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FIELD VALIDATION OF ACOUSTIC LEAK DETECTION IN AN AGING URBAN WATER DISTRIBUTION SYSTEM: INFLUENCE OF AGING INFRASTRUCTURE ON ACOUSTIC LEAK DETECTION

Catrinel-Raluca GIURMA-HANDLEY[1][0009-0005-3518-078X], Alexandru POSTAVARU[1*][0009-0008-6733-1468], Ion GIURMA[1][0009-0009-5724-1984], Petru CERCEL[1][0009-0008-8924-9801]

[1] "Gheorghe Asachi" Technical University of Iasi, Faculty of Hydrotechnics, Geodesy and Environmental Engineering, Professor Ph.D Eng, Bd. D. Mangeron 65, Iași, 700050

Abstract

Water losses in distribution networks pose a major challenge for regional water utilities, exacerbated by aging infrastructure and the increasing frequency of failures in pipeline sections beyond their service life. This paper presents two case studies on field validation of acoustic leak detection in an urban water distribution system, focusing on how pipe materials influence signal propagation and localization efficiency. Investigations were carried out on representative sectors, including old metallic pipelines affected by corrosion, deposits, and deteriorated joints, as well as rehabilitated/replaced sections using high-density polyethylene (HDPE) pipes. The methodology involved the use of acoustic correlators and dedicated sensing equipment, followed by targeted field verification and, where required, confirmation through controlled excavations. The results highlight significant differences between the acoustic behavior of aged and modern pipelines: in legacy networks, losses are typically associated with structural defects and vulnerable joints, while background noise and pressure variability can mask leak signals; conversely, on HDPE sections, signal attenuation requires adjustment of instrument settings and measurement spacing, yet the material's reliability reduces the likelihood of major failures. The study demonstrates that real-world validation, correlated with pipe material type and degradation condition, enables optimization of interventions and supports risk- and performance-based rehabilitation decisions, contributing to NRW reduction and improved operational efficiency.

Keywords: acoustic leak detection; water losses (Non Revenue Water); aging pipelines; high-density polyethylene (HDPE); network rehabilitation.

Introduction

Water losses in distribution networks pose a major technical and economic challenge for public utility operators, intensified by aging infrastructure and the continued operation of pipeline sections beyond their design service life. In many urban systems, old metallic pipes (steel, cast iron) exhibit internal and external corrosion, deposits, weakened joints, and vulnerability to pressure fluctuations, which promotes the development of microcracks and localized defects. A significant share of these failures remains "hidden" for long periods, with no surface manifestations—especially under permeable soils, deep burial conditions, or paved roadways—leading to cumulative losses and increased operating costs [1, 2, 3].

In this context, reactive approaches become insufficient, and active leak detection assumes a critical role. Acoustic technologies (correlators, noise loggers) enable identification of leak-specific signals and their localization through analysis and correlation, reducing the investigation area and optimizing interventions. However, the performance of acoustic leak detection depends strongly on pipe material, diameter, soil conditions, pressure regime, and background noise level.

The transition to modern materials—particularly high-density polyethylene (HDPE)—provides advantages such as corrosion resistance and joint tightness, but also introduces specific characteristics in terms of acoustic signal propagation and attenuation, requiring adaptation of measurement methodologies [2], [3].

This paper aims to validate acoustic leak detection under real operating conditions in a heterogeneous urban system, highlighting the influence of aging pipelines versus modernized sections (HDPE and other solutions) on leak localization accuracy and on decision-making for interventions and rehabilitation [1], [2], [4].

Experimental

In field operations, the NRW (Non Revenue Water) Unit employs an integrated portfolio of equipment and technologies to identify, locate, and confirm water losses in distribution networks. Dedicated acoustic listening devices (e.g., SebaKMT HydroLux HL 7000 or LeakPen) are used, along with noise correlators to determine the most probable failure location between two measurement points, and equipment for tracing and identifying metallic pipelines and buried network components [2], [5].

