Water Offset Infrastructure Platform: A Measurement-Based Framework for Verifying Water Recovery Credits Using Electrical Resistance Testing and AI

by Chuck Hansen[1], Mike App[2], Matt Campos[3], Sean Blottie[4], Michael Simpson[5], Charles Wilmut, PE[6], Doug Davis[7]

[1] Chairman & CEO, Electro Scan Inc., Sacramento, CA, chuck@electroscan.com
[2] Executive Vice President, Electro Scan Inc., Syracuse, NY, mike@electroscan.com
[3] Vice President, Electro Scan Inc., Fair Oaks, CA, matt@electroscan.com
[4] Director, Engineering, Electro Scan Inc., Sacramento, CA, sean@electroscan.com
[5] President, M.E. Simpson & Co., Inc., Valparaiso, IN, mike@mesimpson.com
[6] Special Advisor, Electro Scan Inc., Mineola TX, charles.wilmut@electroscan.com
[7] CEO & Executive Chairman, VisionWave Holdings, Inc., West Hollywood, CA, ddavis@vwav.inc

ABSTRACT

Data center developers and owners have committed to being water positive by 2030. Meaning they want to return (or replenish) more water than they use to operate their facilities. Think about it like a bank account. Withdrawals equal water used for cooling systems, humidification, and operations. Deposits equal water returned through fixing leaks (reducing losses), recycling, reuse, and funding water projects like aquifer recharge and conservation that add more water to a utility's system, Figure 1.

If a data center uses 100 million gallons/year, to be water positive it must return 100 million gallons/year (directly or indirectly). But, not all returned water is equal. The best water saved or returned is from the same local watershed. Less ideal is water offset from somewhere else. Bottom line, data centers are committing to leave water systems better off than before they found them. This paper explains how to do that, in accordance with Volumetric Water Benefit Accounting (VWBA 2.0).

1. KEY TAKEAWAYS

- ☞ The most expensive water a utility produces is the water they treat, pump, transport, and then lose through leakage before arriving at a customer's meter—and never get paid.
- ☞ USEPA estimates treated water losses of 6 billion gallons per day.
- ☞ Every gallon of water recovered from a repaired leak is a gallon a utility doesn't have to build, permit, treat, pump, or distribute.
- ☞ 100+ Million Gallons per Year (MGY) of water loss does not require fixing catastrophic leaks or breaks. Instead it is usually hundreds of small & medium-sized leaks that are typically undetected by legacy leak detection methods.
- ☞ Recovering 200 Gallons per Minute (GPM) in leaks is the equivalent of 105 MGY— that can be found in a mix of small (less than 2 GPM), medium (2-5 GPM), and large (5-10 GPM) water leaks.
- ☞ Small and medium-sized leaks often cost less to fix than large leaks, and electrical resistance testing (ERT) is the only technology able to identify and measure leaks in GPM.
- ☞ The water industry's use of American Water Works Association (AWWA) M36 Water Loss standard, is a top-down estimation of water loss, not tied to specific assets or pipelines.

Figure 1. AI and cloud infrastructure data center facility.

- ☞ VWBA 2.0 provides a valuable framework for quantifying water benefits, but has historically lacked measurement tools to accurately determine volumetric changes—accounting for leakage rates in GPM, before and after repairs.
- ☞ Fixing leaks is a one-time cost that yields permanent & recurring water supply.
- ☞ Utilities are 'OK' at finding & fixing large, catastrophic-sized leaks, but not finding small or medium-sized leaks that go undetected in their system and represent the majority of water losses.
- ☞ The adoption of plastic pipes (HDPE, PVC, etc.) and the inability to detect accurate locations of one or more leaks using acoustic listening devices or correlators, has become a major roadblock for utilities to pinpoint water losses.
- ☞ Electro Scan's TRIDENT leak detection product is pipe material agnostic, not dependent on ambient noise, groundwater levels, customer usage, pipe velocities, or pipe bedding materials.
- ☞ A global competitive benchmark by Saudi Aramco, seeking a leak detection solution for their oil & gas facilities, ranked Electro Scan TRIDENT #1, Figure 2.
- ☞ Electro Scan's TRIDENT has been included in AWWA's M77 Condition Assessment of Water Mains since 2019.
- ☞ Assessing water mains using electrical resistance testing—reliably measures water leaks in GPM and is routinely used to QA/QC pipe repairs to confirm leak reduction.
- ☞ Ideal project of 50 miles of piping would test, identify, repair, and confirm recovery ~200 GPM of leakage (~105 MGY).
- ☞ Every gallon of water recovered from leakage is a gallon that doesn't have to be built, permitted, treated, or pumped.

Figure 2. Electro Scan's Electrical Resistance Testing and AI

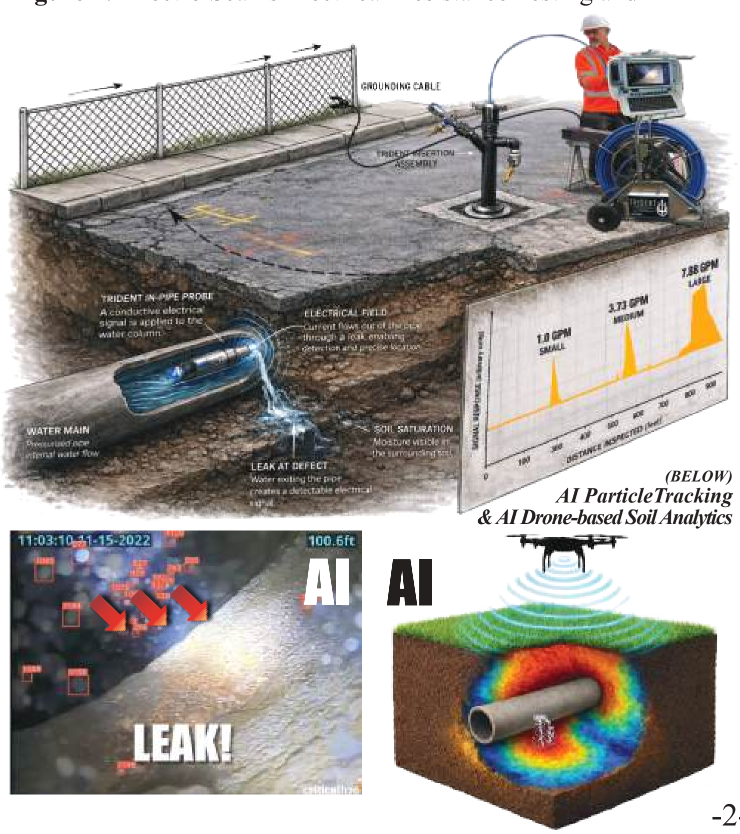
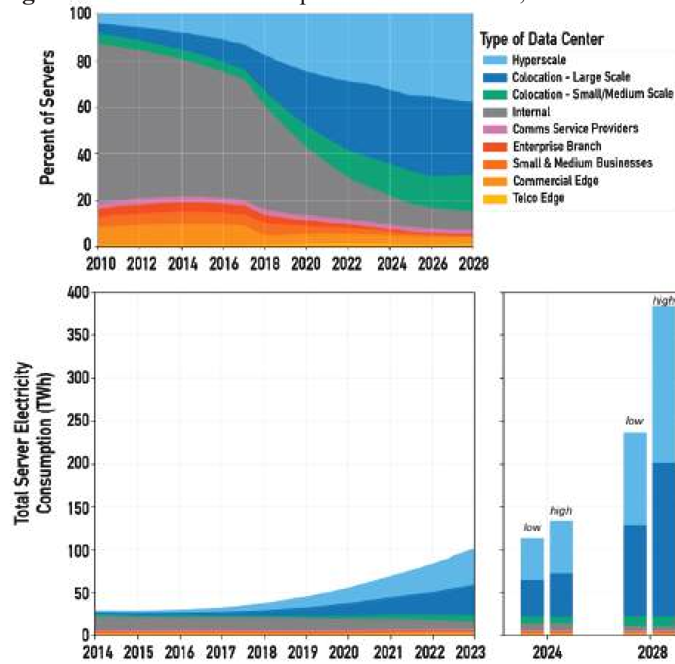


Figure 3. Data Center Composition and Growth, 2010-2028



Source: 2024 United States Data Center Energy Usage Report

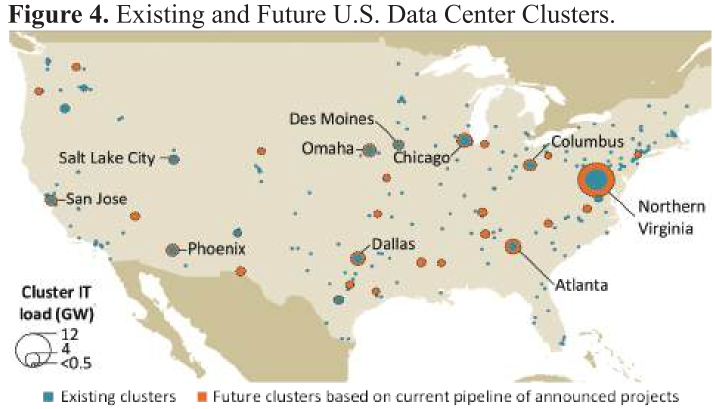
2. WATER POSITIVE 2030 CHALLENGE

Water losses from drinking water distribution systems represent one of the largest untapped sources of recoverable water supplies globally. Yet, leak measurement has been elusive. Often relying on estimations, hydraulic models, and fuzzy math. In the United States, the U.S. Environmental Protection Agency (EPA) estimates that approximately six billion gallons per day of treated potable water are lost due to leakage and system inefficiencies. This loss corresponds to more than two trillion gallons annually, representing not only a volumetric deficit but also embedded energy consumption, treatment costs, and deferred infrastructure investment, available to data centers for offsets, Figure 3 & 4.

It is well known that the rapid expansion of hyperscale data centers and artificial intelligence (AI) infrastructure has significantly increased local water demand. Data centers may require between 0.5-to-5 million gallons of water per day for cooling. And, in water-constrained regions this demand is increasingly becoming a limiting factor in site selection and expansion.

Despite these pressures, existing frameworks for water loss accounting—most notably the **American Water Works As-**

Figure 4. Existing and Future U.S. Data Center Clusters.



Source: 2025 World Energy Outlook Special Report

sociation (AWWA) M36 Water Audit methodology and the **International Water Association (IWA)** water balance—remain fundamentally estimation-based. While these approaches provide valuable system-level diagnostics, they lack the spatial resolution, measurement fidelity, attribution, and testing repeatability, necessary for financial-grade accounting, regulatory enforcement, or environmental credit generation.

Recognizing these drawbacks, corporate data center developers and owners have adopted **Volumetric Water Benefit Accounting** (VWBA 2.0) as its standard to measure water withdrawals and deposits. Unlike traditional audit methods, this approach enables direct detection and quantification of leakage at the defect level, supports optimized repair strategies, and allows for verification of volumetric recovery through pre- and post-intervention (repair or renewal) measurements.

VWBA 2.0 represents a significant advancement in corporate water stewardship, moving beyond simplistic offsetting toward more rigorous, basin-aware accounting. But critiques argue that projects are difficult to prove benefit, that volumetric reductions may have occurred naturally, that it relies heavily on hydraulic models and user behavior, and has an over-reliance on offsets.

To solve these challenges, what is needed is a measurement-based framework for water recovery, termed **Water Offset Infrastructure Platform** (WOIP), that is asset-specific based. Borrowing from AWWA M36 established water loss standards and VWBA 2.0's need to measure volumetric improvements, Sacramento based Electro Scan Inc. (founded 2011) utilizes its patented physics-based Electrical Resistance Testing (ERT) solution to find, fix, and verify water losses, expressed in gallons per minute, to support pre- and post-rehabilitation measurements of water benefit.

Drawing on field deployments in Arlington, TX, Cleveland, OH, and Los Angeles, CA, as well as controlled validation studies conducted with major UK water companies and Saudi Aramco, Electro Scan has demonstrated that ERT inspection can identify 50 to 150 defects per mile, or more, and enable recovery of approximately 0.5 to 5 million gallons per year (MGY) per mile. Furthermore, analysis of defect distributions confirm that leakage follows a Pareto-like behavior, in which a small subset of defects contribute disproportionately to total water loss. Targeted repair of the highest-impact 1–10% of defects can yield between 30% and 70% of recoverable volume.

These findings establish both a technical and economic foundation for an infrastructure-based water recovery program and suggests a pathway for evolving water accounting standards toward measurement-based verification. In doing so, it enables the creation of a first-ever Water Recovery Credits (WRCs) system, analogous to carbon credits but grounded in direct physical measurement and infrastructure-specific repair intervention.

3. PROBLEM SCALE AND SCOPE

Water is increasingly emerging as a binding constraint on economic growth, infrastructure development, and environmental sustainability. While much attention has been focused on the development of new water supplies—through desalination, reuse, acquifer recharging, and inter-basin transfers—far less emphasis has been placed on the inefficiencies embedded within existing distribution systems. In particular, leakage in potable water networks represents a persistent and under-addressed challenge.

As previously stated, the US EPA estimates that approximately six billion gallons of treated water are lost each day due to leakage. This figure is striking not only in magnitude but also in its implication. Unlike raw water losses in natural systems, these losses occur after significant capital and operational investments have already been made in treatment, storage, and distribution. As a result, leakage represents both a loss of resource and a loss of economic value.

Non-revenue water (NRW)—defined as water that is produced but not billed due to leakage, theft, or metering inaccuracies—is a major issue for water utilities, worldwide.

It is well documented that water utilities traditionally lose 20-30% of their treated water capacity, before delivery to customers, due to pipe leakage that is often unseen and not heard. Where infrastructure is aging or under-maintained, NRW can exceed 40% or more. And, in the case of New Orleans Sewer and Water, Louisiana, water loss is routinely above 75%. Given the industry's reliance on legacy acoustic-based leak location technologies and limited financial resources, data center hyperscalers can supplement government efforts and utilize a find-fix-verify model to permanently add-back water losses, at scale, using ERT technology.

Water that was already treated and paid for, can now become a recoverable water supply that helps data centers achieve becoming "water positive" by 2030, in months not years, meaning they can (possibly) replenish more water than they consume, Figure 5.

At the same time, demand for water is increasing in new and often unexpected ways. One of the most significant drivers of this demand is the expansion of digital infrastructure. Hyperscale data centers, which support cloud computing, artificial intelligence, and global connectivity, require substantial volumes of water for cooling. Depending on design and climatic conditions, a single data center may require between 0.5 and 5 million gallons per day. But, corporate data centers do not want more pilots of one city, one dataset, and one condition.

Instead, corporate stewards want repeatability, geographic diversity, and statistical confidence; only accomplished by testing **urban v. rural**, **large v. small**, **old v. new** water systems, in **warm v. cold** weather climates.

Rise of the Data Center

AI data centers have an insatiable thirst for water, and communities are scrambling to keep up. A new study shows U.S. facilities could require up to 1.45 billion gallons per day of new peak capacity. That's according to Shaolei Ren, associate professor at the University of California, Riverside.

Data center water consumption is projected to more than double by 2030, driven heavily by the intensive cooling requirements of artificial intelligence (AI) infrastructure. Research indicates that global data center water consumption could surge from roughly 560 billion liters annually to nearly 1,200 billion liters by 2030.

Because these data centers operate continuously, they generate massive heat from servers and IT infrastructure. Liquid cooling techniques prevent overheating, but they also consume huge amounts of water through evaporative cooling towers. A large state-of-the-art data center can require 1-5 million gallons per day during peak periods.

AI's Impact on Water Consumption

- **Massive Cooling Needs**: AI servers generate significant heat, requiring large-scale, often water-intensive, cooling methods, such as evaporative cooling towers.
- **Projected Surge**: One study estimates AI data centers globally might consume as much as 1.7 trillion gallons of water by 2027.
- **AI "Water Footprint"**: Researchers estimate that AI-related infrastructure could consume more water globally than the entire nation of Denmark by 2027.
- **Specific Examples**: A 100-megawatt (MW) facility can consume around 2.5 billion liters (660 million gallons) of water annually. In the state of Georgia, a Meta data center consumes roughly 182.6 million gallons per day of water.
- **Rising Corporate Usage**: Microsoft has internally projected that its water usage will more than double by 2030 compared to 2020, driven by the AI boom.

To address the growing demand, Ren and his colleagues recommend requiring data centers to disclose their maximum daily water needs, not just yearly totals, so communities can properly plan infrastructure. They also support developing corporate-community partnerships to fund infrastructure upgrades so residents don't shoulder the entire burden, which is estimated to be between $10 billion and $58 billion.

A single AI data center can use over a million gallons of water in a day. That's the daily consumption of a small town. And the bill for the infrastructure to support it? Up to $58 billion.

New research from UC Riverside puts a staggering number on the hidden cost of our AI boom: water. The intense heat from high-performance servers requires massive, continuous cooling.

The study highlights Google's data center in Iowa, which used 2.7 million gallons on a single day in 2025, Figure 5.

This convergence of supply inefficiency and demand growth creates a structural imbalance. On one hand, utilities are investing heavily in developing new water sources, often at significant cost and with long permitting and construction lead times. On the other hand, a substantial fraction of existing treated water supply is being lost within distribution systems.

This raises a fundamental question: ***Why is new supply being developed while existing supply is being lost?***

The answer lies in measurement.

Historically, water loss has been managed through estimation-based frameworks. The AWWA M36 (2024) manual, which provides the industry standard for water audits, relies on a system-wide water balance approach. While this approach is useful for benchmarking and program planning, it does not provide direct measurement of leakage at the asset level. As a result, utilities can estimate how much water they are losing, but not precisely where it is being lost, how much is associated with specific defects, or how much is recovered when repairs are made, Figure 6.

Figure 5. Google Data Center, Council Bluffs, Iowa

This lack of measurement has profound implications. Without direct measurement, it is not possible to establish causal relationships between interventions and outcomes. Without causality, it is not possible to verify performance. And without verification, it is not possible to create financial instruments, regulatory incentives, or environmental credits based on water recovery.

In contrast, other environmental domains have undergone a transition from estimation to measurement. Carbon markets, for example, rely on Monitoring, Reporting, and Verification (MRV) frameworks that enable the creation of tradable credits. Renewable energy markets similarly depend on metered generation to support Renewable Energy Certificates (RECs). In both cases, measurement is the foundation of market formation.

This paper argues that water is at a similar inflection point.

Recent advances in inspection technology—particularly

Figure 6. EPA Service Line Inventory dashboard.

