InfraSense: Envisioning Future Interaction with Urban Water Infrastructure Through Muon-Based Sensing

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Abstract. Urban water infrastructure is essential to the function of cities, yet much of the U.S. system remains hidden and poorly monitored, with failures often detected only after leaks or breaks occur. In New York City, aging pipes and fragmented monitoring practices contribute to water loss, high excavation costs, and service disruptions, highlighting the need for more anticipatory approaches to infrastructure management. This paper presents a conceptual design for *InfraSense*, an intelligent system that employs muon-based sensing to detect structural anomalies in buried water pipes without excavation. Focusing on underground water infrastructure as a concrete instantiation, the system combines non-invasive detection with Machine Learning-enabled analysis to deliver continuous, predictive monitoring of water distribution networks. Grounded in the Double Diamond design framework, the study applies both a speculative lens and deep tech inspiration to reimagine future interactions with buried urban infrastructure, proposing a distributed and anticipatory system to support resilient and sustainable smart city management.

Keywords: Muon Sensing · Distributed Interaction Systems · Water Infrastructure Monitoring

1 Introduction

New York City's water distribution infrastructure is among the largest and most complex in the world, delivering over one billion gallons of drinking water daily [1] through more than 7,000 miles of mains and pipes [2]. With 40% of pipes installed before 1941 [3] and ongoing infrastructure management inefficiencies, such as patchwork repairs that create weak points in the system, the city currently loses approximately 15% of its water daily due to leaks and main breaks [4].

Current monitoring practices rely primarily on acoustic detection supplemented by community alerts via NYC's 311 system, which allows residents to report visual water leaks. The Department of Environmental Protection (DEP) deploys acoustic monitoring devices called LMics, which attach to water valves to listen for sounds indicating leaks

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in water mains or distribution pipes. However, this approach faces significant operational constraints: teams of technicians monitor 40,000 ft of main per night [5], limiting coverage across the city's extensive infrastructure network. More critically, these methods are fundamentally reactive, responding to leaks after they occur, rather than enabling preventive intervention. The scale and age of NYC's water system compound these challenges, making comprehensive real-time monitoring nearly impossible with current technology. This reactive stance results in high excavation costs, prolonged service disruptions, and substantial preventable water loss.

InfraSense is a conceptual system designed to address these challenges through muon-based [6] sensing and machine learning (ML) - enabled analysis [7], offering a non-invasive, continuous monitoring solution for underground water infrastructure as a concrete case. While designed with current conditions in mind, InfraSense is oriented toward future smart infrastructure systems—particularly utilidors, or shared utility corridors—which enable coordinated, modular, and digitally integrated management of multiple services. By aligning with this emerging urban infrastructure model, InfraSense shifts from reactive maintenance to anticipatory, data-driven stewardship of urban water systems.

1.1 Urban Water Infrastructure Context

New York City's underground water infrastructure began with hollow wooden water pipes [Fig. 1.] laid by Dutch settlers in the 1800s, replaced by iron mains as the growing city demanded more.

Fig. 1. Wooden water pipes discovered in 2006 during routine utility upgrades in Lower Manhattan [8].

As electricity arrived in the late 19th century and telecommunications exploded in the 20th, successive generations simply layered new systems atop the old: power cables winding around water pipes, fiber optics threading through tunnels, subway lines crossing gas mains, all added piecemeal by different utilities with no master plan [Fig. 2.]. The result is a chaotic subterranean tangle that engineers call "spaghetti," where much of the original infrastructure continues aging invisibly beneath the streets [9]. While New Yorkers enjoy cutting-edge innovation and modern towers above, the city rests precariously on a hidden foundation of century-old pipes and entangled utilities that grows more challenging to maintain, repair, or even locate with each passing year.