In addition, ground-penetrating radar is used for subsurface investigation and for highlighting anomalies associated with voids, moisture zones, or changes in stratigraphy—particularly in areas with difficult access or paved surfaces. UAVs (drones) equipped with thermal cameras are also deployed for rapid screening of large areas and for identifying temperature contrasts that may indicate leakage-related infiltration. In specific situations, detection is further strengthened by tracer-gas methods (hydrogen), which enable confirmation of leaks on non-metallic pipes or under unfavorable acoustic conditions, thereby improving diagnostic robustness and reducing uncertainty before interventions (e.g., excavations/targeted field checks) [6], [7].

Acoustic Method

Acoustic leak detection is based on capturing and interpreting the sound signals generated by water discharging under pressure through a pipeline discontinuity (crack/break). Specialized acoustic sensors, such as hydrophones or geophones, are positioned along the pipeline alignment to record the characteristic noise of leaks; subsequently, the data are processed and analyzed to estimate and pinpoint the source [5], [6], [7].

A relevant case involved the investigation of an infiltration issue in the vicinity of the E10 residential building, Staircase A, on Păcii Street in the city of Piatra Neamț (Fig. 1) – (*source: authors' own processing map, based on field investigations and network plans*). The infiltration manifestation was observed near the building's associated sewer manhole, while the nearest water supply main was located at approximately 6 m, consisting of an unprotected DN 150 mm steel pipe.
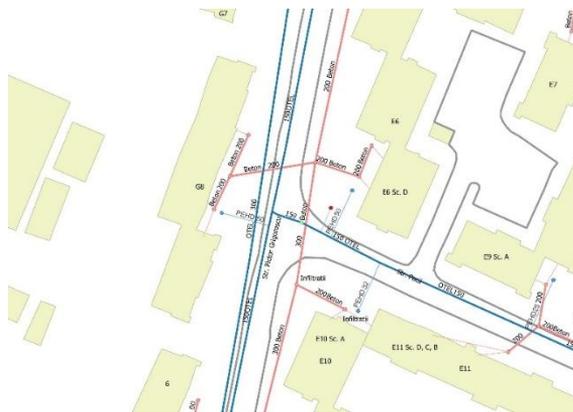

Fig. 1. Pipeline routes and intersections/nodes; points marked as "Infiltrations"
(areas with potential infiltrations/network defects)

To clarify the origin of the phenomenon, a verification campaign was carried out exclusively using the acoustic method, consisting of a systematic listening survey along the entire route and across all pipelines present in the analyzed area, in order to identify any potential failures [5], [6].

Ground Penetrating Radar (GPR)

Another investigated case concerned the area on Traian Street, at the intersection with Lămâiței Street (Fig. 2) – (*source: authors' own processing map, based on field investigations and network plans)*, following notifications submitted by the homeowners' associations of buildings A7 and A8 regarding indications of potable-water infiltration in the basements. The situation was assessed by applying acoustic leak detection methods in parallel with GPR investigations, using the equipment available within the NRW Unit [9], [10].
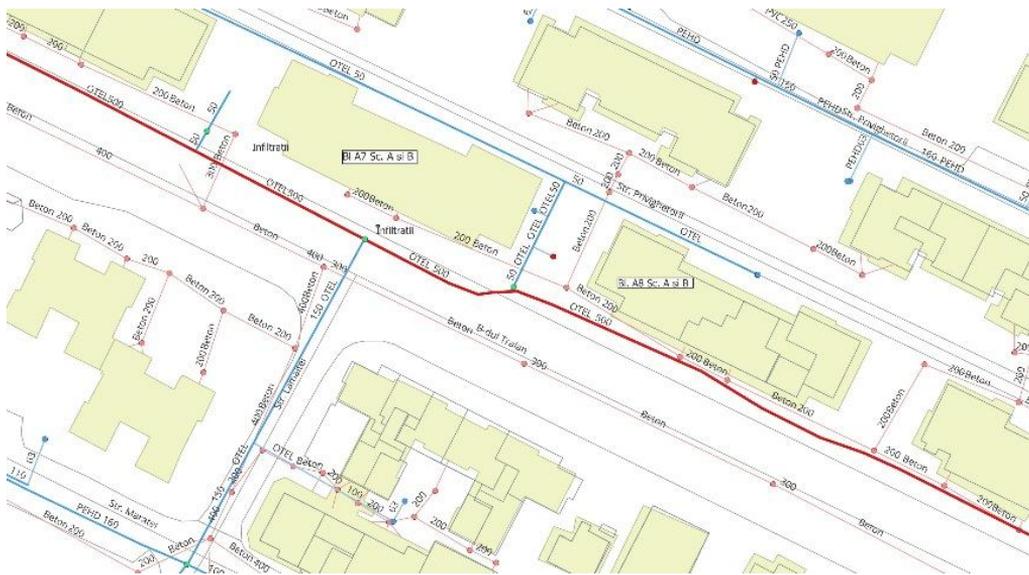