Electrical Resistance Testing (ERT)—now makes it possible to measure leakage directly within pressurized pipelines. By detecting electrical current escaping through defects, ERT provides a means of identifying, locating, and quantifying leaks at a level of detail that was previously unattainable and expressed in GPM.

This capability enables a new paradigm: one in which water loss is not merely estimated but measured, not merely managed but optimized, and not merely reduced but monetized.

The central contribution of this paper is to formalize this paradigm into a coherent framework: the **Water Offset Infrastructure Platform** (WOIP), supported by Volumetric Water Benefit Accounting (VWBA 2.0). Together, these concepts provide a pathway for transforming water loss from a hidden inefficiency into a measurable, verifiable, and financially valuable asset.

4. LITERATURE REVIEW

While AWWA M36 remains a valuable tool for system-level benchmarking and utility management, it is structurally incapable of supporting measurement-based accounting, performance verification, or financial instruments. In contrast, VWBA 2.0 has provided the basic measurement fidelity, causal attribution, and auditability required for corporate data center to consider infrastructure finance and environmental parities.

Volumetric Water Benefit Accounting (VWBA)

VWBA has emerged as the key framework for quantifying and validating corporate water stewardship efforts, particularly in the context of "water positive" commitments. VWBA 2.0 represents an evolution of earlier methodologies, introducing greater rigor, standardization, and basin-level contextualization. This literature review synthesizes the development, methodology, applications, and critiques of VWBA 2.0, with emphasis on its relevance to infrastructure-intensive sectors such as data centers, utilities, and industrial operations, including needs for improvement and emerging directions.

Origins of VWBA

VWBA was initially developed through collaboration between:

- World Resources Institute (WRI), Washington, DC
- The Coca-Cola Company, Atlanta, GA
- The Nature Conservancy (TNC), Sacramento, CA
- LimnoTech, Ann Arbor, MI

The original framework (VWBA 1.0) focused on:

- Quantifying volumetric water benefits (VWBs) from projects such as watershed restoration, agricultural efficiency, and recharge initiatives
- Aligning corporate water offset claims with measurable hydrologic outcomes

Early applications were primarily tied to Coca-Cola's goal of "replenishing" 100% of the water used in its beverages.

Evolution to VWBA 2.0

VWBA 2.0 (formalized circa 2019–2022) reflects a shift from simple volumetric offsetting toward contextual water stewardship.

Key guidance documents include:

- WRI's updated VWBA methodology reports
- CEO Water Mandate's publications on water positivity
- Basin-level accounting frameworks from TNC and WWF

Key Advancements in VWBA 2.0

There are numerous compelling reasons that industry has selected VWBA 2.0 as its standard for water replenishment validation, including:

Contextualization

- Water benefits must be evaluated within the hydrologic impact basin
- Emphasis on water stress, scarcity, and competing demands

Additionality

- Projects must demonstrate outcomes beyond business-as-usual

Durability

Benefits must persist over time (multi-year/permanent impacts)

Quantification Rigor

Standardized methods for calculating:

- Recharge volumes
- Efficiency gains
- Return flows

Risk Adjustment

Incorporation of uncertainty factors & performance variability

Methodological Framework

VWBA 2.0 categorizes water benefits into three primary types:

A. Watershed Restoration
   - Wetland restoration
   - Forest management
   - Benefits:
     - Increased infiltration
     - Reduced runoff
     - Measurement:
     - Hydrologic modeling (e.g., SWAT, WEAP)

B. Agricultural Water Use Efficiency
   - Drip irrigation conversion
   - Crop switching

   Benefits:
     - Reduced consumptive use
     - Key challenge: avoiding rebound effects (i.e., saved water being reallocated)

C. Urban/Industrial Reuse & Recharge
   - Wastewater recycling
   - Managed aquifer recharge (MAR)
   - Benefits:
     - Direct volumetric offsets to withdrawals
     - Increasing relevance for:
     - Data centers & semiconductor manufacturing

Application to Corporate Water Strategy

VWBA 2.0 has become central to "water positive" commitments by major hyerscalers:

- Amazon AWS
- Apple iCloud
- ByteDance (TikTok)
- CoreWeave
- Google Cloud
- IBM Cloud
- Meta (Facebook)
- Microsoft Azure
- Nvidia
- Oracle
- ServiceNow
- Snowflake

These firms (to varying degree) may use VWBA 2.0 to:
- Quantify water replenishment portfolios
- Prioritize high-stress basins
- Report progress in ESG disclosures

Hyperscale operators apply VWBA 2.0 by:
- Investing in watershed restoration near data center clusters
- Funding municipal reuse infrastructure
- Offsetting cooling water consumption

Strengths of VWBA 2.0

A. Standardization
- Provides a common accounting language
- Enables comparability across projects and regions

B. Scalability
Applicable across sectors:
- Agriculture
- Energy
- Technology

C. Integration with ESG Reporting, aligns with:
- Carbon Disclosure Project (CDP) water disclosures
- Science-Based Targets for Nature (SBTN)

Limitations and Critiques

Despite improvements, VWBA 2.0 faces several criticisms, including:

A. Volumetric Reductionism may overlook:
- Water quality impacts
- Ecological needs
- Timing of flows

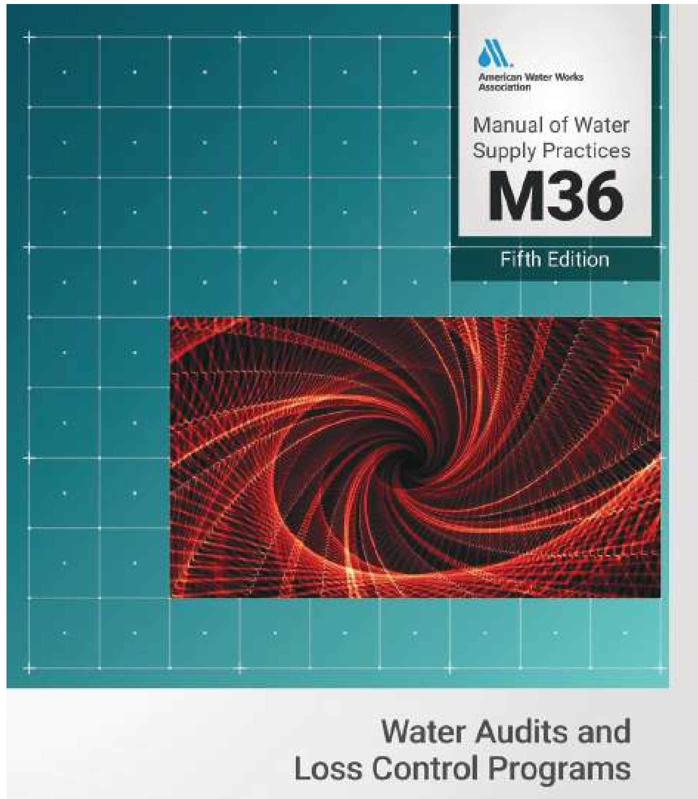
B. Basin Mismatch Risks, i.e. that benefits may not occur:
- In the same watershed
- At the same time as withdrawals

C. Additionality Challenges
- Difficult to prove projects that might have occurred anyway

D. Over-Reliance on Offsetting, where critics argue VWBA:
- Can enable continued water-intensive operations
- Delay necessary efficiency improvements

E. Data and Modeling Uncertainty, with heavy reliance on
- Hydrologic models
- Assumptions about user behavior

Figure 7. AWWA M36, 2024



Emerging Directions

A. Integration with Water Quality Metrics moving toward:
- Nutrient reduction
- Contaminant removal

B. Real-Time Monitoring using:
- Remote sensing and continuous metered flows
- IoT sensors
- Reduced reliance on modeled estimates

C. Regulatory Convergence, VWBA concepts influencing:
- State-level water accounting
- ESG disclosure requirements

D. Nexus with Energy and Carbon, increasing focus on:
- Water-energy nexus
- Indirect water use from electricity generation
- Reconciliation with AWWA M36, Figure 7 and Table 1.

Table 1. AWWA M36, 2024

Area	M36 2016 (4th Edition)	M36 2024 (5th Edition)
Audit Software	v5.x	v6.0 integration (major upgrade)
KPIs	Present, but evolving	Standardized, emphasized, bench-mark-focused
Utility Scope	Primary retail	Includes wholesale systems
Leakage Control	Established Practices	Updated, more advanced & proactive
Program Focus	Audit-centric	Programmatic NRW management
Data Quality	Important	Central (grading, validation, analytics)
Sustainability	Limited	Emerging emphasis

E. Relevance to Infrastructure and Utilities
For utilities and infrastructure providers (including water utilities, consulting engineering firms, pipeline rehabilitation contractors), VWBA 2.0 has implications for:

- Leak detection and reduction
- Direct volumetric benefits from non-revenue recovery
- Asset management
- Quantifying avoided losses as VWBs
- Regulatory reporting
- Potential re-alignment with future water accountability frameworks

VWBA 2.0 represents a significant advancement in corporate water stewardship, moving beyond simplistic offsetting toward more rigorous, basin-aware accounting. While it provides a valuable framework for quantifying water benefits, its effectiveness depends on careful implementation, transparency, and integration with broader sustainability strategies.

Future developments will likely focus on improving measurement accuracy, incorporating water quality, and aligning with regulatory standards. For sectors with significant water footprints—such as data centers and utilities—VWBA 2.0 offers both an opportunity and a challenge: to demonstrate meaningful, measurable contributions to water sustainability while addressing the limitations inherent in volumetric accounting approaches.

In recent years, advances in inspection technologies have begun to address this gap. Acoustic methods, including fixed sensors and free-swimming devices, have been used to detect leaks based on sound signatures. While moderately effective for larger leaks, these methods have limitations in sensitivity and are often unable to detect small, background, or multiple leaks in the same pipe.

Electrical Resistance Testing represents a further advancement. By directly measuring electrical current associated with leakage, it provides a fundamentally different approach—one that is not dependent on acoustic signatures, visual observations, or tracer gas, and that can detect a broader range of defect types.

Despite these technological advances, the integration of measurement into accounting frameworks has lagged. Existing standards remain rooted in estimation, and there is currently no widely accepted framework for translating measured leakage reduction into financial or environmental credits.

This gap between measurement capability and accounting framework is the central focus of this working paper.

American Water Works Association (AWWA)

The management of water loss has been a subject of extensive study and practice by the national and municipal water industry over the past several decades.

Central to this field is the concept of NRW, which encompasses both real losses (physical leakage) and apparent losses (meter inaccuracies, theft, and data handling errors). The development of standardized frameworks for quantifying and managing NRW has been led by organizations such as the AWWA and the International Water Association (IWA).

First published in the early 2000s and updated in subsequent editions, the **AWWA M36 Manual** provides a comprehensive methodology for conducting water audits and developing loss control programs. The core of M36 is a water balance equation, in which system input volume is reconciled against authorized consumption to estimate losses. This framework has been widely adopted across North America and has become the de facto standard for utility reporting, Figure 8.

Major Upgrade to AWWA M36 (2016 - 2024)

Similarly, the IWA water balance framework provides a conceptual model for categorizing water flows within a distribution system. It distinguishes between authorized consumption, apparent losses, and real losses, and provides guidance on performance indicators such as the Infrastructure Leakage Index (ILI).

While these frameworks have significantly advanced the field,

Figure 8. AWWA M36, 2024, Water Equation.

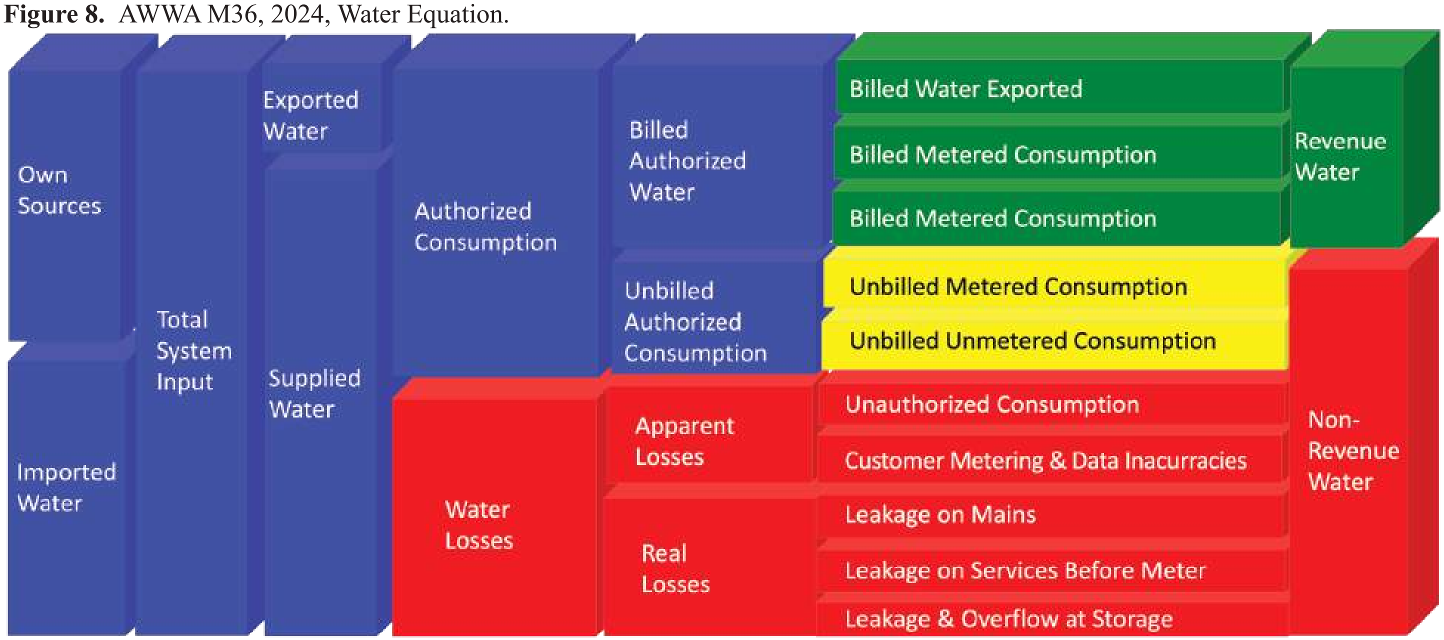
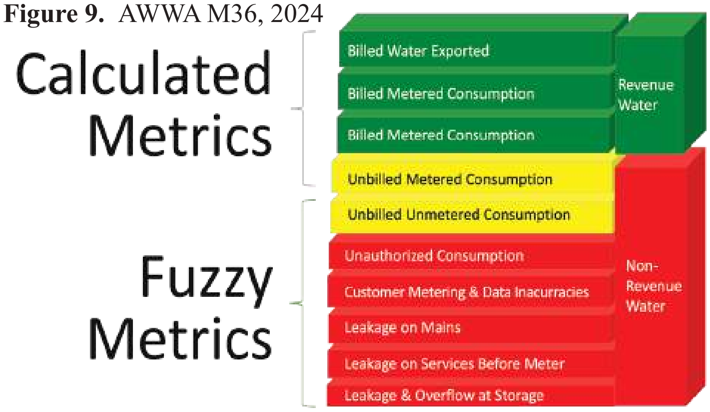


Figure 9. AWWA M36, 2024



they are fundamentally based on top-down estimations rather than bottom-up measurements. Water loss is inferred as the residual of a balance equation, rather than directly measured at the point of occurrence.

This highlights several limitations for AWWA's M36.

Drawbacks of AWWA M36

AWWA M36, including its 2024 update, remains a foundational standard for water audits and non-revenue water (NRW) management, but it exhibits several important limitations when evaluated against modern expectations for measurement accuracy, asset management, and sustainability reporting. One of the most significant shortcomings is its continued reliance on modeled and estimated data. Many key inputs—such as real losses, unauthorized consumption, and meter inaccuracies—are not directly measured but inferred through a top-down water balance. While the 2024 edition improves data grading, the framework still permits substantial estimation, which introduces uncertainty and limits the defensibility of reported volumes, particularly in contexts such as Environmental, Social, and Governance (ESG) disclosures or volumetric water benefit accounting, Table 2.

First, the accuracy of the water balance depends on the accuracy of its inputs. Meter inaccuracies, data handling errors, and estimates of unmetered consumption all contribute to uncertainty. These uncertainties propagate through the calculation, resulting in overall uncertainty that can be substantial, Figure 9.

Second, the water balance provides no spatial resolution. It does not identify where within the network losses are occurring, nor does it distinguish between different types of defects or failure modes. As a result, it provides limited guidance for targeted intervention.

Third, the framework lacks temporal resolution. Water audits are typically conducted on an annual basis, and changes in system performance are assessed over relatively long time scales. This limits the ability to evaluate the impact of specific interventions in real time.

In parallel with these frameworks, a substantial body of research has been developed on the behavior of leakage in distribution systems. Lambert (2002) introduced key concepts in leakage management, including the relationship between pressure and leakage and the use of performance indicators. Farley and Trow (2003) further explored operational strategies for reducing losses, including pressure management and active leakage control.

A consistent finding across these studies is that leakage is not uniformly distributed. Instead, it exhibits non-linear behavior, often approximated by a Pareto distribution. A relatively small number of defects—such as major leaks or structural failures—account for a large proportion of total water loss, while a larger number of minor defects contribute relatively little individually.

This insight has important implications for management strategies. It suggests that targeted interventions, focused on the most significant defects, can yield disproportionately large benefits. However, implementing such strategies requires the ability to identify and quantify defects at a granular level—capabilities that are not provided by traditional audit frameworks.

Closely related to this is M36's limited ability to directly measure real losses. The methodology quantifies leakage indirectly rather than requiring field validation or leak detection. As a result, utilities can estimate how much water is lost but cannot precisely determine where losses occur or verify the effectiveness of specific interventions. This lack of spatial resolution is another core limitation.

M36 outputs are typically aggregated at the system or district level, offering little insight into pipe-level or segment-level conditions. Consequently, the framework is less effective as a tool for targeted asset management or capital planning, where localized intelligence is critical.

Temporal resolution is similarly constrained. M36 is designed around annual audits, which provide only a snapshot of system performance. This approach does not capture short-term variability, seasonal effects, or transient leakage events, and it is not aligned with the capabilities of modern continuous monitoring technologies.

Furthermore, although M36 references leak detection, it does not fully integrate advanced methods such as in-pipe inspection, permanent acoustic monitoring, satellite, metering or AI-based approaches. This creates a disconnect between the audit framework and the rapidly evolving technological landscape described in complementary guidance such as AWWA M77.