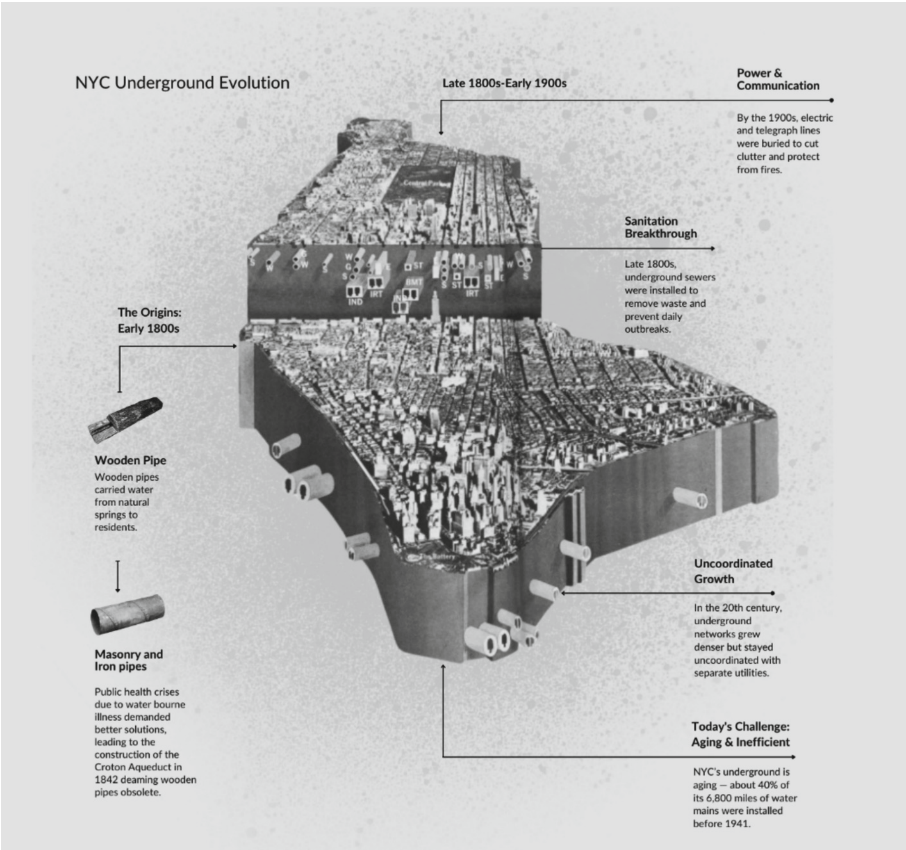

Fig. 2. Depiction of New York City's underground evolution from 1800 to present. Image adapted from 'Underground New York', 1949, Life Magazine, 7 November, p. 80. New York: Time Inc. [10].

A 2024 audit reports that New York City—specifically, its Asset Information Management System (AIMS)—is not accurately assessing the condition of the city's water infrastructure and stresses that existing inspection methods, protocols, and technologies are either ineffective or obsolete, with current practices focusing on superficial inspection. In addition, the Office of Management and Budget (OMB) inspection methodology explicitly excludes the evaluation of structural conditions behind walls, underwater, or below the surface [11]. This limitation also applies to cases where visible surface conditions suggest deeper material damage. This avoidance of inspecting areas difficult to access has resulted in emergency contracting when infrastructure fails.

2 Motivation

In cities like New York, subsurface utilities, including water, energy, and telecommunications, often operate independently of the real-time, adaptive frameworks that characterize surface-level urban technologies; here we focus on underground water infrastructure within this broader context. As smart cities evolve, utility corridors are emerging as the infrastructural foundation for integrated, responsive urban systems [9].

While muon detection has previously been applied to mining and construction systems [12], this work repositions the technology within a broader urban context, exploring its potential as part of a pervasive, distributed, and anticipatory sensing and analysis layer. We treat underground water infrastructure as a dynamic interaction space where data flows inform long-term planning and real-time decision-making.

3 Methodology

This study follows the Double Diamond design framework [13] as its primary methodological structure, guiding the process from contextual inquiry to conceptual system development. The four stages—Discover, Define, Develop, and Deliver— structure our approach to envisioning future interactions with underground water infrastructure systems in urban settings.

During the Discover and Define phases, we conducted informal, unrecorded conversations with municipal stakeholders and domain experts in water infrastructure, smart city planning, and urban sensing. These discussions served to contextualize the design challenge and identify system-level constraints rather than collect empirical data. We followed ethical design principles of informed participation, voluntary engagement, and responsible representation in early-stage conceptual design.

The Develop and Deliver phases were guided by a Research-through-Design orientation [14], incorporating principles from speculative design [15] to construct and communicate the InfraSense concept. This included the development of a system-level architecture that spans distributed sensing, data processing, and anticipatory decision-making interfaces. The concept leverages advances in muon tomography and ML-enabled analysis to propose a plausible near-future infrastructure monitoring platform.

As an early-stage conceptual design study, this work serves both as a design provocation and a conceptual system design artifact for future empirical evaluation, participatory co-design, and field deployment. By embedding InfraSense within the evolving discourse on pervasive and anticipatory smart systems, the study contributes to HCI scholarship on future infrastructure interaction, urban data ecologies, and system design for sustainability. Table 1 summarizes how the Double Diamond framework guided the study's design activities and the resulting conceptual system design artifacts.