Fig. 2. Pipeline alignments and connection points (intersections/nodes), as well as the locations flagged as "Infiltrations," representing areas with potential infiltrations or network defects

Ground Penetrating Radar (GPR) [2], [3], [9], [10] is a non-invasive geophysical method that uses the transmission and reception of high-frequency electromagnetic pulses to investigate and map subsurface structures. The technique is particularly effective for detecting buried objects, identifying changes in the dielectric/electromagnetic properties of materials, and highlighting geotechnical discontinuities such as voids, cavities, and cracks within the ground mass [9].

Geophysical surveys were conducted using the Duo system along the alignment of the DN 500 steel transmission main [11], in the vicinity of the area where water infiltration had been reported. The investigation aimed to identify subsurface anomalies correlated with potential network losses, such as zones of increased moisture, localized washout of backfill material, incipient cavities, or discontinuities in stratification [9], [10].

The survey was performed using multiple parallel and/or transverse passes [5], [9], [10] relative to the pipeline axis, to ensure the most comprehensive coverage of the investigated area and to improve interpretation of the electromagnetic response. The acquired data were analyzed in conjunction with available network plans and field observations to delineate sectors with a high probability of failure and to prioritize subsequent interventions (targeted checks, acoustic correlation) [1], [12], [13], [14].

Results

Using the Acoustic method

In the first case analyzed, related to Păcii Street, the use of the SebaKMT HydroLux HL7000 acoustic device (commonly referred to as an "electronic ear") enabled delineation and identification of the sector with a high probability of failure, based on the noise level and the spectral signature associated with a pressurized leak (Fig. 3) – (*Source: authors' own processing map, based on acoustic field investigations*).
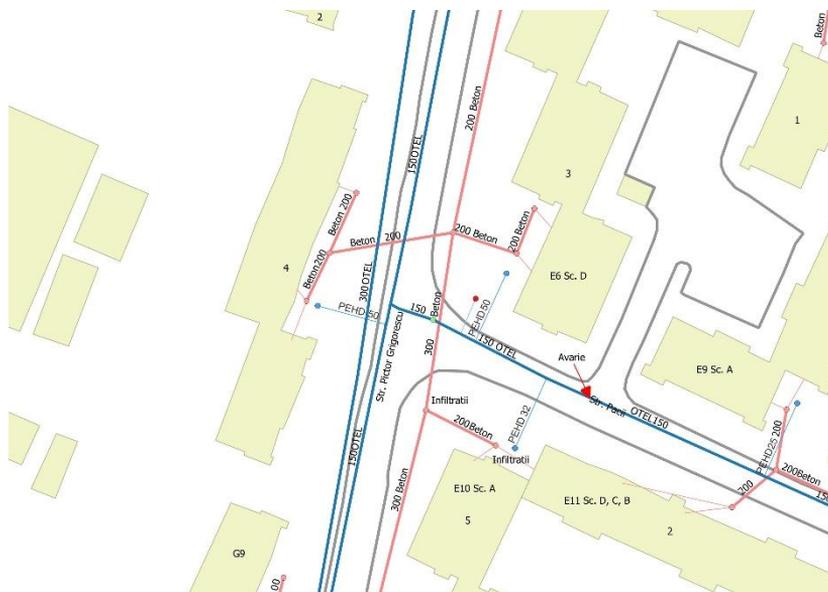

Fig. 3. The estimated location of the "Failure/Leak," marked with a red arrow on the section along Păcii Street

In the HydroLuxView HL7000 report without any filter applied (Fig. 4), the frequency spectrum reflects the energy distribution of the acoustic signal captured at the measurement point [8], including both components potentially associated with a leak and background noise originating from the network and the surrounding environment. The value "Level = 78.5 dB" represents the overall (integrated) level of the recorded signal rather than the amplitude at a single frequency, and its high magnitude suggests the presence of a relevant acoustic source nearby or an efficient transmission of vibrations to the sensing point. From an interpretive standpoint, this value is most useful when compared with measurements taken at successive points along the same section under similar conditions; using it as a universal "absolute" threshold for confirming a failure is less appropriate [6], [7], [8].