Another limitation lies in the treatment of uncertainty. While the standard includes data grading, it does not rigorously propagate uncertainty through the water balance, which can result in NRW values that appear more precise than they actually are. This becomes problematic when audit results are used for regulatory, financial, or sustainability purposes. In addition, M36 tends to emphasize accounting over action. Utilities may complete audits to satisfy compliance or reporting requirements without necessarily translating findings into effective leakage reduction or system improvements.

From a strategic perspective, M36 shows limited alignment with contemporary sustainability frameworks. It operates strictly within the utility boundary and does not account for basin-level hydrology, environmental flows, or competing water demands. As a result, its outputs are not easily transferable to frameworks such as VWBA 2.0, CDP Water, or Science-Based Targets for Nature. The standard also does not explicitly address the energy or carbon implications of water loss, an increasingly important consideration in integrated resource planning.

Table 2. VWBA 2.0 vs.AWWA M36 2024

Dimension	VWBA 2.0 Measurement-Based Framework	AWWA M36, 2024 Water Audit Framework
Core Purpose	Measurement, verification, and monetization of water recovery	Utility performance benchmarking and water loss estimation
Accounting Basis	Bottom-up defect-level measurement & aggregation	Top-down system balance (Input – Consumption)
Primary Output	Verified volumetric recovery (WRCs)	Estimated total system losses (NRW)
Measurement Type	Direct physical measurement (ERT)	Indirect (calculated residual)
Spatial Resolution	Centimeter-scale defect localization	None (system-level only)
Temporal Resolution	Continuous / pre-post intervention measurement	None (system-level only)
Granularity	Defect-level, asset-level, and system aggregation	System-wide
Causality (Attribution)	Directly attributable to specific repairs	Not established
Baseline Definition	Measured pre-repair leakage (Q_pre)	Estimated system input vs consumption
Post-Intervention Validation	Direct measurement (Q_post)	Not possible
Uncertainty Type	Localized (±25–30% per defect, reducible)	Systemic (±15–25% typical)
Uncertainty Reduction	Reducible through aggregation & repeat measurement	Not reducible (correlated errors)
Leak Detection Capability	Embedded (high-res detection 50–150+ defects/mile)	Not included (relies on external tools)
Detection Sensitivity	High (pinhole to structural defects)	Limited (dependent on acoustic/visible leaks)
Defect Distribution Insight	Explicit (Pareto distribution quantified)	Not available
Repair Optimization	Core feature (ranked by volumetric impact)	Not supported
Economic Optimization	Enabled through marginal recovery curves	Not enabled
Additionality Credit (Criteria)	Explicitly measurable and attributable	Cannot be demonstrated
Verifiability (MRV)	High (instrument-based, repeatable measurement)	Limited (self-reported inputs)
Permance Tracking	Supported via reinspection and persistence factors	Not supported
Auditability	Full audit trail (defect → repair → recovery)	Limited documentation
Data Type	High-resolution engineering data	Aggregated administrative data
Integration w/Digital Solutions	High (compatible w/digital twins & analytic platforms)	Low (manual reporting)
Real-Time Capability	Yes (near real-time measurement and verification)	No
Regulatory Use Case	Performance-based regulation and verification	Benchmarking and compliance reporting
Financial Readiness	Suitable (credit generation, performance contracts)	Not suitable
ESG Reporing Compatibility	Strong (measured, auditable outcomes)	Weak
Carbon Accounting Integration	Direct (linked to measured water-energy nexus)	Indirect (derived estimates)
Scalability	High (technology-driven, scalable across networks)	High (administrative)
Infrastructure Planning Utility	High precision (asset-level prioritization)	General guidance
Suitability for Water Offsets	Highly suitable (local, measurable, verifiable)	Not applicable
Market Enablement	Enables water credit markets (WRCs)	None
Alightnment w/MRV Standards	Strong (aligned with carbon/energy frameworks)	Poor
Fundamental Limitations	Requires deployment of measurement technology	Cannot measure or verify recovery
Overall Classification	Measurement, verification, financial accounting system	Management and audit tool

Additional practical challenges persist. The framework requires high-quality input data, yet many utilities lack accurate metering, calibration, or asset records, leading to variability in results and difficulties in benchmarking. M36 is also less well suited to large-diameter transmission systems, where leaks are harder to detect and quantify, and it does not adequately address intermittent supply systems. Finally, while the 2024 update improves guidance on KPIs and program implementation, the standard does not fully leverage digital transformation trends such as IoT-enabled monitoring, real-time analytics, or digital twins.

In summary, while M36 remains a valuable and widely adopted framework for water loss accounting, it is fundamentally a top-down methodology that estimates system-wide losses rather than measuring them directly. As water utilities and corporations increasingly seek precise, auditable, and context-aware volumetric data, particularly for sustainability and regulatory purposes, the limitations of M36 highlight the need for complementary approaches that provide higher spatial resolution, real-time insight, and direct measurement of water savings.

Comparison of VWBA and AWWA M36

Highlights below attempt to emphasize the best of both worlds.

1. **Core Purpose of Measurement**
   VWBA is designed to measure water benefits outside the system boundary, focusing on:
   - Water replenishment / offsetting
   - Corporate sustainability claims
   - Basin-level impacts

   M36 is designed to measure water losses within a utility system, focusing on:
   - Non-Revenue Water (NRW)
   - Operational efficiency
   - Infrastructure performance

2. **Definition of "Volume"**
   VWBA: Functional / Modeled Accounting, often based on models, assumptions, and project-based estimations
   - Volume = Estimated hydrologic benefit
   - Recharge
   - Conservation savings
   - Avoided consumption

   M36: Physical Accounting grounded in mass balance
   - Volume = Actual measured or estimated water flows
   - Leakage (real losses)
   - Meter inaccuracies
   - Authorized consumption

3. **Measurement Boundary**
   VWBA
   - Watershed / basin boundary that may include indirect impact and third-party projects
   - Spatial separation between water use (e.g., data center) and water benefit (e.g., watershed restoration)

   M36 is highly localized and auditable.
   - Strict utility system boundary
   - Treatment → distribution → customer

4. **Treatment of Leakage**
   VWBA leakage reduction can be counted as a volumetric benefit (VWB). Only if:
   - It is additional
   - It is quantified and verified
   - It leads to recoverable water in the basin

   M36 leakage reduction = direct volumetric recovery
   - Leakage is a loss to be minimized
   - Core metric of real losses (gallons/day, gallons/mile, ILI)

5. **Data Quality & Verification**
   VWBA includes uncertainty factors and risk adjustments.
   - Accepts modeled outcomes
   - Accepts scenario-based estimates

   M36 volume must be measured or defensibly estimated and reproducible with a strong emphasis on:
   - Data grading
   - Meter accuracy
   - Audit validation

6. **Temporal Considerations**
   VWBA has a time lag between Action → benefit realization
   - Multi-year impacts:
   - Recharge over time
   - Long-term watershed benefits

   M36 Immediate, operational timeframe, including
   - Annual accounting:
   - Year-over-year performance tracking

7. **Strategic Implications**
   VWBA "offsets the impact"
   - ESG reporting
   - Corporate water neutrality claims
   - External investments

   M36 "fixes the system" driving
   - Operational decisions
   - Capital planning
   - Asset management

8. **Key Conceptual Difference**
   VWBA Volumetric Equivalency asks "How much water did we give back (somewhere)?"
   M36 Volumetric Accuracy asks "How much water did we lose?"

9. **Where They Can Intersect, But Seldom Do**
   Water saved via M36 programs (e.g., leak detection, NRW reduction) have the possibility of becoming VWBA-eligible volumetric benefits:

   IF savings are:
   - Quantified (M36 doesn't typically provide this rigor)
   - Additional (beyond baseline)
   - Basin-relevant

10. **Critical Tension**
    Given the gap between VWBA and M36, a new technology has emerged to deliver on the promise of both standards that acknowledges that not all leaks are the same.

As shown in Table 3, Large, Medium and Small leaks have decidedly different levels of detectability and mix of total leaks. Designed and developed by Sacramento-based Electro Scan Inc., the company's TRIDENT product is designed to specifically locate in-pipe leaks and estimate each leak's severity in gallons/minute (GPM) using electrical resistance testing (ERT), capable of converting "lost water" into the most defensible form of volumetric water benefit available today.

Table 3. Leak Type by % of Total Leaks and Detectability

Leak Type	% of Total Leaks	Detectability
Large Leaks	5-10%	Easy (acoustic)
Medium Leaks	20-30%	Sometime detectable
Small Leaks	60-80%	Rarely detected

5. EVOLUTION OF LEAK DETECTION IN WATER INFRASTRUCTURE

Leak detection has evolved from rudimentary observation techniques to sophisticated, multi-sensor, data-driven systems capable of identifying leak location, severity and assessing the structural condition of buried pipelines. As described in AWWA M77 Chapter 10, today's leak detection encompasses a wide spectrum of acoustic and non-acoustic technologies, each with distinct capabilities, limitations, and historical origins, Figure 10.

Early Origins: Observation and Surface Indicators

The earliest forms of leak detection were entirely observational. Water utilities and municipal operators relied on visible signs such as wet spots, flowing water at the surface, sinkholes, or reduced pressure complaints from customers. In many ways, these techniques were reactive rather than proactive—leaks were discovered only after they had grown large enough to manifest at the surface or disrupt service.

Most approaches were inherently inefficient. Many leaks, particularly in large transmission systems or deep-buried pipes, remained hidden for extended periods. These undetected leaks contributed to significant water loss, infrastructure degradation, and eventual pipe failure. Even today, M77 emphasizes that small leaks often precede major breaks, underscoring the importance of early detection. And, some leaks began at installation; creating incorrect starting baselines that worsen without notice.

Emergence of Acoustic Methods (Early–Mid 20th Century)

The first major technological advancement in leak detection came with the recognition that pressurized leaks generate sound. As water escapes through a defect, turbulence produces acoustic vibrations that propagate along the pipe and through surrounding soil. Early practitioners used simple listening devices—mechanical rods, ground microphones, or "listening sticks"—to detect these sounds. And, some methods are routinely used today, Figure 11.

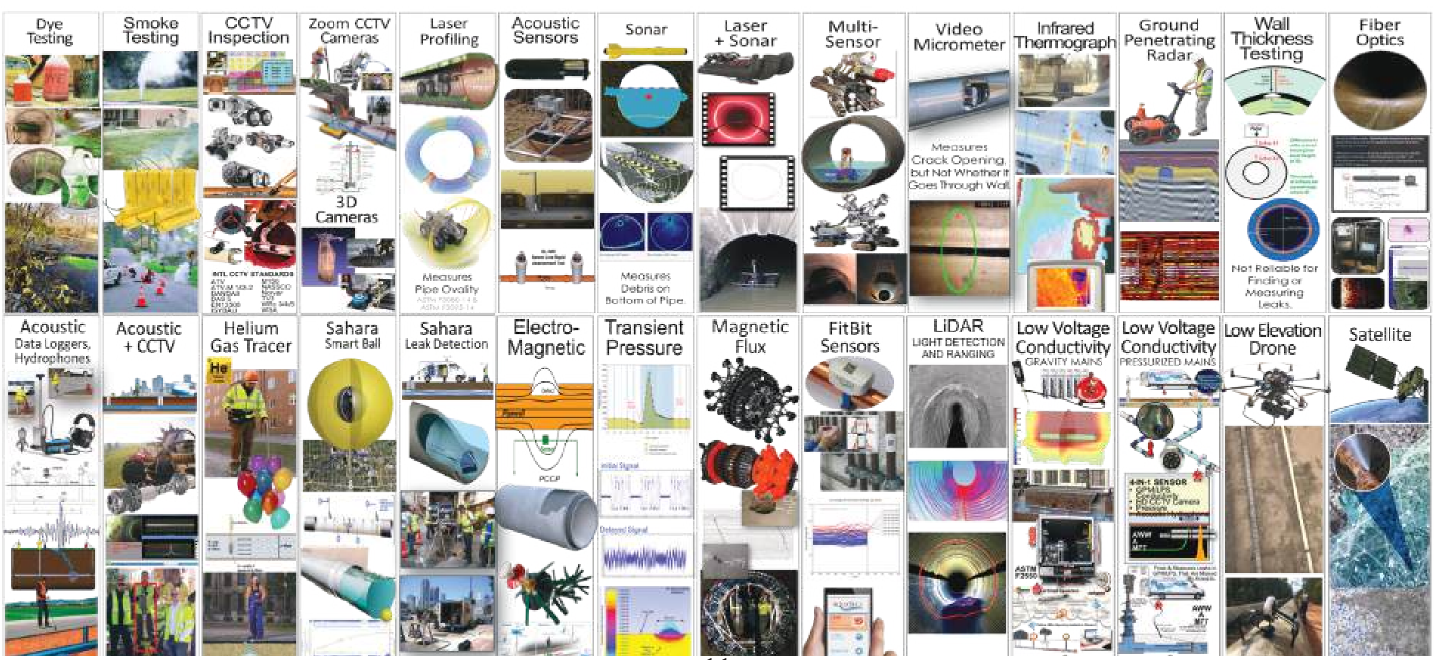
Figure 11. The role of listening sticks to find leaks, continues.

As technology advanced, manual listening techniques evolved into:

- Electronic ground microphones
- Hydrophones inserted into pipelines
- Leak noise correlators

Correlators represented a major breakthrough. By placing sensors at two points along a pipe and analyzing the time delay between detected signals, operators could calculate the location of a leak with improved accuracy. This marked the transition from detection to precise localization.

Figure 10. Modern Methods for Pipeline Leak Detection

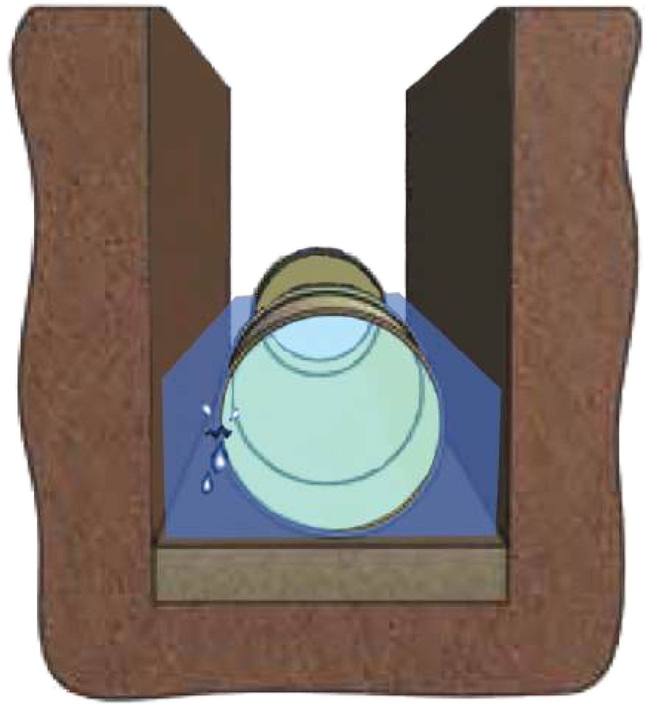


Despite these advances, acoustic methods remained constrained by physics. Sound transmissions vary significantly depending on pipe material, diameter, soil conditions, pressure, and groundwater levels. For example, acoustic signals travel more effectively in metallic pipes than in plastic or concrete systems, but plastic has become the pipe of choice, despite the emergence of micro-plastics.

Expansion of Acoustic Techniques: External & Internal Systems
By the late 20th century, acoustic methods diversified into two major categories, ***External Acoustic Systems***, including surface-based sensors (microphones, correlators), permanent or temporary noise loggers, and distributed monitoring networks; and ***Internal Acoustic Systems***, including tethered devices, free-swimming sensors, and hydrophone-equipped probes.

Figure 12. Acoustic hydrophones.

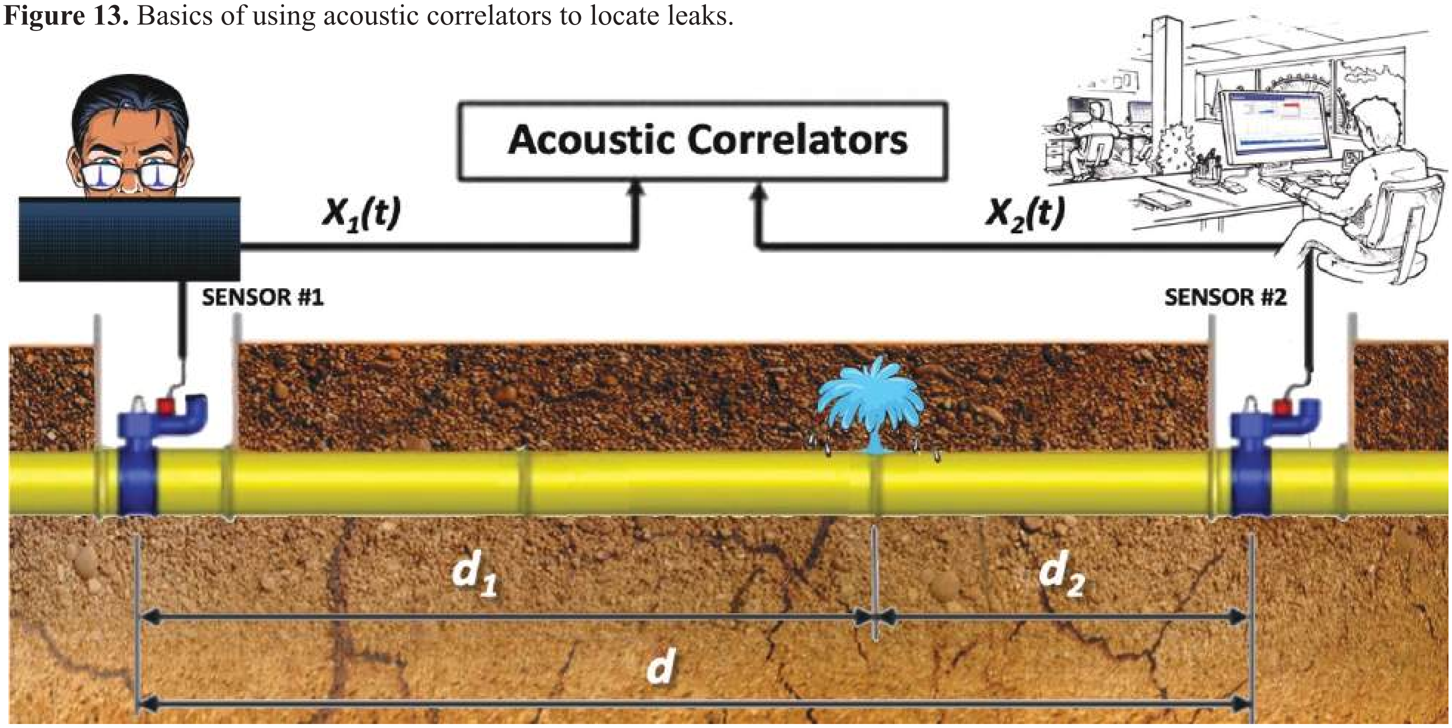
Figure 14. Groundwater ponding surrounding a leak typically camoflages leaks from acoustic sensors.