Table 1. Double Diamond phases and resulting design artifacts.

Phase	Design Activities and Inputs	Resulting Artifacts / Knowledge
Discover	Secondary research on urban water infrastructure; technology research on muon tomography; informal stakeholder conversations	Problem framing grounded in infrastructural constraints and sensing opportunities
Define	Synthesis of infrastructural, technological, and stakeholder insights; identification of ethical, security, and governance considerations	System boundaries; interaction goals; non-functional requirements
Develop	Research-through-Design-informed conceptual exploration; speculative and interdisciplinary synthesis	Conceptual system architecture and sensing–analysis–decision flows
Deliver	Design articulation through interface concepts, and scenarios	Conceptual system design artifact, including interface and decision-support concepts

4 Conceptual Design

The design of InfraSense is grounded in the Human-in-the-Loop Cyber-Physical Systems (HiLCPS) framework which emphasizes the integration of sensing, automation, and human judgment in complex systems. Within this framework, we apply the Situational Awareness (SA) model [16] to structure system interactions across three key stages.

- Sensing - InfraSense deploys embedded muon sensors to detect anomalies in underground water infrastructure conditions. These sensors enable continuous, passive data collection without disrupting surface-level urban operations.
- Understanding - Data from the sensing layer is processed through ML models that classify patterns, detect anomalies, and interpret potential signs of failure or degradation in real time.
- Projection - based on model outputs, the system generates predictive insights and visualizations to support municipal experts in prioritizing interventions, simulating potential outcomes, and initiating preventive actions.

This model informs the overall system architecture, in which real-time detection, intelligent analysis, and human decision-making is dynamically integrated. The goal is to transition infrastructure monitoring from a reactive paradigm to an anticipatory, distributed model of engagement.

The design reflects a synthesis of insights gathered during early-stage contextual exploration (as described in the Methodology), and translates them into a speculative, yet technologically grounded concept. In this way, InfraSense envisions how machine learning-assisted sensing capabilities and civic interaction can be organized to support pervasive intelligence for underground water infrastructure.

4.1 System Components

InfraSense includes three interconnected components: Detection, Data Collection & Analysis, and Integration into ambient 3D interfaces, which together transform muon-derived structural data into actionable insights for urban infrastructure management [Fig. 3.]. The detection layer employs muon sensors [6] to identify subsurface anomalies and structural weaknesses in water infrastructure. Data from these sensors are transmitted securely and processed using energy-efficient computing and ML-enabled analysis [7], allowing both real-time monitoring and long-term forecasting. The processed information is then integrated into ambient 3D interfaces that mirror physical infrastructure and support decision-makers with prioritized alerts, visual overlays, and predictive maintenance recommendations.