In the image in Fig. 5, the report with the 160–800 Hz filter applied enabled isolation of the frequency band [8] considered relevant for identifying the characteristic noise of leaks, reducing spurious contributions from low and high frequencies. The recording indicates an overall acoustic level of 74.1 dB, and the spectrum highlights energy concentrated predominantly in the mid-frequency range, suggesting a clearer, more stable acoustic signature for interpretation.

By restricting the spectrum to this band, the analysis becomes more robust and more comparable between successive measurement points, facilitating delineation of the section with a high probability of failure [6], [7], [8].
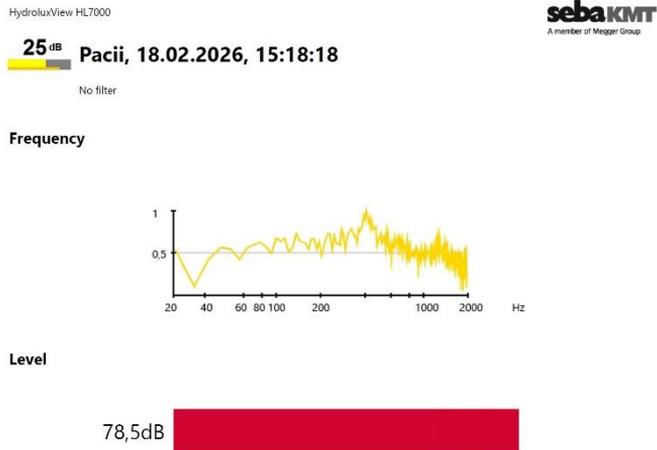
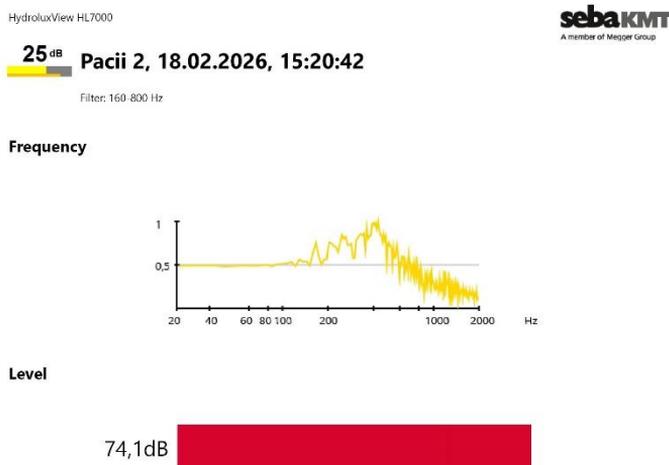**Fig. 4.** Unfiltered acoustic detection graph

Fig. 5. Filtered acoustic detection graph

In the second investigated case, related to the Traian Street area—at the intersection with Lămâiței Street (Fig. 6) – (*Source: authors' own processing map, based on acoustic field investigations),* detection equipment [8] enabled, following a campaign of measurements and successive verifications at representative points of the network, delineation of the sector with a high probability of failure. Analysis of noise levels and spectral signatures revealed consistent variations between the investigated points, indicating an acoustic source localized within the analyzed perimeter [1].