However, even as acoustic methods became dominant, limitations persisted. Acoustic detection depends heavily on leak-generated noise, which may be weak or absent in certain conditions. Research and field experience have shown that many leaks produce minimal acoustic signatures, especially at low pressures or in non-metallic pipes, Figures 12, 13, and 14.

Development of Non-Acoustic Techniques (Late 20th Century)
Recognizing the limitations of acoustic methods, engineers began developing alternative approaches that did not rely on sound

Figure 13. Basics of using acoustic correlators to locate leaks.



propagation. These methods expanded the detection toolkit and enabled leak identification in previously challenging environments.

Tethered Acoustic and CCTV systems represent a legacy yet still widely used in-pipe inspections. These systems combine visual inspection with acoustic sensing by inserting a probe and/or camera into the pipeline, Figure 15.

Helium Tracer Gas detection is a non-acoustic method that involves injecting helium (often mixed with nitrogen) into a pressurized pipeline. As the gas travels with the water and escapes through leaks, it rises to the surface where it can be detected by sensitive instruments, Figure 16.

Free-swimming acoustic devices, often referred to as acoustic balls, are deployed within pipelines and carried by the flow. Equipped with hydrophones, they detect acoustic signatures of leaks as they travel through a pipe. Well-suited for large-diameter transmission mains they can cover long distances efficiently, Figure 17.

Electromagnetic leak detection methods focus on identifying anomalies in pipe wall integrity associated with leaks. These methods are particularly useful for detecting corrosion, defects, or changes in material properties, Figure 18.

Satellite-based leak detection uses radar and multispectral imaging to identify subsurface moisture anomalies associated with potable water leaks. By analyzing electromagnetic signatures, satellites may detect leaks, Figure 19.

Figure 15. Tethered Acoustic & CCTV

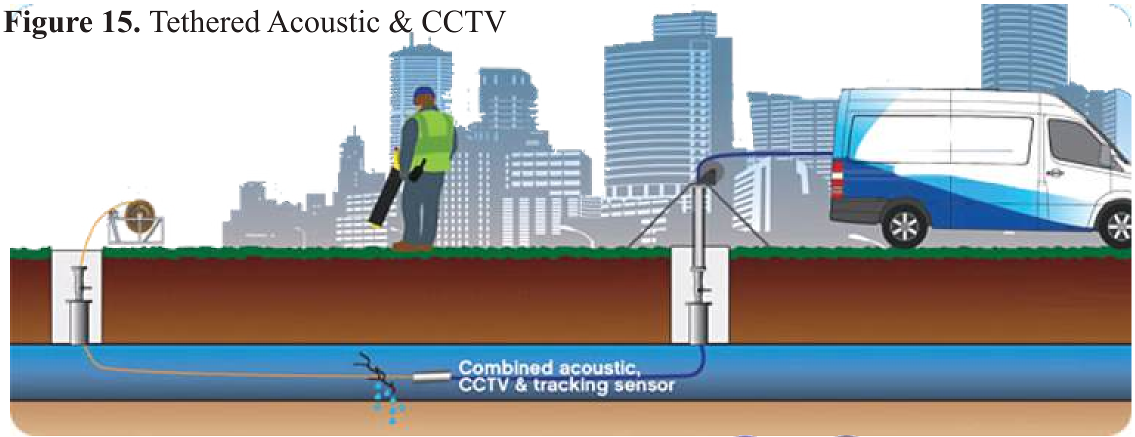


Figure 16. Helium Tracer Gas

Figure 17. Un-Tethered Free-Flowing Acoustic Ball

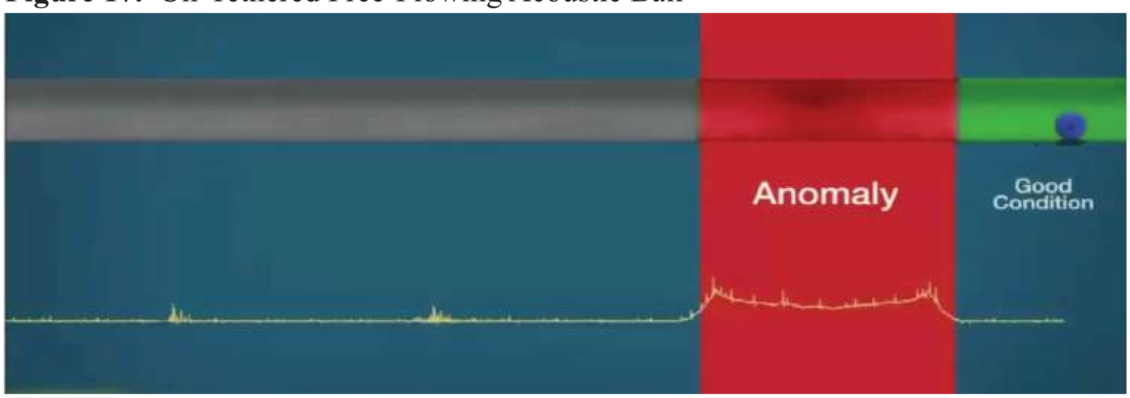


Figure 18. Electromagnetic Sensors

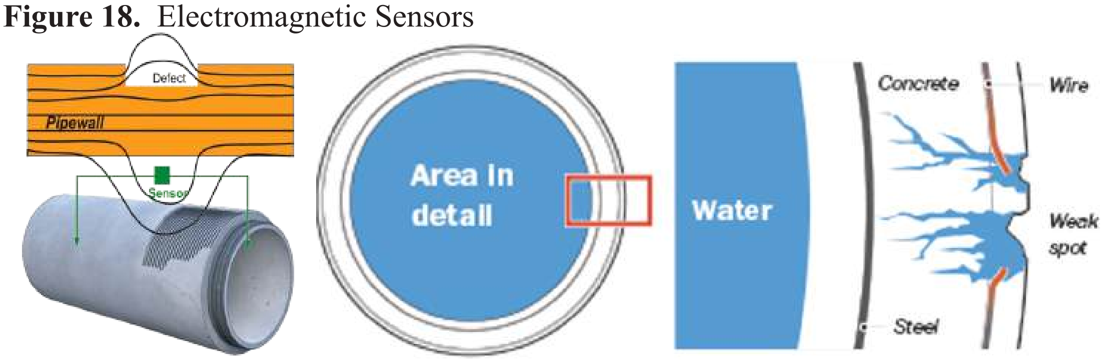
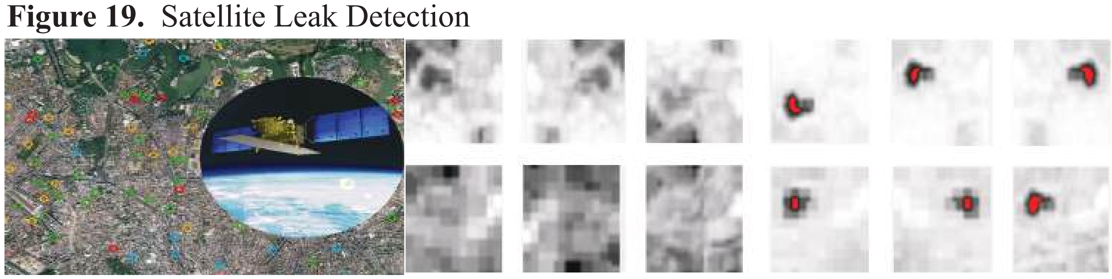


Figure 19. Satellite Leak Detection



A common drawback of most advanced leak testing regimes has been the universal lack of the ability to measure leaks, not to mention the large number of false anamolies that are not, in fact, leaks.

Field-based studies have consistently shown actual leakage is often 1.5× to 3× higher than reported. Why? Because not all leaks are typically found, and cannot be accurately measured due to:
- Small leaks (background leakage)
- Non-acoustic leaks
- Low-pressure leaks or hidden by groundwater conditions
- Leaks in non-metallic pipes
- Long-duration undetected leaks, possibly since installation

Most water is lost from leaks that are NOT acoustically detectable. Using a realistic example, a utility might report (M36)
- System input: 100 MGD
- Reported NRW: 12%
- or a 12 MGD loss

Field reality (measured systems) that have actual leakage: 18–25 MGD, meaning M36 is missing 6–13 MGD (or a 50–100% underestimation).

Pipe material and geometry further limit acoustic leak detection. Sound travels efficiently in metallic pipes, but much less so in plastic, concrete, or large-diameter transmission mains, where acoustic energy attenuates quickly. The longer the distance between the leak and the sensor, the more the signal degrades, often blending into background noise. Additionally, joints, fittings, and changes in pipe geometry disrupt sound transmission, making it difficult to accurately locate leaks even when they are detected.

Another critical limitation is that acoustic methods are inherently indirect and interpretive. They rely on human judgment or algorithmic pattern recognition to distinguish leak noise from background signals. This introduces subjectivity and variability, particularly in complex systems where multiple noise sources coexist. As noted in the document, "judgment" is identified as a major factor, underscoring that even when signals are present, accurate interpretation is not guaranteed.

Perhaps the most important structural limitation is that acoustic systems are biased toward detecting larger, actively flowing leaks, while missing the smaller leaks that often precede major failures. These small leaks may not generate sufficient acoustic energy to be detected, yet they represent a significant portion of total water loss and are critical indicators of pipeline deterioration. The material explicitly states that acoustic technologies can miss a substantial percentage of leaks—highlighting the systemic gap between what is detectable and what actually exists in the system.

In summary, acoustic leak detection is constrained by weak signal generation, signal attenuation through pipe materials and soils, interference from environmental and hydraulic noise, and reliance on subjective interpretation. These limitations mean that a large share of real-world leaks—particularly small, early-stage, or structurally significant leaks—remain undetected in pressurized water mains. As a result, while acoustic methods remain useful as screening tools, they are inherently incapable of providing comprehensive, reliable detection across the full spectrum of leaks.

6. THE ROLE OF ERT IN WATER POSITIVE 2030

Unlike traditional VWBA projects that rely on modeled or indirect estimates and top-down assessment of AWWA M36, M77, Electro Scan's TRIDENT, using ERT, delivers measured, immediate, in-basin volumetric recovery, Figure 20.

ERTs Value Proposition (VWBA Context)

A. Direct Volumetric Benefit
- Leak detection → repair → immediate reduction in real losses
- No modeling required
- 100–150 MGY per deployment
- VWBA-aligned measurement
- Auditable, defensible reporting
- Deployment in your priority basins

B. Strong alignment with VWBA "additionality" requirement
- Targets previously unknown / unreported leaks
- Produces savings that would not occur otherwise

C. Basin Fidelity, which eliminates a major criticism of VWBA offsets
- Water is recovered within the same system and watershed
- No spatial mismatch

D. Temporal Immediacy
- Benefits realized as soon as leaks are repaired
- No lag (unlike recharge or restoration projects)

E. Measurement Credibility, creating an audit-ready volumetric benefits grounded in:
- M36 audit framework
- Field-verified leak detection
- Before/After flow validation

F. TRIDENT vs. Traditional VWBA Projects
VWBA needs TRIDENT more than TRIDENT needs VWBA, since VWBA struggles with:
- Credibility
- Additionality
- Measurement uncertainty

TRIDENT solves all three:
- Real water
- Real savings
- Real verification

G. Positioning Statement
"TRIDENT enables utilities and contractors to generate high-integrity volumetric water benefits by converting non-revenue water into measurable, immediate, and basin-relevant water savings—fully aligned with AWWA M36 and directly compatible with VWBA accounting frameworks."

TRADITIONAL VWBA:
Water use → Offset project → Modeled benefit → ESG claim

TRIDENT-ENHANCED VWBA:
Water use → Leak detection → Measured recovery → Verified Pre- and Post-repair benefit (Figure 21) → ESG claim

H. Bottom Line
- **VWBA** provides the reporting framework
- **TRIDENT** provides the validated recovery mechanism

Figure 20. AWWA M77, published 2019.

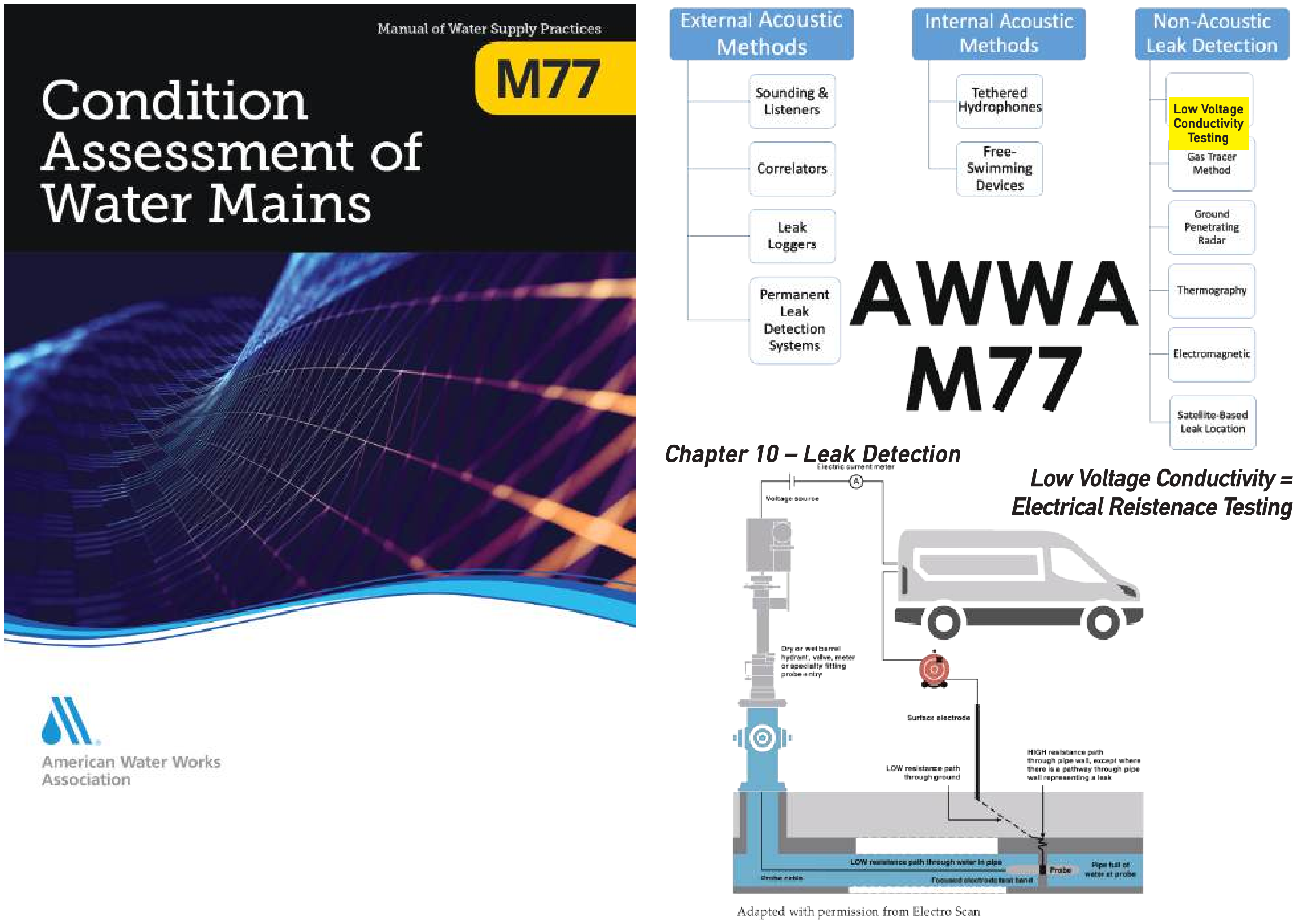
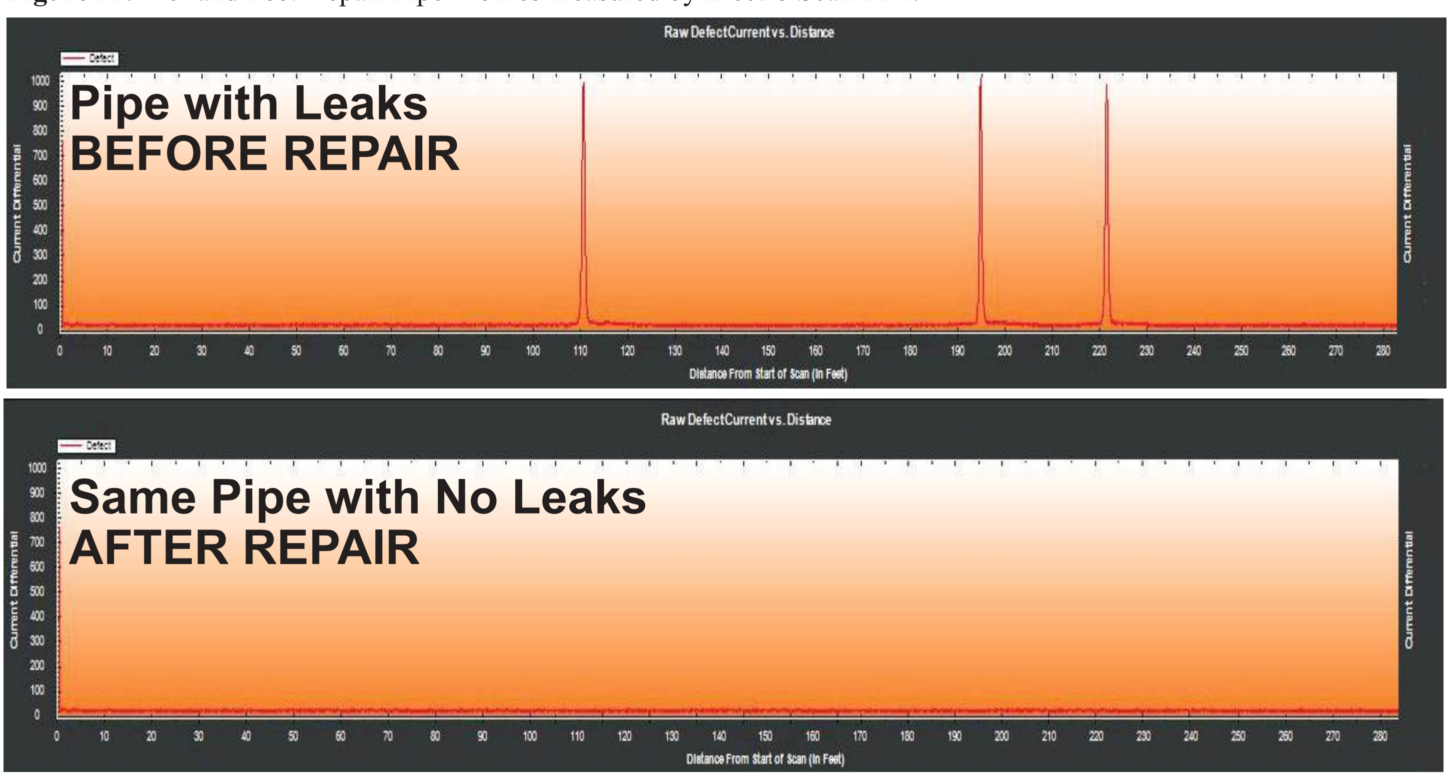


Figure 21. Pre- and Post-Repair Pipe Profiles measured by Electro Scan ERT.