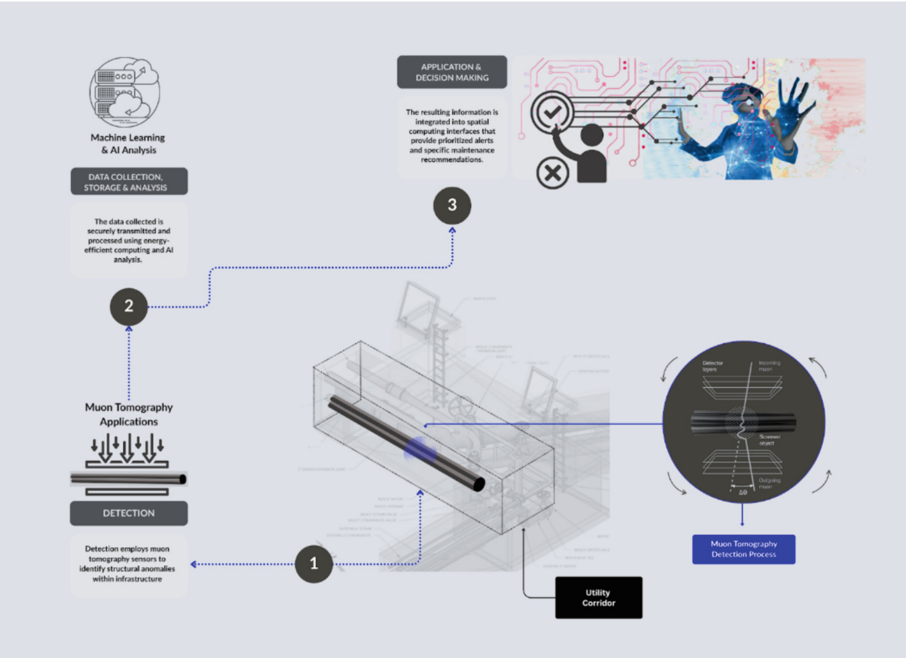

Fig. 3. InfraSense comprises three components: Detection (Muon Sensors), AI/ML-powered Data Collection & Analysis, and Integration into ambient 3D interfaces, that together enable continuous, non-invasive monitoring of urban water infrastructure. Conceptual illustration of muon tomography–based subsurface imaging (bottom right corner) for underground infrastructure assessment adapted from the GScan Technology webpage, GScan: The science behind our muon tomography technology. https://www.gscan.eu/technology [accessed 30 Jan 2026]. [17].

4.2 Detection

Muon sensing, in combination with tomographic reconstruction techniques, enables muon tomography, the process of mapping the structure of materials by tracking changes in the path of muons as they pass through matter. Cosmic rays at the Earth's surface consist primarily of naturally abundant charged particles called muons, which account for approximately 98% of all cosmic rays [6]. Due to their relatively high mass and low energy loss when traversing matter, muons can penetrate deeply into dense materials [18], making them well suited for sensing subsurface infrastructure.

As muons pass through matter between two detectors in the InfraSense detection phase, they interact with atomic nuclei and scatter. By measuring the angle of deflection of individual particles, it is possible to indirectly infer the density of the material encountered, such as that of distribution pipes and water mains within NYC's underground water infrastructure. These density estimates allow material types (e.g., PVC, HDPE, steel, cast iron, pig iron) to be inferred based on their characteristic atomic properties derived from scatter data.

Aggregating density measurements from successive muon interactions yields localized density maps that provide insight into material integrity at specific locations (point of impact). While updates occur only as additional muons traverse the same region, the sensing process is effectively continuous, with temporal resolution dependent on muon flux at any given time. Over time, this continuous data stream enables three-dimensional image-based reconstructions of subsurface material properties using multiple scattering imaging [18].

InfraSense is designed to utilize muon sensing and tomography to detect and reconstruct image-based representations of NYC's buried water infrastructure, identifying structural weaknesses (e.g., leaks, breaks) that are transferred to the Data Collection & Analysis phase.

4.3 Data Collection and Analysis

The Collection phase involves aggregating and storing data from muon detectors, converting these data into operational indicators (e.g., volume-related changes in surrounding soil), and supplementing them with contextual information including weather patterns, flood zone designations, water pressure readings, and other environmental factors that may influence infrastructure degradation. The InfraSense system is designed to analyze these inputs by applying unsupervised machine learning techniques such as dimensionality reduction for compressing time-series data and autoencoders for anomalous activity detection.

These analytical approaches can yield practical insights for infrastructure management. Specifically, they support prioritized maintenance scheduling through severity-based clustering of material degradation, enable predictive maintenance by tracking how infrastructure clusters evolve along failure trajectories, and help identify leak precursor signatures through density estimation of subtle pre-failure patterns. Results of these analyses are intended to support extended service life for distribution pipes and water mains, alongside reduced maintenance frequency and downtime.

4.4 Integration or Application and Decision Making

Integration represents the final stage within the InfraSense system. Its muon tomography detection capability, combined with data collection and analysis, transforms raw sensor outputs into actionable intelligence that can be integrated into existing water management frameworks to support decision making. This stage serves as the bridge between advanced detection technologies and water infrastructure management practices. Decision makers access the data through an intuitive spatial computing interface that presents water infrastructure integrity parameters in interpretable formats.

The interface highlights potential issues through role-specific indicators for different stakeholder groups [Fig. 4.] (e.g., Field Worker, Supervisor, and Planner). These indicators can surface information such as the average age of failure in a given zone, suggest replacement rates relative to the historical failure age, and reveal differential settlement or undue stress on new pipes that indicate decreased structural integrity. Figure 4 below shows a proposed design for the Planner view interface.