In the HydroLuxView HL7000 report for the "Traian" point in Fig. 7, acquired without any filter, the frequency plot [6], [8] shows the energy distribution of the acoustic signal across the entire analyzed range, including both components potentially associated with a leak and background noise. The value "Level = 69.9 dB" denotes the overall integrated signal level at the measurement point, indicating the presence of a perceptible acoustic source, but it does not separate parasitic contributions typical of low- or high-frequency regions. Consequently, the interpretation of this result is most meaningful when compared with measurements taken at

successive points along the same section, to observe variations in level and spectral signature [4], [5] as the survey approaches the suspected area [6], [7].
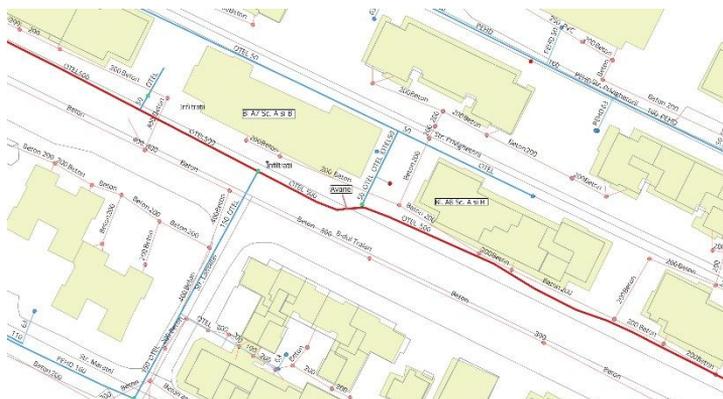

Fig. 6. Estimated location of the "Failure/Leak," marked with a red arrow on the section along Traian Street
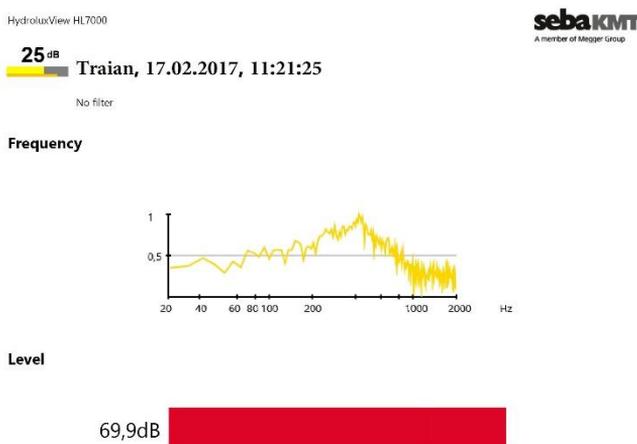

Fig. 7. Unfiltered acoustic detection graph on Traian Street

In the HydroLuxView HL7000 "Traian" report, with the 160–800 Hz filter applied [5] (Fig. 8), the frequency plot [6] captures only the spectral component relevant to leak-specific noise, largely removing parasitic influences at low and very high frequencies. The recorded overall level is "Level = 67.0 dB," an integrated value across the filtered band, indicating a detectable acoustic signal within the "cleaner" interpretation range. The spectrum highlights an energy concentration [2], [3], [4], [5] in the mid-frequency region (with a peak around a few hundred Hz), which enables more robust comparison between successive measurement points and supports a more accurate delineation of the sector [1] with a high probability of failure [6], [7], [8].

Using G.P.R.

Additionally, in the Traian Street area, the GPR system was used as a complementary method to validate the results obtained from the acoustic investigations [9], [10].

The radar scans were aimed to highlight subsurface anomalies in the vicinity of the pipeline alignment, such as zones of increased moisture, stratigraphic discontinuities, or incipient cavities that could be associated with a loss. Correlating the acoustic information with the electromagnetic

response from GPR narrowed the search area and increased confidence in identifying the section with a high probability of failure, before confirmation through targeted interventions [9], [10].
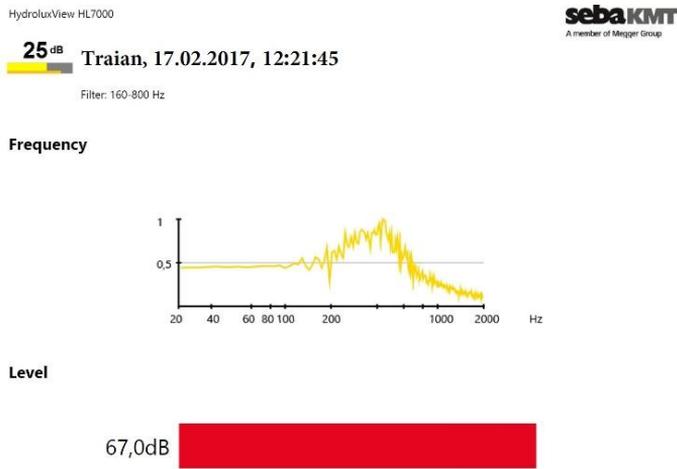