- **M36** provides the water regulatory water loss backbone

Together, they create the first fully defensible water-positive pathway based on real water, not modeled estimates.

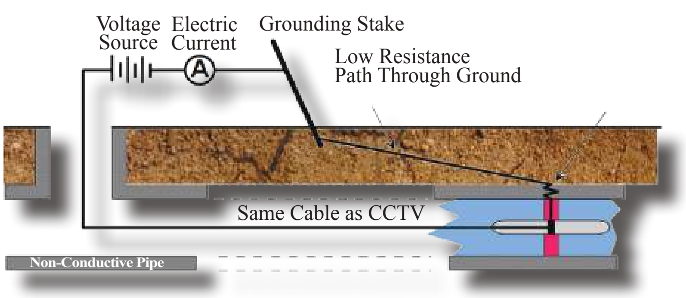
Some might argue that data center hyperscalers don't need another project. Instead they need independent, validated infrastructure tools to make water positive achievable.

Why Was ERT Developed and How Does it Work

Testing solutions have been repeatedly sought to create an accurate cost-effective and repeatable way to certify the water tightness of pipeline repairs & renewals. Especially before installation or repair warranty expirations. Complicating matters has been the seemingly endless combinations of pipe materials, diameters, shapes, depths, lengths, gradients, soil types, and age profiles, all having potentially different decay and repair curves.

The science of using low voltage conductivity is straightforward, and physics-based. A similar application known as holiday testing, was first introduced in 1948 to evaluate protective coatings for exposed pipes, rooftops, and reservoir linings. The technology needed to assess full-length,

Figure 22. Electrical Resistance Testing Scientific Principle

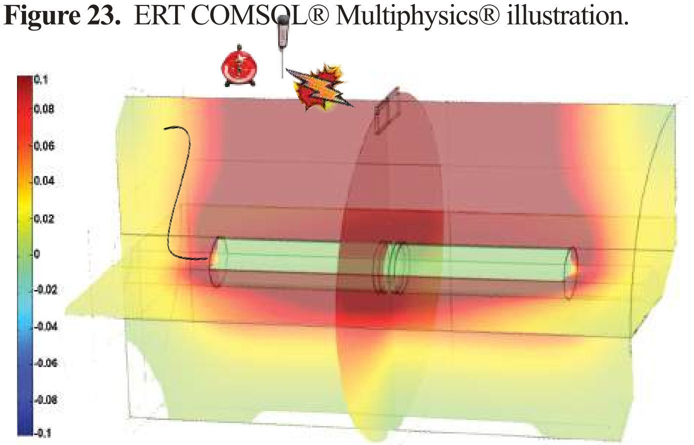


Source: ASTM F2550 (2006, 2013, and 2018).

360-degree pipe wall integrity—allowing existing flow conditions during inspection—and began field testing in 2001, Figure 22.

Most water pipe materials such as brick, cement, clay, concrete, plastic, etc., are poor conductors of electrical current. As a result, if a defect exists in the wall of a pipe, then leakage of electrical current will indicate the location and size of the defect (or exit path). The measured intensity and duration of the electrical signal emanating from the pipe

Figure 23. ERT COMSOL® Multiphysics® illustration.



can be correlated to a flow rate in GPM, whether or not water infiltrates (leaks in) or exfiltrates (leaks out) of the pipe. An approach was developed by establishing a low, 12-volt electrical circuit with a 40 milliamp (mA) signal, using water as a conductor, which allowed two ends of the circuit to connect and close the loop. Applied to an underground pipe, one side of the circuit would remain inside a non-conductive pipe (e.g., asbestos cement, brick, epoxy-coated ductile iron, high density polyethylene, plastic, resin-based liner, vitrified clay pipe, etc.). Connected to a grounding stake, any defect current would need to travel to the surface to confirm a corresponding pipe wall defect, through a leak or orifice (opening to ground).

If the loop is never closed, whereby an electrical circuit is closed, the pipe would be shown to have no defects. Conversely, if the loop is closed, whereby an electrical connection is made, then an opening or defect exists in the pipe wall, allowing a pathway from inside of the pipe to ground. Since water leakage and electric current are highly correlated, the intensity and duration of measured current can provide a specific defect size and corresponding flow rate in gallons per minute.

At first, desktop pipe simulation tools showed how variable impedance of the electric circuit consistently located leaks. Confirming probe dimensions, power settings, grounding sources, data capture, repeatability of results, precise locational accuracy was also easily proven. Important also to defect location is quantifying a leakage rate. Basic assumptions related to hydraulic head conditions on a defect and surrounding pipe burial soil conditions were made to develop a calculation for a relative leakage rate that is not made by other existing leak location products.

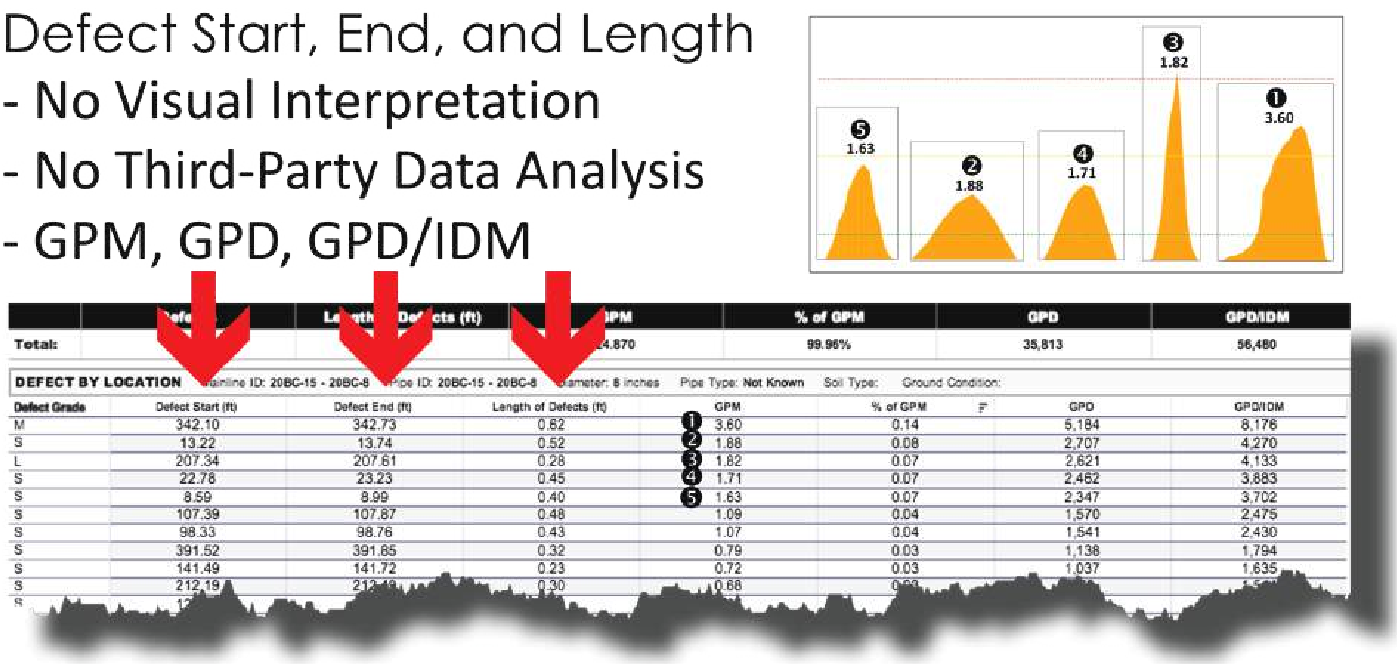
Following the principal operation of AC circuits, a grounding source was needed to simulate a conductive rod driven into the earth near the operation of the device to complete its circuit. The frequency of signal sources provided direction with regards to the system physics. In other words, modelling and thinking of electric fields, current and charge sources were done under the assumption of steady state or "static" conditions.

Analyzing electric fields and current densities were performed under several static conditions including, but not limited to, pipe size, material, defect size, voltage levels, and defect location along the pipe, relative to the probe.

ERT technology developed by Electro Scan was evaluated using COMSOL® tools. Figure 23 shows, COMSOL® simulation results and data, along with the 3D image processing of ERT data and verification plots, confirmed consistently repeatable leak location results to within three-eighths (3/8th) of an inch, or one (1) centimeter (cm), accuracy in all non-conductive (i.e., non-metallic) pipes. Results are an industry breakthrough for leak location.

When the probe approaches a pipe defect as illustrated in Figure 23, AC current levels on the electrodes increase with spatial dependence inside a pipe, comprising the most important conduction characteristics that make the device perform. In other words, pipe defects are identified by the probe—measured in current levels. The measured area beneath the current spike curve can be used to compute the flow quantity of the defect (without actual

Figure 24. ERT Gallon per Minute (GPM), Gallons per Day (GPD, and Gallons per Day per Inch Diameter Pipe (GPD/IDM)



flow). Flow rates can then be provided in any customary unit of measure, such as GPM or liters per second.

Metrics for each defect (Figure 24), include:

- Starting Point, Ending Point, and Maximum Defect Current.
- Defect Classification as Large, Medium, or Small.
- Flow Classification as Sever, Moderate, or Minor Defect Readings.
- Total Estimated Defect Flow in units of volume over time.
- Total Pipe Segment Defect Flow in units of volume over time, by pipe diameter & length.

A benefit of using COMSOL® Multiphysics® was the ability to model, test, and confirm single and multiple pipe defects, in minutes across multiple pipe materials. While COMSOL® easily accommodates multiple pipe materials, internal pipe pressures, gradients, and water conductivity, desktop results needed to be field validated to account for environmental constraints and demands of working in residential, commercial, and open areas.

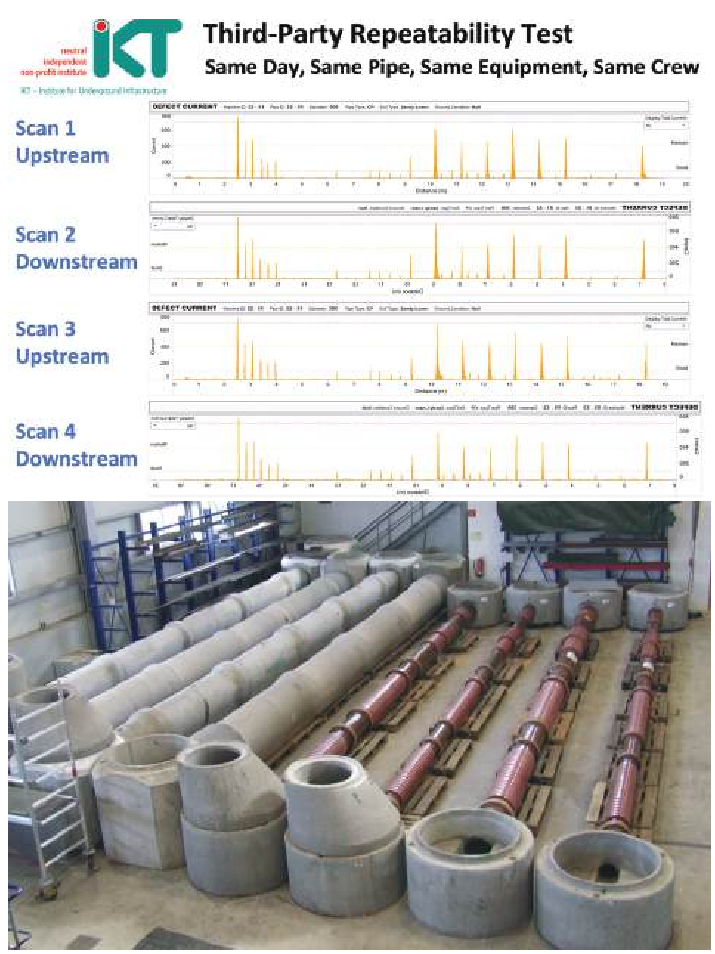
Repeatability Field Testing

ERT has a unique capability: to deliver the same measurement on a repeatable basis. Sounds easy enough, but few if any leak detection technologies are able to make such a claim given human interpretation and hydraulic conditions. As shown in Figure 25, German testing by IKT (Gelsenkirchen, Germany) did repeated same day testing of ERT on recent pipe repairs, Figure 25.

A key advantage for ERT is its significant global industry testing of leaks, including leak promulgation (i.e. increase in leakage at the same location over set periods of time) and leak reduction (i.e. the ability to quantify the reduction in water loss or leakage by comparing pre- and post-repairs, rehabilitation, or replacements). The ability to perform quality assurance/quality control testing of repairs, is a hallmark application of ERT. In fact, ERT has repeatedly uncovered repairs that did not achieve 100% reductions in flow, and in some cases, resulted in increased (defect) flows due to improper or incomplete repairs.

A major result of IKT testing was confirming the positional accuracy of small leaks or pinholes. Electro Scan algorithms had initially excluded small electrical anomalies as data noise in earlier

Figure 25. Same-Day Testing, IKT, GERMANY



software versions. IKT had actually placed these smaller pinhole leaks to see if ERT had the ability to accurately calculate the volumetric leakage rates of pinhole leaks, i.e. small (tiny) leaks in cure-in-place (CIPP) liners, that often developed into larger leaks if left uncorrected as part of initial installation.

As of 2020, Electro Scan began including the estimated leakage rates of pinhole leaks in its cloud applications.

As shown in Figure 26, the US EPA (2011) was the first to test ERT with a sixty-day repeatability test. Concluding that Electro Scan's ERT provided repeatable results.

In Figure 27, Miami-Dade Water and Sewer Department, Florida, conducted a 140-day repeatability test (October 28, 2015 to March 18, 2015, or 142-days apart), concluding mirrored results of both leak locations and severity. Approximate total defect flows of 7.96 GPM compared to 7.04 GPM was within the margin of error.

In other independent studies, Electro Scan was tested at WRc plc facilities in Swindon, England (2015), where Thames Water was invited to observe all facets of the repetitive testing of a single pipe. As shown in Figure 27, Electro Scan confirmed both positional accuracy (x-axis) and severity of leaks (y-axis), independent of a probes directional flow.

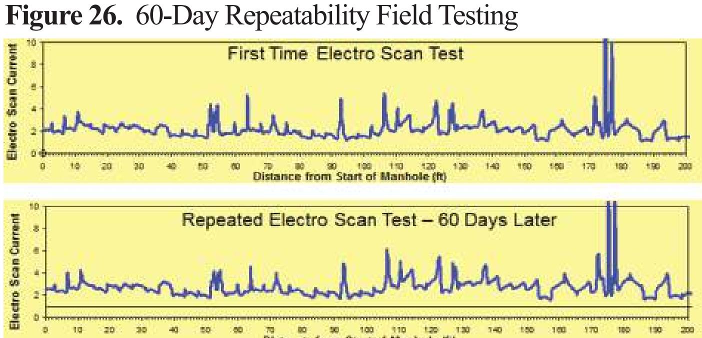
In Figure 29, the City of Roseville, California requested Electro Scan Inc. to conduct a Post-Cured-In-Place Pipe (CIPP) warranty evaluation to assess potential leaks in a newly rehabilitated pipe. Then conducting a second test on the same pipe 643-days after the first test (March 17, 2017 to December 19, 2018) to see if any additional leakage had occurred.

As shown in the figure, multiple wet weather events had occurred during the 643-day period with poor quality liner creating multiple pinhole leaks.

Figure 30 illustrates a similar pipeline rehabilitation warranty for Sacramento County, CA that assessed pipe conditions at 865-days or 2 years, 4 months after initial repair (July 14, 2017 to November 25, 2019). Again, showing Electro Scan replicated precise defect locations and identified increases in defect flow that occured.

It should be emphasized, that the U.S. pipeline repair and rehabilitation market, does not guarantee that all pipes will have a 100% reduction in leakage, i.e. before repair compared to after repair. As a result, QA/QC is a major requirement for testing.

Figure 26. 60-Day Repeatability Field Testing



Finally, as shown in Figure 31, testing of a previously repaired pipe confirmed that a previous point repair (i.e. where a section of the pipe was repaired), achieved leak-free status through the majority of the pipe. However, the end points appear to have significant leaks and the remainder of the pipe still has multiple leaks not identified using a legacy leak detection technologies.

Repeatability is the cornerstone of any measurement science, yet it has historically been absent from most leak detection technologies. Traditional acoustic, visual, or tracer-based methods rely heavily on operator interpretation, environmental conditions, and signal variability, making it difficult—if not impossible—to reproduce identical results across repeated tests. Electro Scan's Electrical Resistance Tomography (ERT) fundamentally changes this paradigm by delivering consistent, quantifiable measurements of leakage that can be reproduced across multiple scans, time intervals, and even testing directions.

Independent validation from organizations such as IKT, WRc, Thames Water, and the US EPA has demonstrated that ERT can reliably reproduce both the location (x-axis) and severity (y-axis) of leaks, confirming that it is not simply detecting anomalies, but measuring them with scientific precision. This repeatability transforms leak detection from a subjective activity into an objective, data-driven QA/QC repair solution, Figure 31.

Figure 27 142-Day Repeatability Field Testing.