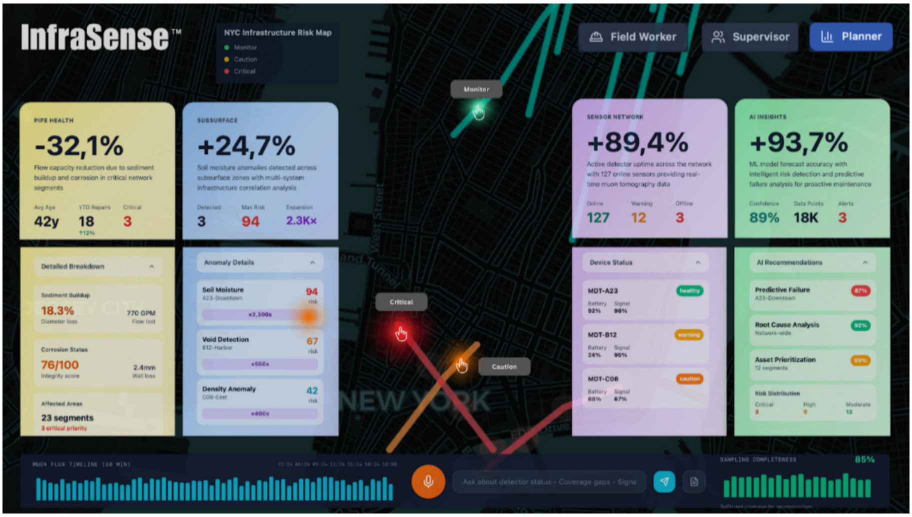

Fig. 4. Conceptual visualization of InfraSense water infrastructure monitoring interface (presented in planner view mode) integrating geospatial risk visualization, pipe health assessment, subsurface anomaly detection, sensor diagnostics, and ML-based predictive analytics. A role-based interface architecture enables to engage with stakeholder-specific key performance indicators and analytical outputs aligned with their respective decision-making roles.

The interface also displays mapping systems and prioritized alerts, enabling quick identification of areas requiring attention [Fig. 5.]. The ML analysis function converts detected patterns into maintenance recommendations, often predicting potential failures weeks or months before they occur. Water management authorities can leverage this information to make evidence-based decisions regarding infrastructure needs, budget allocation, and workforce deployment. The system supports assessment of the potential impact of alternative decisions, enabling more effective resource distribution across competing infrastructure needs.

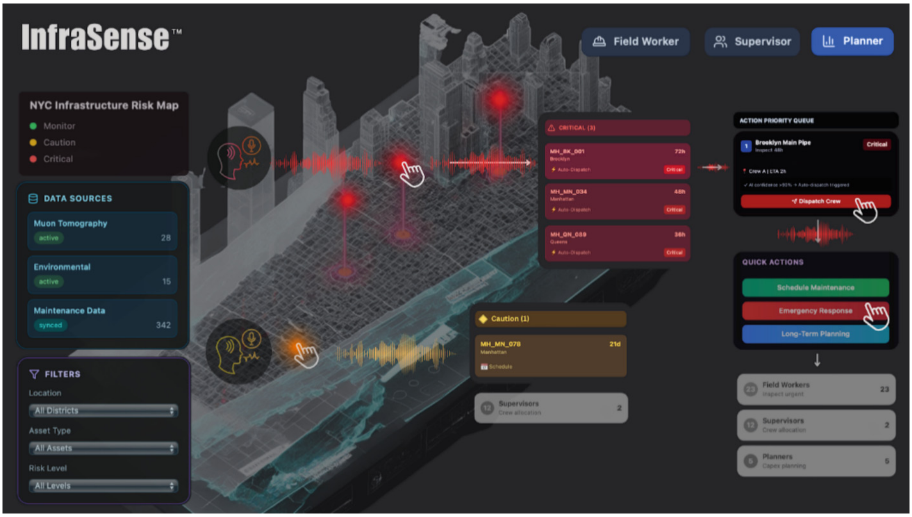

Fig. 5. InfraSense spatial computing interface operating in planner view mode—a stakeholder-specific conceptual visualization designed to support evidence-based decision-making through the systematic initiation of response protocols and the integration of aggregated data into short-, medium-, and long-term planning models for water infrastructure replacement and intervention strategies. This interaction includes a fragment of an AI generated image to illustrate the future of map functionality. The AI generated image includes the map and buildings. All other elements were customized by hand.

When critical integrity threats are detected, the system can support the initiation of appropriate response protocols, ranging from scheduling routine maintenance for minor issues to immediate emergency response for severe integrity threats. Beyond addressing immediate concerns, aggregated infrastructure data can be incorporated into long-term planning models, enabling authorities to forecast infrastructure needs decades in advance and develop sustainable replacement strategies aligned with projected budgets and urban development plans.