Fig. 8. Filtered acoustic detection graph on Traian Street

The image in Fig. 9 shows a radargram acquired with the DUO GPR on Traian Street, displayed in two processing windows: "Shallow" (for near-surface structures) [9] and "Deep" (for deeper zones) [9]. A well-defined "hyperbola" anomaly can be observed in the central area, characteristic of a buried linear object (typically a pipe) [3], [13], accompanied by disturbance of the surrounding stratification with infiltration zones, which may indicate changes in the medium (moisture/voids) [9], [10] associated with the infiltration phenomenon.

The indicator on the right shows a point marked at a distance of ~40.79 m along the profile and an estimated depth of ~1.5 m.
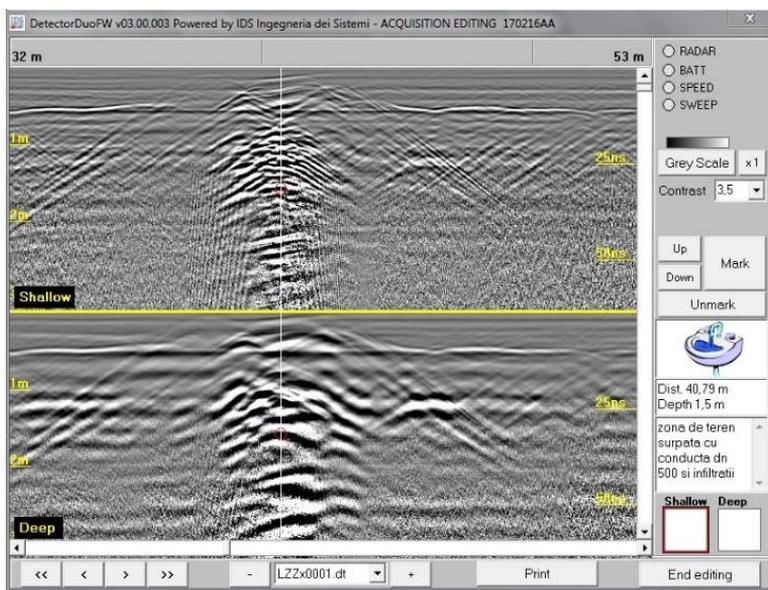

Fig. 9. Radargram on Traian Street

Discussions

The present study provides field-based evidence that acoustic leak detection remains an effective operational tool in urban water distribution systems, but the physical and hydraulic characteristics of the investigated sector strongly condition its performance. In agreement with previous reviews of acoustic leak localization in pressurized pipelines, the interpretation of acoustic signatures cannot rely on a single absolute sound level; instead, it must be based on comparative measurements, spectral behavior, and consistency between successive points along the investigated alignment [1], [3], [5]. The results from the two case studies confirm this practical requirement under real-world network conditions.

In the Păcii Street case, the unfiltered measurement indicated an overall acoustic level of 78.5 dB, whereas the application of the 160–800 Hz filter yielded 74.1 dB. Although the filtered value is slightly lower, the filtering stage improved the interpretability of the signal by isolating the frequency band most relevant for leak-related noise and by reducing parasitic low- and high-frequency components. This observation is consistent with the literature, which shows that leak identification is not determined only by signal amplitude, but also by the spectral quality of the signal and by the ability to distinguish leak-induced vibrations from background network noise, traffic, or operational disturbances [4], [6], [3]. Therefore, in this case, the main benefit of filtering was not simply noise reduction in a numerical sense, but the production of a cleaner and more stable acoustic signature for field interpretation.

In the Traian Street case, the acoustic measurements showed an overall level of 69.9 dB without filtering and 67.0 dB with the 160–800 Hz filter. As in the previous case, the filtered result did not yield a stronger signal in absolute terms, but rather a more selective one, enabling better comparison between adjacent measurement points and a more reliable delineation of the sector with a high probability of failure. This is consistent with prior work indicating that acoustic leak detection in real networks is highly dependent on signal discrimination rather than on raw sound intensity alone, particularly in environments affected by background noise and mixed-frequency interference [4], [5], [6], [7].