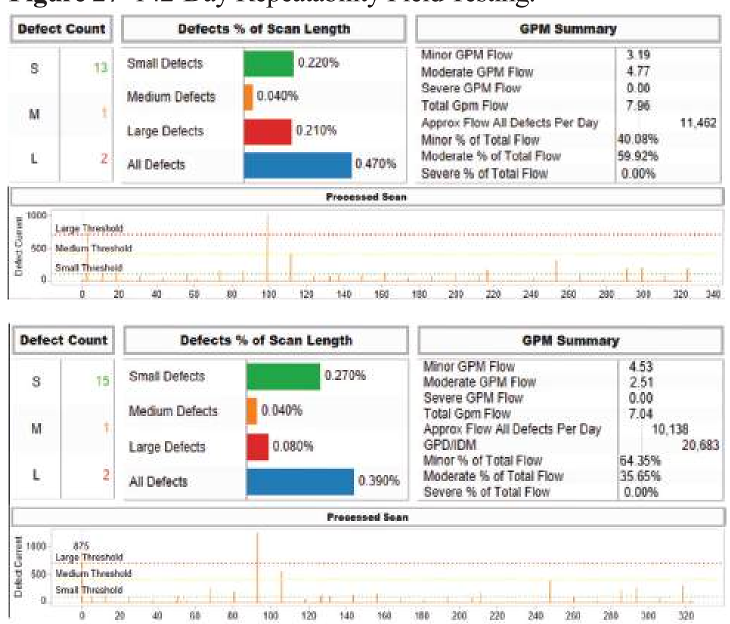


Figure 28. Same-Day Field Testing, WRc & Thames Water, UK

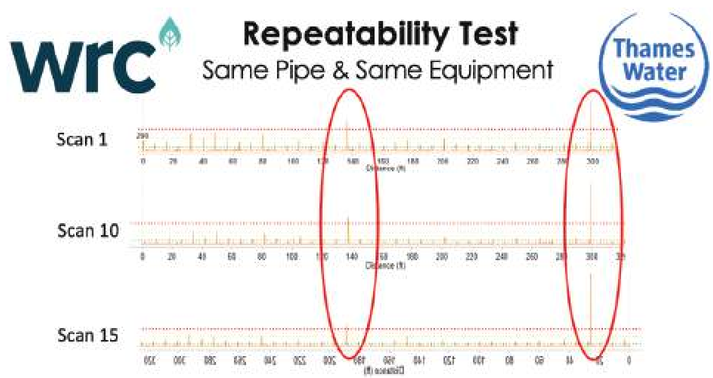


Figure 29. 643-Day Repeatability Field Testing.

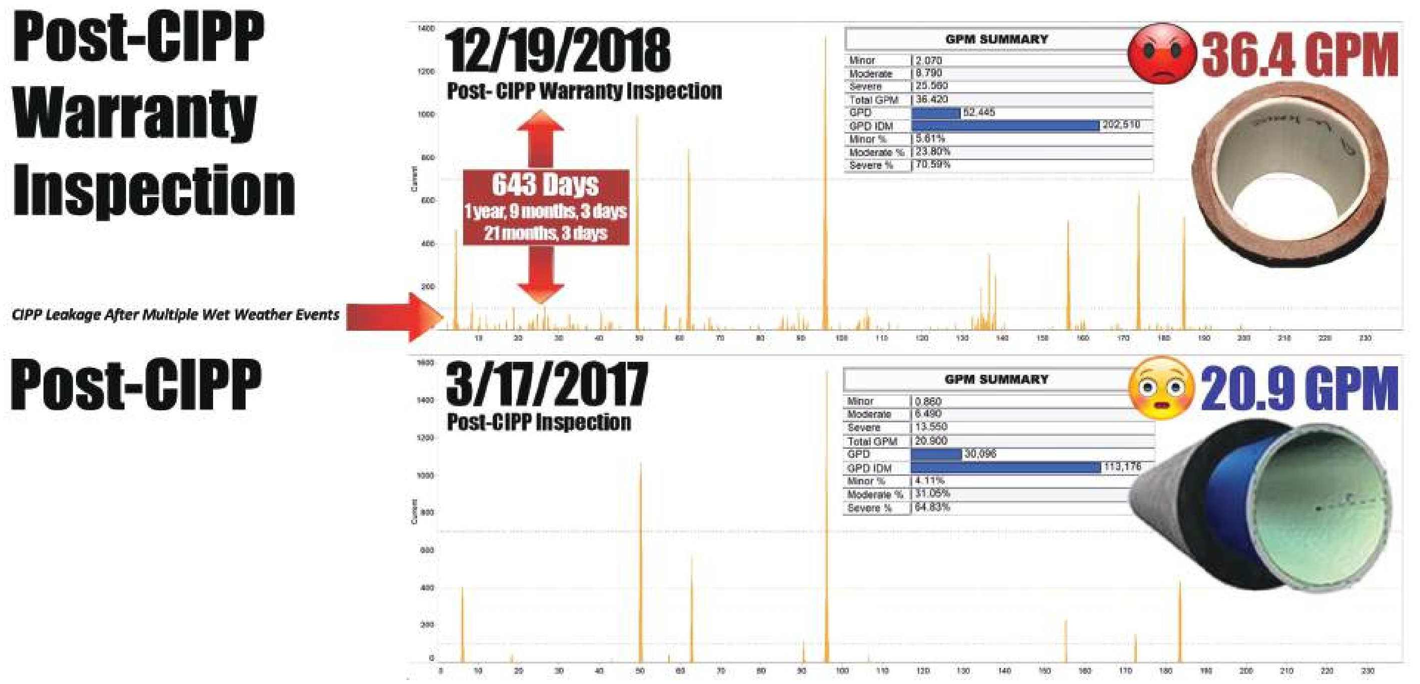
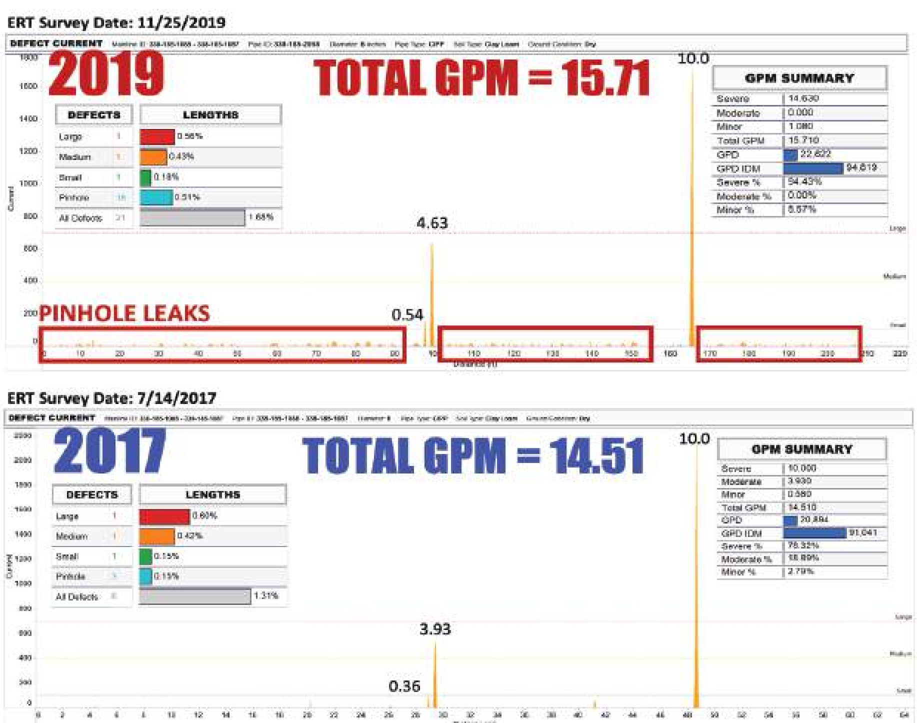


Figure 30. 865-Day Repeatability Field Testing.



	Defects	Length Ft	GPM	% of GPM	GPD	GPD/IDM
Total:	21	3.530	15.730	100%	22,651	94,940

DEFECT BY LOCATION Mainline ID: 338-185-1088 - 338-185-1087 Pipe ID: 338-185-2058
Diameter: 6 inches Pipe Type: CIPP Soil Type: Clay Loam Ground Condition: Dry

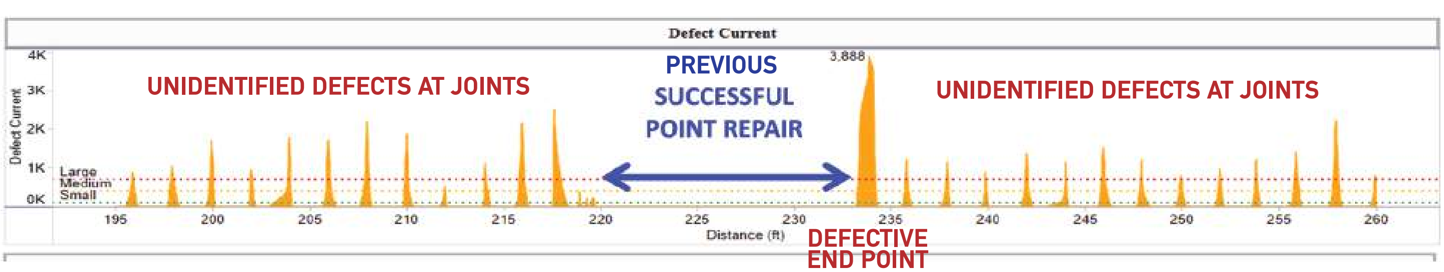
Defect Grade	Defect St..	Defect E..	Length (f..	GPM	% of GPM	GPD	GPD/IDM
X	13.17	13.27	0.10	0.06	0.38%	86	362
X	74.11	74.13	0.02	0.01	0.06%	14	60
X	74.28	74.41	0.12	0.06	0.38%	86	362
X	74.41	74.43	0.03	0.02	0.13%	29	121
X	74.56	74.61	0.05	0.03	0.19%	43	181
X	80.02	80.02	0.00	0.01	0.06%	14	60
X	82.87	83.17	0.30	0.12	0.76%	173	724
X	83.12	83.12	0.00	0.01	0.06%	14	60
S	97.49	97.87	0.38	0.54	3.44%	778	3,259
M	99.19	100.09	0.90	4.63	29.47%	6,667	27,945
X	139.50	139.67	0.17	0.08	0.51%	115	483
X	150.29	150.29	0.00	0.01	0.06%	14	60
X	150.46	150.54	0.08	0.03	0.19%	43	181
X	150.61	150.71	0.10	0.04	0.25%	58	241
X	150.82	150.84	0.03	0.01	0.06%	14	60
X	151.24	151.24	0.00	0.01	0.06%	14	60
L	165.39	166.56	1.18	10.00	63.65%	14,400	60,356
X	178.28	178.28	0.00	0.01	0.06%	14	60
X	178.38	178.41	0.03	0.02	0.13%	29	121
X	178.48	178.53	0.05	0.02	0.13%	29	121
X	178.83	178.83	0.00	0.01	0.06%	14	60

	Defects	Length Ft	GPM	% of GPM	GPD	GPD/IDM
Total:	6	2.651	14.510	100%	20,894	91,041

DEFECT BY LOCATION Mainline ID: 338-185-1088 - 338-185-1087 Pipe ID: 338-185-1088 - 338-185-1087 Diameter: 8 inches Pipe Type: CIPP Soil Type: Clay Loam Ground Condition: Dry

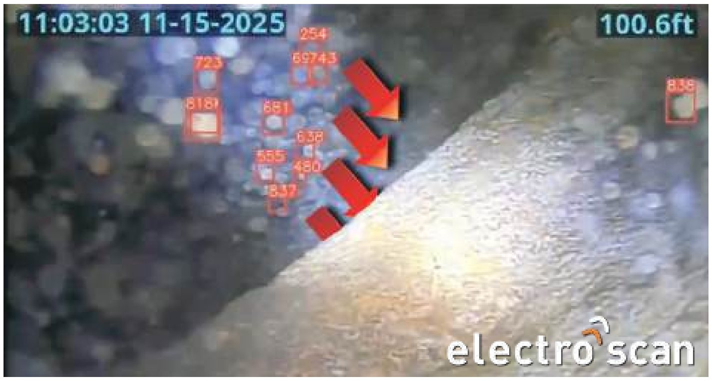
Defect Grade	Defect St..	Defect E..	Length (ft)	GPM	% of GPM	GPD	GPD/IDM
X	14.25	14.25	0.00	0.01	0.07%	14	63
X	66.34	66.39	0.05	0.04	0.28%	58	251
S	94.79	95.08	0.30	0.36	2.48%	518	2,259
M	96.46	97.31	0.85	3.93	27.08%	5,659	24,658
X	134.94	135.19	0.25	0.17	1.17%	245	1,067
L	159.53	160.73	1.20	10.00	68.92%	14,400	62,743

Figure 31. ERT Field Testing of a Pipe With a Previous Point Repair



The ability to conduct pre- and post-repair testing further elevates ERT beyond traditional methods by enabling direct quantification of water loss reduction. Rather than assuming a repair was successful, ERT measures actual leakage rates before and after intervention, providing verifiable evidence of performance. This capability is critical in a market where repairs do not always achieve complete leak elimination.

Figure 32. Electro Scan's AI-CCTV Particle Tracing.

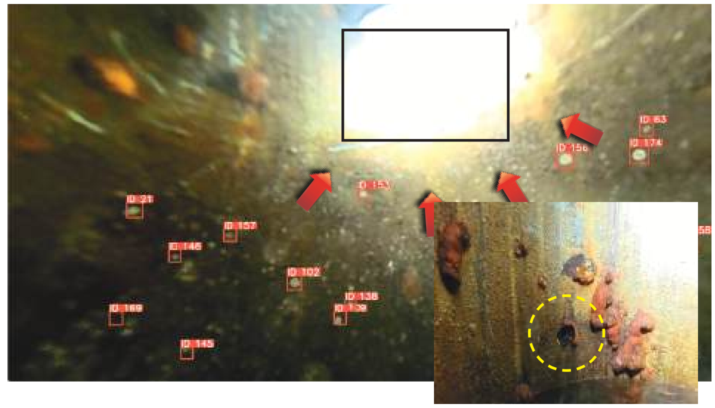


(Top) TRIDENT set-up using ERT to first locates & measures individual leaks, then (Bottom) using AI-CCTV Particle Tracing to confirm leak location & clock position to prevent digging dryholes for repairs.

Figure 33. Electro Scan's Field Set-Up.

AI-based Particle Tracking. High-resolution in-pipe camera-based inspections have not been extensively used in pressurized water systems with filled pipes. Why? It just didn't tell you very much. While serving as a navigational aid to identify obstructions, pipe bends, and water clarity, CCTV has not been recognized as a valid leak detection solution given that the majority of leaks occur exiting a pipe, not entering.

Figure 34. El Dorado Irrigation District, Leak Detection, 2026

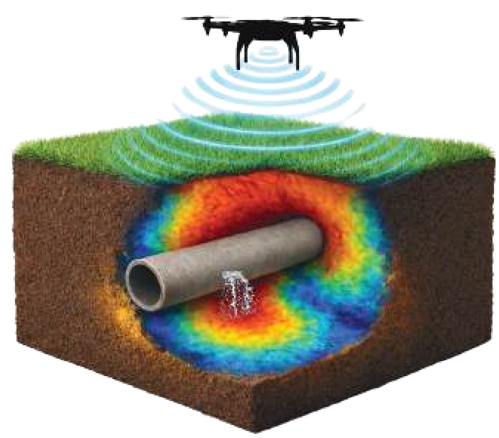


But, camera-based image processing materially changes if you already know where a leak is located. If you have the ability to STOP or IDLE the camera where a pipe has a 'suspected' water particles freely move, allowing the camera to confirm leak locations by a pipe's clock position, Figures 32, 33, & 34.

The key requirement: Knowing where to STOP the camera. How do field operators know where to stop the camera? Fortunately, Electro Scan's electrical resistance readings are displayed in real-time during an in-pipe field survey. As a result, field operators have a roadmap where the leaks are located and able to position the camera in front of each defect during the withdrawal of the probe.

Drone-based Soil Assessment. Electro Scan has identified AI and RF technologies from VisionWave Holdings, Inc. (Nasdaq: VWAV) to help triage large areas of pipe. VisionWave's below-surface radio frequency-based sensors can differentiate subsurface moisture conditions adjacent to buried pipelines, enabling precise identification of leak-induced wet soils, rather than relying on indirect surface indicators or thermal anomalies. In contrast to satellite-based methods that are limited by resolution, depth penetration, and environmental noise, VisionWave provides higher-fidelity, localized triage of leak zones to help reduce non-critical areas and target TRIDENT deployments, Figure 35.

Figure 35. VisionWave Drone-Based Soil Assessment



7. ERT VOLUMETRIC METHODOLOGY & WATER OFFSET INFRASTRUCTURE PLATFORM

This section presents the technical foundation of Electrical Resistance Testing (ERT) as a defect-level measurement system that enables quantified leakage recovery to be translated into a scalable Water Offset Infrastructure Platform (WOIP).

7.1 Design and Analytical Framework

The methodological framework adopted for an ERT-based VWBA 2.0 compliant solution is designed to bridge the gap between defect-level detection and system-level volumetric recovery accounting. Unlike traditional audit approaches, which infer losses through top-down reconciliation, this methodology is explicitly bottom-up, beginning with direct measurement at the point(s) of leakage.

The analytical workflow consists of four sequential phases:

1. High-resolution defect detection using ERT
2. Defect classification and severity ranking
3. Repair prioritization using optimization curves, Figure 36-38.
4. Volumetric recovery estimation using VWBA 2.0

This structure ensures that each stage—from detection to economic valuation—is causally linked and measurable.