5 Conceptual Design

InfraSense is framed as a speculative system design that envisions underground water infrastructure as part of a broader urban ecosystem supporting resilient and responsive cities. While oriented toward future possibilities, the design is grounded in existing operational conditions and explores how muon-based sensing might integrate with current subsurface systems, including utility corridors and buried water distribution networks.

To ground this conceptual design in plausible operational conditions, we consider where muon sensors could be placed within existing subsurface access points and maintenance workflows.

Manholes provide established access points to subsurface water infrastructure where muon sensors could be deployed without requiring new excavation or dedicated utility corridors. Leveraging these existing network nodes enables near-term, incremental deployment without requiring new utility corridors, facilitates piloting alongside routine maintenance activities, and reduces dependency on long-term urban redevelopment timelines. The strategic use of existing road-cut permits could further facilitate deployment in coordination with ongoing infrastructure work. Over time, extending InfraSense across additional segments of urban water infrastructure, such as wastewater, sewer, and water reuse systems, could enhance scalability and increase its relevance across municipal stakeholders and operational contexts within the urban ecosystem.

5.1 Privacy and Security

The design of InfraSense raises important privacy and security considerations due to the sensitive nature of the infrastructure data it would generate. Detailed, three-dimensional representations of underground water infrastructure could, if improperly accessed or misused, expose vulnerabilities in critical municipal systems. As a result, privacy and security must be addressed from the earliest stages of system design rather than treated as downstream implementation concerns.

InfraSense is therefore conceived with security-by-design principles in mind, emphasizing controlled access, protection against unauthorized use, and resilience against both cyber and physical threats. These considerations align with established guidance in the NIST Cybersecurity Framework [19], which emphasizes early identification of risks and the integration of protective measures throughout the system lifecycle. Considering adversarial risks during the conceptual design phase helps ensure that future implementations balance the benefits of enhanced infrastructure visibility with the responsibility to safeguard critical urban services and public trust.

5.2 Ethics and Governance

InfraSense is envisioned as a system that operates within clearly defined ethical and governance principles guiding data access, use, and decision-making. These principles are intended to promote fairness, transparency, and accountability as part of the system's conceptual design, shaping how insights derived from infrastructure data may inform public-sector action. The proposed governance model [20] adopts a systems-level perspective, emphasizing responsible use of data in ways that support community well-being, particularly in historically underserved areas.

The ethics and governance framework is structured around three core principles. Responsible data practices emphasize appropriate data stewardship and regulatory compliance, ensuring privacy and accountability throughout the system lifecycle. Transparent governance supports traceable and reviewable decision-making processes, helping align infrastructure actions with public interest and planning priorities. Equitable decision-making focuses on the fair distribution of insights across municipalities and agencies, with the goal of enabling timely infrastructure interventions in communities that have been historically under-resourced.

6 Contribution

The central contribution of this study is the conceptual framing of muon-based sensing as a distributed, real-time interaction mechanism for underground water infrastructure, situated within the broader context of emerging smart city systems. InfraSense presents a speculative yet technically grounded conceptual system design that integrates muon-based detection, ML-enabled analysis, and interactive three-dimensional interfaces to support anticipatory, human-in-the-loop decision-making across complex water infrastructure networks. By treating underground water infrastructure as an active civic interaction space rather than a passive technical substrate, this work proposes a pervasive sensing and interaction layer that supports coordination between automated analysis and municipal expertise at scale.

In addition, the study contributes an interdisciplinary synthesis that brings together perspectives from physics, infrastructure engineering, data science, and human–computer interaction to explore the implications of non-invasive sensing for water distribution networks. Rather than offering a feasibility assessment, the work provides insights into how muon-based sensing could enable continuous, distributed monitoring and real-time sensemaking in existing and future infrastructure contexts. These insights establish a foundation for future experimental studies, participatory design efforts, and pilot deployments, supporting both near-term exploration within existing built infrastructure and longer-term consideration within evolving smart city environments.

7 Conclusion

This work reframes underground water infrastructure as an interactional domain that can be engaged proactively rather than managed reactively. By articulating a conceptual system design grounded in non-invasive sensing and interdisciplinary insight, the study points toward new possibilities for how cities might monitor, interpret, and act upon conditions beneath the urban surface. More broadly, InfraSense highlights the potential of distributed, pervasive interaction paradigms to reshape relationships between infrastructure, data, and municipal decision-making. These perspectives invite future research and design exploration that further examine how emerging sensing technologies can support resilient, equitable, and sustainable urban infrastructure systems.

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