An important contribution of this study is that it evaluates acoustic detection not under controlled laboratory conditions, but under real urban operating conditions, where uncertainty is significantly higher. Buried metallic infrastructure, aging components, road traffic, variable surrounding materials, and local hydraulic conditions influence the sectors under investigation. In this respect, the study complements prior literature by demonstrating that field validation must integrate technical interpretation with operational judgment. While many published studies focus on algorithmic localization, sensor performance, or controlled experimental settings [3], [6], [7], the present work demonstrates the practical value of stepwise field verification in a heterogeneous aging network.

The results also support the literature indicating that pipe material has a major influence on leak signal propagation and localization reliability. In aged metallic systems, such as the investigated steel transmission/distribution sectors, corrosion, deposits, and joint deterioration increase the probability of hidden losses but may also create complex acoustic environments through reflection, damping irregularities, and interference from surrounding infrastructure. At the same time, these pipe materials can transmit leak-generated vibrations over useful distances, which explains why acoustic delineation remained feasible in both study areas. By contrast, the literature reports that plastic pipes such as HDPE tend to attenuate acoustic energy more strongly, requiring shorter spacing between measurement points, adapted instrument settings, and, in some cases, complementary methods to maintain localization accuracy [2], [3], [6].

This distinction is especially important for utilities operating mixed-material systems and planning rehabilitation priorities.

A further relevant aspect is the role of GPR as a complementary, uncertainty-reducing technique. In the Traian Street case, acoustic investigations were strengthened by radar data

showing a significant anomaly at approximately 40.79 m along the profile and an estimated depth of about 1.5 m. The presence of a hyperbolic feature associated with disturbance of the surrounding stratification supports the interpretation that the investigated area was affected by moisture-related subsurface changes compatible with the reported infiltration phenomenon. This is in line with studies showing that GPR can improve leak investigation by identifying moisture anomalies, disturbed subsurface structure, and pipe-related responses that help reduce the excavation area and increase confidence before intrusive intervention [9], [10]. In our study, the combined use of acoustic detection and GPR did not replace direct verification, but significantly improved the pre-intervention diagnosis and targeting process.

Compared with previously reported approaches, the main added value of the present study lies in its operational realism. Rather than presenting a purely methodological or theoretical comparison, the paper documents how acoustic field measurements, spectral filtering, and geophysical cross-validation can be integrated in decision-making for loss localization in an aging urban network. The findings, therefore, contribute practical evidence that leak detection efficiency depends not only on sensor capability, but also on infrastructure age, pipe material, local hydraulic conditions, and the use of complementary validation tools. This has direct implications for NRW management, excavation planning, and risk-based prioritization of rehabilitation works.

In this context, the project to replace the transmission main on Traian Boulevard aligns with the rationale of a structural intervention targeting sections that have exceeded their service life and exhibit a high failure frequency. According to the technical documentation, the DN 500 main is specified as a spirally welded steel pipe grade S275JR, with internal [11], [12], [13], [14], [15], [16], [17], [18], and external protection (250 μm) in accordance with SR EN 10289, having dimensions De 508 × 7.1 mm and a designed length on the order of 1.42 km.

Installation requirements include placement within the carriageway, parallel to the existing pipeline and at a minimum offset of 1.50 m, together with associated works: construction of connection nodes/chambers (fittings, valves, instrumentation such as insertion flowmeters and pressure/flow loggers), undercrossings using a protective steel casing OL DN700 [11], [12], [13], [14], [15], [16], and an overcrossing of a watercourse with supports and reinforced-concrete bearings. From a durability standpoint, epoxy coatings compliant with EN 10289 are recognized solutions for the anticorrosive protection of buried steel pipelines, with a direct effect on long-term integrity and on reducing recurrent failures.

The overlap between network works and the major urban mobility project highlights a practical constraint: rehabilitation of the water transmission main becomes a critical step for restoring the road structure and for minimizing subsequent interventions in the carriageway. Furthermore, local public communications indicate that the "water project" influenced the schedule of the Traian–Decebal corridor, precisely due to the complexity of connections and handover/acceptance stages. Looking ahead, the use of "innovative" materials in potable-water systems is oriented toward solutions with watertight joints and increased resistance to degradation: PE100-RC HDPE (resistant to slow crack growth) [11], [12], [13], [14], [15], [16], [17], [18], optimized welding solutions (electrofusion), and fully standardized system solutions, which reduce losses by eliminating weak points at joints and by providing better tolerance to external loads.