7.2 Hydraulic and Material Conditions

The pipelines analyzed are expected to span a range of typical municipal conditions. Pipe diameters range from 4 to 12 inches, capturing the majority of distribution system assets responsible

Figure 36. Optimized Repairs

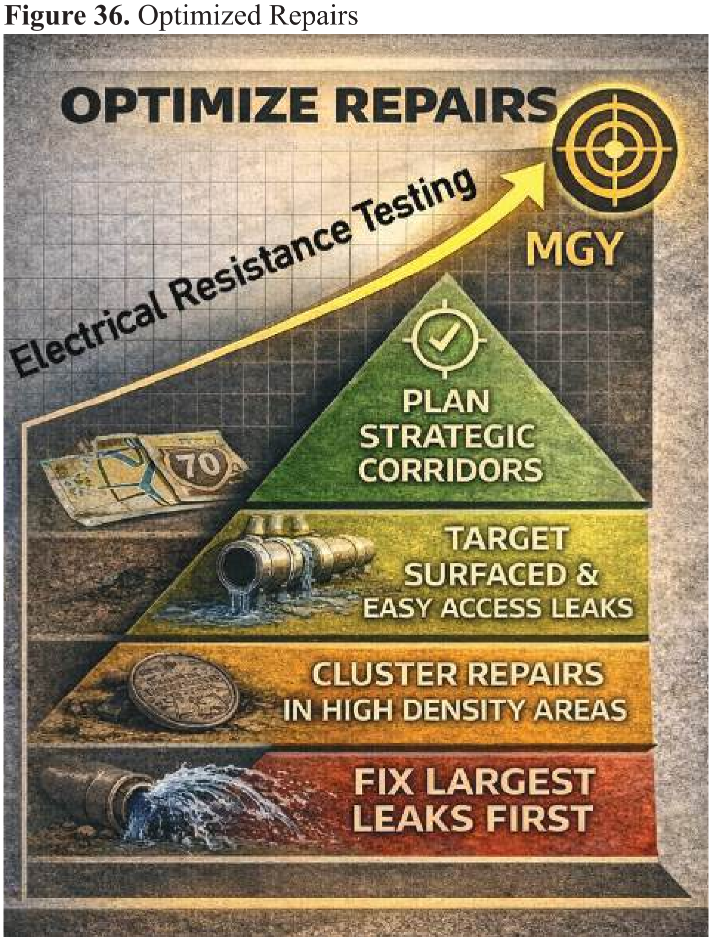
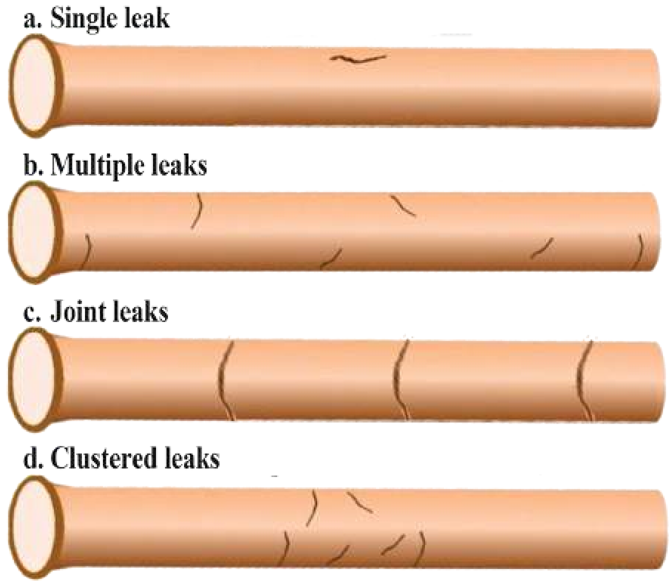


Figure 37 Repair Profiles, by Type of Leak



a.	Single leak	**This is what acoustic sensors do best. Identify a single leak, unless it is high density polyethyln or plastic pipe.**
b.	Multiple leaks	**Difficult if not impossible for acoustic systems. Most likely false positives.**
c.	Joint leaks	**Rythmic display of leaks, equal distances apart are clear signs of joints.**
d.	Clustered leaks	**The most difficult for legacy inspection tools to decipher, but make or break replacement planning.**

Figure 38. Expected Number of Leaks Found Per Mile

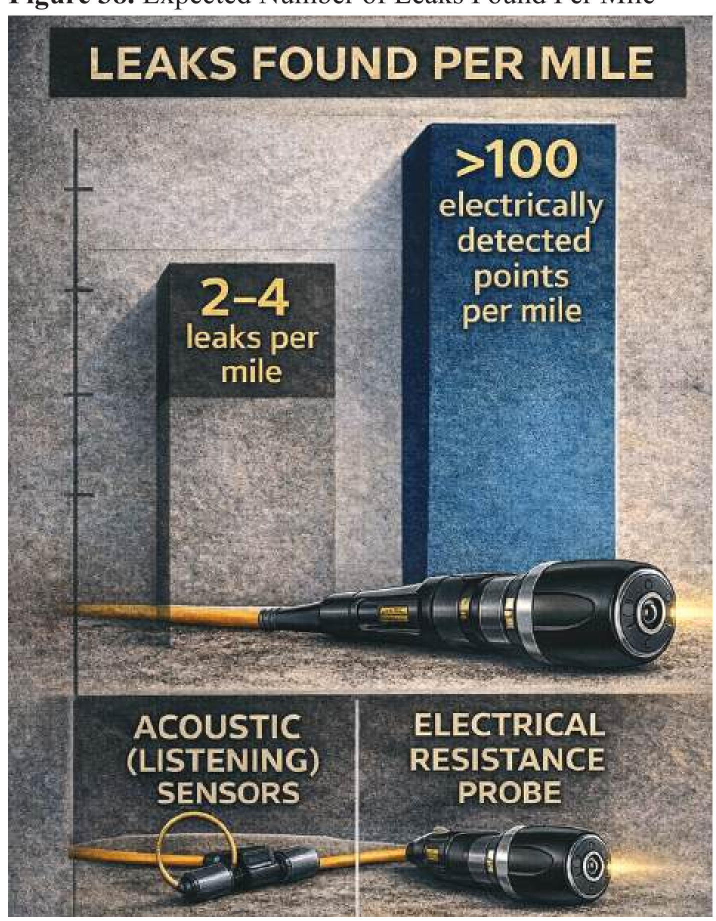


Figure 39. Common Methods for Water Main Repairs & Replacement

for localized service delivery. Materials will include polyvinyl chloride (PVC) pipes, including high-density polyethylene (HDPE) pipe, ductile iron (DI), cast iron (CI), and asbestos cement (AC) pipe, each of which exhibits distinct failure modes and leakage characteristics. Operating pressures are expected to range from 40 to 120 pounds per square inch (psi). Pressure is a critical variable influencing leakage rates, as leakage flow is non-linearly related to pressure through orifice and crack mechanics. This variability was incorporated into defect severity interpretation and repair decision support, Figure 39.

7.3 ERT — Measurements in GPM

ERT operates on fundamental electro-hydraulic principles. When a voltage potential is applied within a conductive fluid (water), current will preferentially escape through points of reduced resistance—namely defects in the pipe wall or joints. The magnitude of current leakage is proportional to defect geometry, hydraulic conditions, and surrounding soil conductivity, Table 4.

Unlike acoustic methods, which detect secondary effects (sound), ERT directly measures the primary phenomenon (water escaping from a hole in a pipe). This distinction is critical, as it allows detection of both active leaks and incipient defects that may not yet produce acoustic signatures.

The instrumentation captures continuous current measurements along the pipe axis, producing a high-resolution signal profile. Peaks in current correspond to leakage events, which are subsequently localized and quantified.

7.4 Signal Processing and Defect Quantification

Raw signal data undergo multi-stage processing, including noise filtering, baseline correction, and peak detection. Advanced clustering algorithms group adjacent signal anomalies into discrete defect events.

Each defect is assigned:

- A spatial coordinate (chainage)
- A relative magnitude score (normalized current intensity)
- A classification based on signal morphology

Relative magnitude serves as a proxy for leakage potential, while absolute flow rates require calibration, relative ranking is sufficient for optimization purposes.

7.5 Repair Optimization Model

Repair prioritization is based on cumulative distribution analysis. Defects are ordered by severity, and cumulative recovery curves are constructed. This enables identification of thresholds at which marginal repair cost exceeds marginal recovery benefit.

Four prioritization strategies are integrated:

1. Largest leaks first (maximizing volumetric recovery)
2. Accessibility optimization (minimizing excavation cost)
3. Spatial clustering (reducing mobilization overhead)
4. Strategic corridor alignment (coordinating with capital projects)

This multi-criteria approach transforms defect detection into actionable CAPEX plans.

7.6 Detection Density and Observability

The most immediate impact of ERT deployment is expected to be the dramatic increase in observable defects. Conventional inspection methods identify only a small subset of active leaks, typically those that produce detectable acoustic signatures. In contrast, ERT reveals a dense distribution of defects, many of which are in early stages of failure.

This shift from sparse to dense detection fundamentally changes system understanding. Leakage is no longer treated as isolated events but as a distributed condition across infrastructure.

Table 4. Standard Leak Rates for 0.635 mm (0.025 in) Wide & Water Head 308mm (12 in)

Electro Scan Gallons Per Minute (GPM) Leakage Computations for Pipes

Clay Pipe Diameter		Pipe Thickness		Area per ΔI	DFes per ΔI		
mm	inch	mm	inch	sq mm	liter/sec	gallon/min	gallon/day
200	8	21.6	0.85	1.96	0.0024	0.036	51
250	10	25.4	1.00	2.31	0.0028	0.042	60
300	12	30.0	1.1	2.73	0/0033	0.049	71

Unless independently calibrated with flow meters, maximum error rates for computing GPM for each variable includes:

Flow/sec/ mm^2	17%
Pipe Thickness	1% (Standard from Manufacturer)
FELL Applied Voltage	1% (Measured)
FELL Defect Current Flow	10% (Estimated)

Basic hydraulics defined by Torricelli's law recognizes that the flow of water (liter/sec, gpm-gallons/minute) through an orifice (a pipe defect) depends on (1) the area of the orifice (the size of the defect); (2) the shape of the orifice (flow through a crack can be two or more times less than through a circular hole of the same area); and (3) the pressure of the water at the orifice (the head of water above the defect).

Since the majority of defects in sewer pipes are cracks, or slots, e.g. defective pipe joints or tap connections, the thinner the slot or area, the lower the flow rate.

Assuming that the smallest significant crack is 0.635 mm (0.025 in) wide, flow measurements were carried out for slots 0.635 wide from 17 mm (0.7 in) to 72 mm (2.8 in) long. For a 304.8 mm (12 in) head of water the flow rate per slot area was found to be 0.0012 +/- 0.0002 liter/sec/mm^2. Wider slots have a greater flow rate per slot area, so if in fact the pipe defect is wider the flow rate estimate for such a defect will be lower than actual.

Torricelli's law states: $v = \sqrt{(2gh)}$

Where v is the speed of efflux of a fluid through a sharp-edged hole at the bottom of a tank filled to a depth h and g is the acceleration due to gravity. This law is considered applicable to an empty buried sewer pipe with the water table above the pipe. As such, the flow rate through a defect in the pipe is dependent on the square root of the height of the water table above the pipe defect. Since defects can occur at any location around the circumference of the pipe, a good estimate is the height of the water table in the sewer trench above the centerline of an empty pipe.

Another consideration with variations of the water table height is the supply of water into the trench, which is dependent on the permeability of the soil surrounding the trench, permeability of the trench backfill material, and height of the regional water table relative to the depth of the trench. Since these parameters are usually not known, for purposes of estimating flow rate it is reasonable to assume that permeability of the surrounding materials is greater than that of the pipe, i.e. infiltration into the pipe does not affect the height of water above the pipe. In most cases, the height of the water table is not known; however for the purpose of estimating the potential contribution of a pipe defect, a uniform water table height of 308 mm (12 in) above the centerline of the pipe is used. Under these conditions measurements have shown that water will flow into the pipe at the rate of 0.0012 liter/sec/mm^2.

Measure of Defect Area from FELL

For a system operating in a pipe manufactured from material with low electrical conductivity, the change in Defect Current through a defect in the pipe, ΔI, is largely related to the electrical resistance, R, of the water filling the defect.

From Ohms Law: $\Delta I = Vo/R$

Where: Vo is the open circuit voltage of the FELL system and is constant.

By definition:

Conductivity = length of conductor / (area of conductor x uniform resistance of conductor)

That is: $\sigma w = T / (A\ R)$

Where: σw = conductivity of the water in the pipe[8]

T = pipe wall thickness

A = the area of the defect

Estimate of Potential Flow Through a Defect

The water flow through a defect estimate from the increase in the defect current of a FELL scan (DFes) is:

DFes liter/sec = $0.0012 * 0.0909\ \Delta I\ T$

That is: DFes liter/sec = $0.000109\ \Delta I\ T$

$\Delta I = A\ \sigma w\ Vo/T$

Transforming: $A = \Delta I\ T / \sigma w\ Vo$

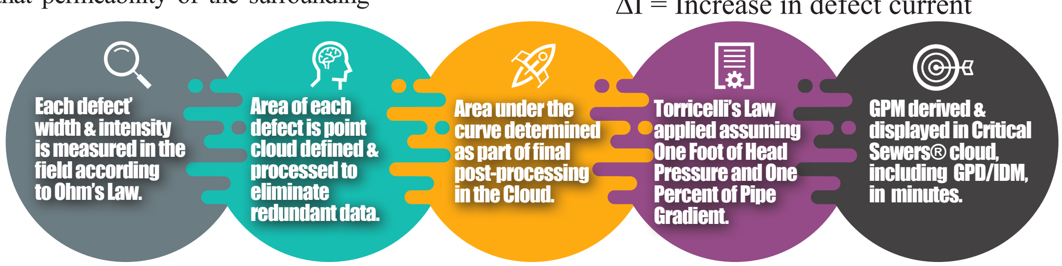
For: σw = 110 microSeimens/mm (sewage conductivity)

T = pipe wall thickness in mm

For FELL: Vo = 10 Volt

ΔI = Increase in defect current

NOTE. GPM for Each Pipe Defect Processed, Stored, and Displayed In 10 Minutes or Less To Facilitate Contractor Repairs While Still in the Field.



[8] Refers specifically to conductivity of the water inside the defect or hole in the pipe.

7.7 Interpretation of High Defect Density

The identification of 50–150+ defects per mile should not be interpreted as system failure, but rather as increased visibility into existing conditions. Traditional methods underreport leakage, leading to systematic underestimation of recoverable supply. As a result, ERT recovery costs compare favorably to alternate water supply costs and time to deploy, Table 5.

Table 5. Alternative Water Supplies Costs and Time to Deploy

Source	Cost ($/AF)	Time to Deploy	Permitting Complexity
Desalination	$2,000-$5,000	5-10 Years	Very High
Advanced reuse	$1,500-$3000	3-7 Years	High
Reservoir Expansion	$2,000-$6,000	10+ Years	Extreme
Leak Recover (ERT)	**$521-$2,933 (lifecycle)**	**Months**	**Low**

7.8 System-Level Implications

When scaled to network level, these findings indicate that utilities possess a substantial, previously unmeasured reserve of recoverable water embedded within existing assets.

The non-linear distribution of leakage enables disproportionate gains from targeted intervention. This is analogous to capital efficiency curves observed in other infrastructure domains. Repair optimization curves demonstrate that early interventions yield the highest marginal returns.

Beyond a certain threshold, additional repairs produce diminishing returns, indicating an optimal stopping point. This has direct implications for capital planning, field planning, allowing utilities to allocate resources with precision rather than attempting comprehensive rehabilitation, with typical neighborhood planning considerations as illustrated in Figure 40

8. ECONOMIC ANALYSIS

Recovering 1,500–2,000 GPM of leakage is equivalent to building a new water plant—without the cost, risk, or delay. And electrical resistance testing provides an automatically assigned GPM for each leak, with one-inch positional accuracy, to allow BEFORE and AFTER REPAIR leak comparison reductions, i.e. pre- and post-pipe renewal to confirm volumetric gains.

For water utilities to 'locate' 100 million gallons per year (MGY) of equivalent water loss that can be returned to the utility on an annual basis, that means:

A Minimum 190 GPM in Leakage Found & Repaired. Throw in a cushion factor of ~30%, and say 250 GPM.

Basic Math:
= 1 Year is also 525,600 minutes, so
= 100,000,000 Gallons per Year ÷ 525,600 Minutes
= 190.26 Gallons Per Minute (GPM) [**Target: 250 GPM**]

But not all water leaks are the same. With combined small, medium, and large leaks expected to total 250 GPM that are repaired.

Given a typical mix of pipes leaks, Table 6
- 70–80% small leaks
- 15–25% medium leaks
- 5–10% large leaks

Table 6. Leak Sizes by GPM and Description

Leak Size	Typical Flow (GPM)	Description
Small	0.25 –1 GPM	Pinhole, weeping joints, small cracks
Medium	2 –5 GPM	Leaks as service connection, cracks, and joints.
Large	5 – 10 GPM	Joints that have lose gaskets, poor construction, or pipe failures.

Figure 40. Electro Scan TRIDENT Field Planning Map

To reach a minimum 100 MGY, field teams are expected to find, fix, and verify:

1.	250 small leaks @ 0.5 GPM =	125 GPM
2.	30 medium leaks @ 3 GPM =	90 GPM
3.	5 large leak @ 7 GPM =	35 GPM
	~285 Leaks Measuring	**250 GPM**

Reframing Water Loss as a Recoverable Infrastructure Asset
Conventional utility practice treats water loss as an operational inefficiency to be minimized through maintenance and system improvements. However, under a measurement-based framework enabled by Electrical Resistance Testing (ERT) and Volumetric Water Benefit Accounting (VWBA 2.0), water loss can be more accurately understood as a distributed, recoverable infrastructure asset.

Each detected defect represents:
- A continuous volumetric loss expressed in GPM
- A measurable and locatable point-of-failure
- A discrete intervention with quantifiable recovery potential

This reframing is critical. Rather than evaluating leak detection solely as an operational expense, it enables utilities and third-party investors to evaluate leak recovery programs as capital deployment strategies with measurable returns.

The economic model presented in this white paper is based on a representative 50-mile of water main assessment program, resulting in:
- A 50-mile water main electrical resistance testing program.
- Identifying 500–1,000 leaks cataloged as single, multiple, joint, & leak clusters, covering 10, 20, or 30-miles of water main.
- Repairing a subset of of 200-400 leaks.
- Re-inspection and verification of repaired pipes to determine pre- and post-repair leak reductions expressed in GPM.

This repair rate reflects the non-linear distribution of leakage, where a small subset of defects contributes disproportionately to total volumetric loss. Under this framework, the program focuses on repairing only the highest-impact defects.

Comparison to Alternative Water Supply Lifecycles
While the economic analysis presented in this study demonstrates that ERT-enabled leak recovery can achieve competitive or "most favorable" cost per acre-foot on a lifecycle basis, it is important to recognize that multi-year benefits are not unique to leak recovery, Figure 41.

Conventional water supply augmentation strategies—including desalination, advanced reuse, and reservoir expansion—also provide long-lived infrastructure benefits, often extending over multiple decades.

