetic Field Sensors	6-7	Medium	Medium
29	Autonomous Repair Systems	6-7	Medium	Medium
30	Fluidic Oscillators	4-5	Medium	Medium
31	Asset Condition Monitoring	8-9	High	Low
32	Mobile LiDARs	8-9	Low	Medium

Glossary [1/3]

Maturity-Technical Readiness Level (TRL)

TRLs are used as a method of assessing the maturity of a technology being developed. It has a scale from 1-9 (from basic principles and research to actual proven systems and full commercial application)

TRL1	TRL2	TRL3	TRL4	TRL5
Basic Technology Research	Applied Research	Critical Function	Laboratory Testing of prototype component or process	Laboratory Testing of Integrated system

Maturity-Market Readiness Level (MRL)

MRLs are used to assess the commercial readiness of a technology offering to give more context. It has a scale from 0-9 (from Ideation to scaling states)

MRL0	MRL1	MRL2	MRL3	MRL4
Hunch	Basic Market research	Needs formulation	Needs validation	Small scale stakeholder campaign

sources:

1. TRL – Definition is designed by NASA https://esto.nasa.gov/files/trl_definitions.pdf. There is detailed description for hardware and software https://www.nasa.gov/pdf/458490main_TRL_Definitions.pdf

2. MRL - By a framework for Assessing Commercial Viability of EU Cloud Services

TRL6	TRL7	TRL8	TRL9
Prototype System Verified	Pilot System Demonstrated	Commercial Design	Full Commercial Deployment

MRL5	MRL6	MRL7	MRL8	MRL9
Large scale early adopter campaign	Proof of traction	Proof of satisfaction	Proof of scalability	Proof of stability

Glossary [2/3]

	Terminology	Description
1	Cloud-Based Platforms	Centralized platforms that integrate data from IoT devices, sensors, Central Event Management [CEM], and SCADA systems to provide real-time leak detection and response coordination.
2	GIS & Geospatial AI	GIS & Geospatial AI combine geospatial data with artificial intelligence to analyze water networks, predict potential leaks, and optimize infrastructure planning.
3	Edge Computing & Edge AI	Edge computing for water networks processes data locally at IoT devices, enabling real-time analysis and rapid decision-making to optimize operations and detect anomalies.
4	Hybrid Hydrological Modeling	Hybrid methods for hydrological simulations combine physics-based models with AI-driven algorithms to simulate and predict water flow dynamics, detect leaks, and assess network performance.
5	Self-Adapting Digital Twins	Digital twin platforms for water networks create real-time virtual replicas of water distribution systems, enabling utilities to monitor, simulate, and optimize network performance.
6	Real-Time Behavioral AI	Real-time behavioral AI describes systems designed to understand and predict the behavior of water distribution networks in real time to autonomously trigger responses.
7	Corrosion-resistant Materials	Corrosion-resistant materials are designed to prevent degradation of pipelines and infrastructure in harsh environments, ensuring durability and reliability over time.
8	Hydrogel Barriers	Hydrogel barriers for leak mitigation use highly absorbent hydrogels that expand upon contact with leaking water, forming a physical barrier to contain and reduce leakage.
9	Sensorial Materials & Coatings	Flexible pipe materials embedded with nano-sensors that detect pressure, moisture, and temperature changes, enabling real-time leak identification.
10	Self-healing Materials	Self-healing materials are innovative substances capable of autonomously repairing damage, such as cracks or leaks, in water pipelines and infrastructure.
11	Graphene-Based Layers	Graphene-coated sensors detect micro-leaks by identifying changes in humidity, temperature, and pressure at a molecular level.
12	Liquid Metal Seals	Highly adaptive seals using liquid metals to respond to pressure changes and prevent leaks.
13	Asset Condition Monitoring	Asset condition detection systems use sensors, data analytics, and monitoring tools to assess the health and performance of critical water infrastructure.
14	Smart Pumps & Valves	Smart pumps & valves use embedded sensors and IoT connectivity to monitor and dynamically adjust water flow and pressure, optimizing efficiency and reducing energy consumption.
15	IoT-based Dynamic Pressure Control	IoT-enabled dynamic pressure control systems use connected sensors and actuators to monitor and optimize water pressure across distribution networks in real time.