Conclusions

This study validated acoustic leak detection under real operating conditions in an aging urban water distribution system and showed that the method is effective for rapidly delineating sectors with a high probability of failure when measurements are interpreted comparatively and supported by field knowledge. In the Păcii Street case, the acoustic survey identified a relevant signal with an overall level of 78.5 dB in the unfiltered spectrum and 74.1 dB after applying the

160–800 Hz filter. Although the filtered level was numerically lower, the filtered spectrum provided a clearer and more stable basis for interpretation by isolating the frequency range associated with leak-related noise and reducing parasitic contributions. In the Traian Street case, the acoustic investigation indicated an overall signal level of 69.9 dB without filtering and 67.0 dB with the 160–800 Hz filter, again demonstrating that the main benefit of filtering was the improvement of interpretability rather than a simple increase in acoustic amplitude. The acoustic results were further strengthened by GPR investigation, which identified a significant subsurface anomaly at approximately 40.79 m along the profile and an estimated depth of about 1.5 m, consistent with the area affected by infiltration.

Overall, the results confirm that acoustic leak detection performance is influenced by pipe material, degradation condition, background noise, and hydraulic regime. The study also demonstrates that combining acoustic measurements with GPR can reduce uncertainty, narrow the intervention area, and support better-targeted excavation and rehabilitation decisions. From an operational perspective, this integrated approach contributes to more efficient NRW reduction and improved management of aging urban water infrastructure.

Limitations and Future Research

The present study has several limitations that should be acknowledged. First, the analysis is based on two field case studies, which provide valuable operational insight but do not allow broad statistical generalization to all pipeline materials, diameters, burial conditions, or hydraulic regimes. Second, the investigated sectors are specific to an urban network affected by aging infrastructure, mixed environmental noise, and local operating conditions; therefore, the observed acoustic behavior may vary in other systems with different materials or network configurations. Third, although the study demonstrates the value of combining acoustic detection with GPR, the results remain primarily field-operational and are not supported by a larger comparative dataset of repeated excavated confirmations across multiple sites.

Future research should extend this approach to a larger number of validated leak events to systematically compare acoustic responses across metallic and plastic pipelines, varying diameters, pressure levels, and burial environments. Additional work is also needed to define more robust operational thresholds for signal filtering, point spacing, and confidence assessment during field investigations. A promising direction is the integration of acoustic and GPR data with GIS- and SCADA-based monitoring systems, as well as the use of AI-assisted signal interpretation to automate anomaly classification and intervention prioritization.

Such developments could improve both localization accuracy and decision support in NRW management and long-term infrastructure rehabilitation planning.

A broader operational perspective is provided by the thematic mapping of leak-prone sectors shown in Fig. 10 – *(Source: authentic map created in QGIS by the authors based on field investigations, acoustic surveys, GPR measurements, UAV flights, utility network records, and authors' own data processing)*, which summarizes the areas identified through integrated field investigations using HydroLux HL 7000 acoustic listening equipment, ground penetrating radar (GPR), noise correlation systems, and UAV-based aerial inspections. This map highlights multiple failure-prone zones distributed across the metallic water distribution network, confirming that water losses in aging urban systems are rarely isolated events and are more often associated with broader patterns of infrastructure deterioration. In practical terms, the mapped sectors include both locations where failures have already been repaired and areas where the level of degradation, recurrence of failures, or diagnostic evidence justified the inclusion of pipe replacement works in the utility's investment plan.

Fig. 10. Map of the areas with failures identified in the metallic water distribution network through integrated investigations using HydroLux HL 7000 acoustic listening equipment, ground penetrating radar (GPR), noise correlation systems, and UAV survey flights

This wider network-scale representation strengthens the operational relevance of the present study by showing that *field* validation is not limited to isolated point investigations but can also support strategic rehabilitation planning and prioritization of long-term interventions.

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