However, the economic and operational characteristics of these alternatives differ fundamentally from leak recovery in several critical dimensions, including capital intensity, deployment timeline, regulatory complexity, energy requirements, and measurement fidelity.

Infrastructure Lifespan and Durability
Traditional water supply projects are typically designed for long operational lifespans:

Supply Type	Typical Asset Life
Desalination	20-40 years
Advanced Reuse	20-30 years
Reservoir Expansion	50+ years
Leak Repair (ERT-enabled)	5-15 years

While leak repairs generally have shorter effective lifespans than large-scale infrastructure, their distributed nature allows for continuous renewal and re-optimization, rather than reliance on a single capital-intensive asset.

Capital Intensity and Financial Risk
A key differentiator lies in capital structure:
Deploying intervention without major capital commitments.

Leak recovery programs can be deployed incrementally, allowing capital to be allocated progressively based on measured performance. In contrast, desalination and reuse projects require substantial upfront investment with long payback horizons.

Figure 41. Alternative Water Supply Augmentation Strategies

Table 7 provides example inspection & repair costs to allow measured water loss recovery.

First a records review is conducted, including past construction records, repair histories, customer complaints (low water pressure), hydraulic studies, etc. Then, RF-equipped aerial drones may survey targeted lines to help define ERT's 50-mile initial inspection area.

TRIDENT testing is then conducted for a selected 50-mile network, identifying and quantifying leak severities and repair locations.

Detailed TRIDENT leak profiles will be then be reviewed for the entire 50-mile network to identify and select specific small, medium, and large repairs to be conducted for likely repairs across 10, 20, or 30 miles of water main.

It is anticipated that repairs may include spot or single repairs, sectional (clustered) repairs, pipe relining projects, especially needed when recurring joint defects are continuously found, and/or full line excavations and pipe replacements, if needed.

Following the completion of each repair, follow-on TRIDENT ERT inspection will be conducted to confirm reduction in leakage. A minimum score of 90% must be recorded for any repair to be accepted, including a quantified water benefit expressed in GPM.

Since verification will be done immediately following all repairs, the project timeline can be expected to occur over a 24-month period.

To achieve Water Positive 2030, ***it is highly recommended that VWBA 2.0 projects be conducted for urban & rural water utilities, representing large & small water systems having old & new infrastructure located in high stress basins with warm & cold weather patterns. One project = pilot. Multiple projects = national multi-basin platform validation.***

Table 7. Example Cost/Benefits of Electrical Resistance Testing & Repair Program.

Repairs Across 30-Miles	# Leaks	Cost of Repair	50-Miles of Initial Inspection	30-Miles of Post-Repair Inspection	COST
Initial Inspection @ $10/ft			$ 2,640,000		$ 2,640,000
Post Repair Inspection @ $7/ft				$ 1,108,800	$ 1,108,800
TOTAL INSPECTION COST					**$ 3,748,800**

Repair Cost	Number of Repairs	Cost of Repairs	Average Leak Size	Total GPM Benefit from Repair	COST
Small	250	$ 5,000	0.5	125	$ 1,250,000
Medium	30	$ 20,000	3	90	$ 600,000
Large	5	$ 75,000	7	35	$ 375,000
TOTAL REPAIR COST	**285**			**250**	**$ 2,225,000**

TOTAL PROGRAM COST	**$ 5,973,800**
LEAKS PER MILE	**9.50**
LEAKS PER 300-FT	**0.5**
COST PER MILE	**$ 119,476**

Repairs Across 20-Miles	# Leaks	Cost of Repair	50-Miles of Initial Inspection	20-Miles of Post-Repair Inspection	COST
Initial Inspection @ $10/ft			$ 2,640,000		$ 2,640,000
Post Repair Inspection @ $7/ft				$ 739,200	$ 739,200
TOTAL INSPECTION COST					**$ 3,379,200**

Repair Cost	Number of Repairs	Cost of Repairs	Average Leak Size	Total GPM Benefit from Repair	COST
Small	250	$ 5,000	0.5	125	$ 1,250,000
Medium	30	$ 20,000	3	90	$ 600,000
Large	5	$ 75,000	7	35	$ 375,000
TOTAL REPAIR COST	**285**			**250**	**$ 2,225,000**

TOTAL PROGRAM COST	**$ 5,604,200**
LEAKS PER MILE	**14.25**
LEAKS PER 300-FT	**0.8**
COST PER MILE	**$ 112,084**

Repairs Across 10-Miles	# Leaks	Cost of Repair	50-Miles of Initial Inspection	10-Miles of Post-Repair Inspection	COST
Initial Inspection @ $10/ft			$ 2,640,000		$ 2,640,000
Post Repair Inspection @ $7/ft				$ 369,600	$ 369,600
TOTAL INSPECTION COST					**$ 3,009,600**

Repair Cost	Number of Repairs	Cost of Repairs	Average Leak Size	Total GPM Benefit from Repair	COST
Small	250	$ 5,000	0.5	125	$ 1,250,000
Medium	30	$ 20,000	3	90	$ 600,000
Large	5	$ 75,000	7	35	$ 375,000
TOTAL REPAIR COST	**285**			**250**	**$ 2,225,000**

TOTAL PROGRAM COST	**$ 5,234,600**
LEAKS PER MILE	**28.5**
LEAKS PER 300-FT	**1.6**
COST PER MILE	**$ 104,692**

Time to Deployment
Time to water delivery is a critical constraint. Leak recovery provides near-term supply augmentation, enabling utilities and industrial users to respond to demand pressures within the same planning cycle.

Energy and Environmental Impacts
Traditional supply augmentation methods are often energy-intensive. Because leak recovery operates within existing infrastructure, it avoids many of the permitting and environmental hurdles associated with new water supply development.

Permitting and Regulatory Complexity
Leak recovery not only recovers water but also reduces the energy required to treat and pump lost water, providing additional environmental benefits.

Measurement, Attribution, and Verification
Perhaps the most significant distinction lies in measurement and verification. Leak recovery enables causal attribution of water savings to specific interventions, a capability that is generally absent in traditional supply projects. Metered production quantities from a water treatment plan are rarely publicly compared to combined metered water customer usage due to the significant water loss amounts. *ERT finds where water loss occurs.*

Scalability and System Integration
Leak recovery scales through incremental expansion, reducing risk and enabling adaptive management.

Strategic Interpretation
The economic advantage of leak recovery is not derived solely from lifecycle cost comparisons, but from a broader set of characteristics that align with modern infrastructure and sustainability requirements.

Leak recovery provides:
- Rapid deployment in response to near-term demand
- Lower capital risk through modular investment
- Reduced regulatory barriers
- Energy and carbon savings
- Direct measurement and verification of outcomes

While traditional water supply infrastructure provides long-lived capacity, it does so at the cost of high capital intensity, long development timelines, and limited measurement transparency. In contrast, ERT-enabled leak recovery represents a measurement-driven, modular, and rapidly deployable alternative, capable of delivering verifiable volumetric benefits within months.

Figure 42. Confirmed water main leak.

Accordingly, leak recovery should not be viewed as a replacement for traditional supply infrastructure, but rather as a complementary and immediately actionable resource, capable of bridging the gap between current system inefficiencies and future water supply needs.

faster + measurable + financeable

9. CONCLUSION
The findings of this white paper suggest that water systems need to begin transition from a paradigm of estimation to one of measurement. This transition is not merely technical, but institutional, affecting how utilities plan, regulate, and finance infrastructure.

Measurement enables new forms of accountability, which in turn enable new forms of capital deployment. This has the potential to fundamentally reshape the economics of water.

This white paper documents and explores the limitations of traditional water audit frameworks that be overcome through direct measurement technologies. Electrical Resistance Testing provides the necessary resolution and reliability to quantify leakage at the defect level, while VWBA 2.0 provides the framework for translating measurements into actionable and monetizable outcomes.

Together, these innovations enable a transition from reactive management to proactive optimization, and from cost-based accounting to asset-based valuation. In doing so, they open the door to a fundamentally new paradigm in water infrastructure management—one in which previously unaccounted-for losses are transformed into measurable, verifiable, and financeable resources.

By enabling defect-level attribution of water loss and recovery, this approach satisfies the core requirements of modern environmental accounting systems: measurability, additionality, verifiability, and persistence. These attributes position VWBA 2.0 not merely as an operational improvement over existing audit methodologies, but as a foundational platform for water credit markets, analogous to the role that measurement and verification protocols have played in the evolution of carbon markets.

Importantly, the implications extend beyond utilities. For industrial water users, regulators, and hyperscale infrastructure operators, the ability to procure locally generated, physically realized, and independently verifiable water offsets introduces a new mechanism for aligning growth with resource constraints. Unlike traditional supply augmentation strategies, which are capital-intensive and time-delayed, ERT-enabled leak recovery provides immediate, modular, and scalable water supply augmentation within existing systems.

Field results have repeatedly shown that ERT can identify incomplete or failed repairs, as well as new or previously undetected leaks that legacy technologies missed. Long-term repeatability studies—ranging from 60 days to multi-year comparisons—demonstrate that ERT can track leak progression (promulgation) and confirm leak reduction, making it uniquely suited for quality assurance and warranty validation of rehabilitation projects such as repairs, rehabilitation, and relining water interventions.

Because ERT delivers repeatable, location-specific, and volumetric measurements of leakage, it is the only technology capable of producing true water-positive outcomes—that is, quantifying actual water savings rather than inferring them. By comparing pre- and post-repair conditions with high accuracy, utilities can directly measure reductions in gallons per minute (GPM), verify contractor performance, and ensure that capital investments result in real water loss recovery.

This closes a critical gap in water management: moving from estimated or assumed savings to verified, defensible metrics. In doing so, the Electro Scan approach enables utilities, regulators, and asset owners to make confident decisions based on measurable impact, positioning it as the only leak detection technology that can consistently deliver auditable, water-positive results.

From a policy and regulatory perspective, the findings suggest that reliance on aggregated, model-based water audit frameworks—such as those embodied in AWWA M36—may be insufficient for applications requiring financial-grade accounting or environmental crediting. In contrast, measurement-based frameworks grounded in direct observation and repeatable instrumentation offer a pathway toward standardization, auditability, and regulatory acceptance.

Ultimately, Electro Scan Inc. and its partners support the conclusion that water loss should no longer be treated solely as an operational inefficiency, but rather as a recoverable infrastructure asset class. By integrating advanced detection technologies with rigorous accounting frameworks, utilities and stakeholders can unlock new sources of value, accelerate infrastructure optimization, and contribute meaningfully to global water sustainability objectives.

In this context, Electrical Resistance Testing and VWBA 2.0 represent a structural shift in how water systems are measured, managed, and valued—with the potential to redefine the economic and environmental foundations of water infrastructure in the decades ahead.

10. NEXT STEPS

Given Electro Scan's partnership with water utilities, nationwide, supported by Core & Main (NYSE: CNM), M.E. Simpson & Co., Inc., and VisionWave Holdings, Inc. (Nasdaq: VWAV), the company believes it can offer a unique, financially viable, defensible, and timely solution that accurately identifies previously unidentified leak locations that can be ranked and prioritized in gallons per minute, and be recouped on a ***gallon used, gallon found*** basis.

In summary, our national solution stack includes:
- VisionWave → AI drone-based soil assessments
- TRIDENT → AI testing, location, and measurement
- Electro Scan Cloud → VWBA reporting
- M.E. Simpson → field execution and support staff
- Core & Main → utility repair supplies at national-scale

Saudi Aramco's Adoption of Electro Scan's TRIDENT Leak Detection Technology

Electro Scan Global Customer

In 2024, Saudi Aramco launched a global leak detection challenge to identify advanced, non-destructive technologies capable of assessing the condition of non-metallic pipelines. The initiative reflected Aramco's increasing reliance on materials such as fiberglass, plastic, and cement-lined systems, and its need for reliable inspection tools that could operate in complex, high decibel industrial environments.

The program was structured as an invitation-only, independently verified field trial, requiring participating companies to travel to the Kingdom of Saudi Arabia (KSA) and test their technologies under controlled but realistic conditions. A key requirement for advancement was the ability to identify at least 80% of pre-installed leaks, ensuring that only high-performing technologies would be considered for future deployment and partnership discussions.

Test Design and Conditions
To ensure objectivity, Aramco's Inspection Technology Unit constructed a blind test environment at its Ras Tanura Refinery, in the Eastern Province of Saudi Arabia, Figure 43.

Two buried pipeline segments were installed and buried:
- A Cement Lined Mortar Steel (CLMS) pipe
- A Glass Reinforced Pipe (GRP)

Both pipes were intentionally modified prior to burial. Aramco engineers introduced known defects, including drilled holes, degraded pipe wall sections, and simulated leaks, without disclosing their locations or quantities to participants.

This blind testing methodology ensured that participating vendors could not rely on prior knowledge and had to demonstrate true detection capability, accuracy, and repeatability.

Electro Scan's Testing Approach
Electro Scan participated in the challenge using its Electrical Resistance Testing (ERT) technology with testing conducted on January 23, 2024. Results were presented the same day.

The company's electrical resistance testing applies a low-voltage current introduced into a water-filled pipe. Any breach in the pipe wall allows current to escape, which is measured, localized, and quantified. This method enables not only detection of leaks but also estimation of their severity in GPM or liters per second.

Importantly, Electro Scan conducted testing without prior exposure or knowledge of the pipes, their layouts, or defect frequenies, configurations, or totals, ensuring full compliance with Aramco's independent testing protocol.

The system successfully:

- Identified all 13 pre-installed leaks
- Accurately located each defect along the pipe
- Provided measurable leakage rates for detected anomalies

In addition, Electro Scan detected a 14th defect that had not been disclosed by Aramco. Initially questioned, this anomaly was later confirmed through excavation to be a previously unknown manufacturing patch defect, validating the system's sensitivity and reliability.

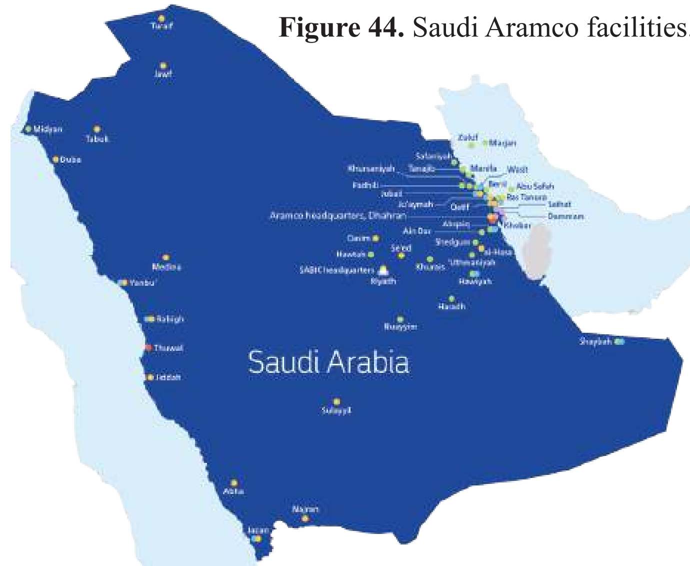
Performance Against the 80% Requirement

Electro Scan's results significantly exceeded the challenge threshold. By identifying 100% of known pinhole leaks in the GRP pipe and successfully detecting and classifying defects in the CLMS pipe, the company surpassed the 80% minimum detection requirement established by Aramco.

Figure 43. Saudi Aramco Benchmark site.

Moreover, the identification of an undisclosed defect demonstrated a capability beyond simple compliance, highlighting the technology's potential for discovering unknown or hidden pipeline failures.

Figure 44. Saudi Aramco facilities.



Key Outcomes and Implications

Several key advantages were demonstrated:

- High detection accuracy, including small pinhole leaks
- Quantification of leak severity, not just detection
- Repeatability of results across multiple scans
- Independence from environmental factors such as pressure, flow, and noise

In 2026, Saudi Americas, on behalf of Saudi Aramco (KSA) issued a $1.3 million purchase order for an intrinsically-safe version the Electro Scan's TRIDENT leak detection solution throughout its facilities in KSA, Figure 44.

References

American Society of Civil Engineers (ASCE). (2021). 2021 Report Card for America's Infrastructure. Reston, VA.

American Water Works Association (AWWA). (2017). Water Transmission and Distribution (3rd ed.). Denver, CO.

American Water Works Association (AWWA). (2020). Buried No Longer: Confronting America's Water Infrastructure Challenge. Denver, CO.

Deb, A. K., Grablutz, F. M., and Hasit, Y. J. (2002). Decision Support Systems for Distribution System Piping Renewal. AWWA Research Foundation, Denver, CO.

Electro Scan Inc. (2023). Machine Intelligent Pipe Inspection for Water Service Line Assessment. Technical white paper, Sacramento, CA.

Electro Scan Inc. (2024). SWORDFISH: Lead Service Line Inspection Technology Overview. Technical brief.

Hansen, C. (2023). "Advancements in Electrical Conductivity-Based Pipe Inspection for Drinking Water Systems." Proc., NASTT No-Dig Show.

Najafi, M. (2010). Trenchless Technology: Pipeline and Utility Design, Construction, and Renewal. McGraw-Hill, New York.

Najafi, M., and Gokhale, S. (2004). Trenchless Technology Pipeline Renewal Methods. ASCE Press, Reston, VA.

North American Society for Trenchless Technology (NASTT). (2019). CIPP Good Practices Guidelines. Houston, TX.

Rajani, B., and Kleiner, Y. (2001). "Comprehensive review of structural deterioration of water mains." Urban Water, 3(3), 151–164.

Reed, D., and Pressinger, J. (2014). "Water main break rates in the USA and Canada." Journal AWWA, 106(2), E83–E94.

Sterling, R., et al. (2012). "State-of-the-art review of rehabilitation technologies for water infrastructure." Journal of Infrastructure Systems, 18(4), 243–255.

Trenchless Technology Magazine. (2023). "Identifying Water Service Line Pipe Materials Using Machine Intelligent Technology." https://trenchlesstechnology.com/identifying-water-service-line-pipe-materials-using-machine-intelligent-technology/ .

U.S. Environmental Protection Agency (EPA). (2023). Technologies for Detecting Lead in Drinking Water Systems. Washington, DC.

U.S. Environmental Protection Agency (EPA). (2024). Lead and Copper Rule Improvements (LCRI). Washington, DC.

Water Research Foundation (WRF). (2018). Condition Assessment of Water Mains. Denver, CO.

electroscan inc.
1745 Markston Road, Sacramento, California, USA 95825
Tel: 800-975-6149, Direct: 916-779-0660 | www.ElectroScan.com | info@electroscan.com