	Terminology	Description
16	Advanced Leak-Isolating Valves	Advanced valves that automatically detect and isolate leaks without disrupting the entire network.
17	Self-Reconfiguring Network Nodes	Intelligent nodes that autonomously reconfigure connections and network topologies to adapt to demand and reduce vulnerabilities.
18	Fiber Optic Sensing	Fiber optic sensing, often in combination with distributed acoustic sensing [DAS], uses optical fibers to detect leaks, pressure changes, and structural strain by analyzing.
19	Ground Penetrating Radar [GPR]	Ground Penetrating Radar [GPR] uses electromagnetic waves to detect subsurface anomalies, such as water leaks and pipeline conditions.
20	Mobile LiDARs	Portable laser scanners [mobile LiDARs] use laser technology to create detailed 3D maps of pipelines and infrastructure, identifying deformations and structural issues.
21	Satellite-based Detection & Diagnosis	Satellite-based leak detection systems analyze remote sensing data to identify changes in soil moisture and surface conditions that suggest water leakage from pipelines.
22	Magnetic Field Sensors	Magnetic field sensor technology monitors variations in magnetic fields to detect structural anomalies, such as cracks or leaks, in pipelines.
23	Optical Emission Spectroscopy	Optical Emission Spectroscopy [OES] analyzes the light emitted by excited atoms in water samples to detect chemical composition changes, contamination, or pipe material degradation.
24	Pressure Wave Sensors	Advanced sensors that monitor pressure waves in real-time and use high-resolution analytics to detect the smallest deviations caused by leaks.
25	Smart Sensor Networks	Smart sensing networks are interconnected IoT sensors that monitor key parameters in water distribution systems, providing real-time data for leak detection and performance optimization.
26	Fluidic Oscillators	Fluidic oscillators analyze variations in flow turbulence and oscillatory patterns within pipelines to identify potential leak locations.
27	Nano-optical Leak Detection	Nanotechnology-enabled optical systems detect leaks by measuring changes in light reflection and refraction caused by water escaping pipelines.
28	Quantum Sensors	Quantum sensors use quantum phenomena like superposition and entanglement to detect minute changes in water pressure or flow that may indicate a leak.
29	Free-swimming systems	Free-swimming systems, such as SmartBall, are autonomous devices equipped with sensors that travel through pipelines to detect leaks, gas pockets, and structural anomalies.

Glossary [3/3]

	Terminology	Description
30	AR Tools for Pipeline Maintenance	Augmented Reality [AR] tools assist pipeline maintenance teams by overlaying real-time data, schematics, and diagnostic information onto the physical pipeline infrastructure.
31	Autonomous Repair Systems	Autonomous repair systems use robotics and advanced tools to detect and fix leaks or structural damage in pipelines without the need for manual intervention.
32	Micro - and Nanobots	Micro- and nano-scale robotic systems designed to navigate and inspect small-diameter pipelines.
33	RAG AI	Retrieval-Augmented Generation [RAG] AI technique combining search and AI responses.
34	Smart Metering	The use of digital devices equipped with sensors and communication technologies to automatically measure, record, and transmit water usage data in real time or at scheduled intervals.
35	Ease of Implementation	The level of practicality and feasibility in deploying a technology within an existing system. This includes factors such as infrastructure readiness, technical complexity, cost of adoption, and required expertise. Technologies with high ease of implementation can be integrated with minimal modifications, while those with low ease of implementation may require extensive adjustments, new infrastructure, or specialized training.
36	Potential Impact	The expected effectiveness and long-term benefits of a technology in addressing key challenges in water management. This includes its ability to enhance efficiency, reduce costs, improve sustainability, and optimize resource use. In wastewater treatment, high-impact technologies contribute to water reuse, energy recovery, and environmental protection, while in smart leakage management, they help reduce water loss, improve network resilience, and enhance operational efficiency.
37	Impact	The measurable outcome and influence of a technology on improving water systems. This includes its contribution to reducing waste, increasing efficiency, conserving resources, and enhancing service reliability. In wastewater treatment, impact is measured through improved water quality and sustainability, whereas in smart leakage management, it is assessed by the reduction of non-revenue water [NRW], enhanced leak detection, and improved infrastructure lifespan.

Our Partners

وزارة البيئة والمياه والزراعة
Ministry of Environment Water & Agriculture

الهيئة السعودية للمياه
Saudi Water Authority

المؤسسة العامة لتحلية المياه المالحة
Saline Water Conversion Corporation

شركة المياه الوطنية
National Water Company

المؤسسة العامة للري
Saudi Irrigation Organization
المملكة العربية السعودية

الشركة السعودية لشراكات المياه
Saudi Water Partnership Company

شركة نقل وتقنيات المياه
WATER TRANSMISSION AND TECHNOLOGIES CO.

مؤسسة سقاية الأهلية
Sekaya Charitable Foundation
أفضل الصدقة

مائي
MAEE


وزارة البيئة والمياه والزراعة
Ministry of Environment Water & Agriculture
نبراس
NPRAS
المنصة الوطنية لاستشراف البحث والابتكار للاستدامة
National Platform of R&I Analytics for Sustainability