

Water leaks as a hidden risk to cultural heritage sites: application of the TEAMWIRE project and the geophysical challenges

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Abstract – One of the most critical threats to the preservation and conservation of archaeological heritage is the persistent presence of moisture within archaeological sites. Humidity, often caused by rising damp or hidden water leaks, contributes to material deterioration, structural instability, and the loss of valuable archaeological and architectural information. This issue becomes even more pressing when an archeological site is located near or above modern water and sewer pipelines. Preventive strategies aimed at mitigating this risk can significantly enhance the long-term in situ preservation of heritage sites. This paper presents the potential application of the TEAMWIRE project, which adopts an integrated geophysical approach to detect underground water and sewer leaks through the combined use of Ground Penetrating Radar (GPR), Time Domain Reflectometry (TDR), and GPS systems. This methodology is not only aimed at increasing the sustainability of water infrastructure, but also has significant potential in the context of cultural heritage conservation.

I. INTRODUCTION

Water leakage presents a significant and often underappreciated threat to archaeological sites and historical cities worldwide. These locations, many of which were never designed with modern water infrastructure in mind, are particularly vulnerable to the destructive consequences of uncontrolled moisture. Leaks can originate from aging pipelines, outdated plumbing systems, or inadequate drainage solutions – each exacerbated by climate change, urbanization, and rising groundwater levels. In historical cities with narrow streets and centuries-old buildings, even small water leaks can destabilize foundations, erode ancient masonry, and foster the growth of mold and vegetation, leading to irreversible structural damage. Chemical changes resulting from alteration of water flow routes or chemical inputs into the deposit (such as leaking sewers or water pipes) can

significantly affect archaeological preservation by modifying the redox conditions within the archaeological layers [1, 2].

In archaeological sites, where excavation and preservation often rely on stable environmental conditions, unexpected water infiltration can destroy delicate layers of soil and wash away irreplaceable artifacts or stratigraphy that provide crucial historical context. Although vast archaeological structures lie beneath towns and cities worldwide, limited attention has been given to how changing hydrological conditions affect these remains [1, 3]. The challenge lies not only in addressing existing leaks but also in detecting them early without disrupting the fragile architecture or altering the cultural landscape. This is where advanced monitoring technologies and efficient infrastructure solutions become critical.

Modern sensor networks, including fiber-optic cables, acoustic sensors, and satellite-based remote sensing, allow for non-invasive, real-time monitoring of water movement and pressure in urban and heritage settings. For example, acoustic leak detection technologies can identify the faint sounds of leaking water through solid structures, even in congested or built-up areas. These are increasingly paired with artificial intelligence (AI) algorithms to differentiate between benign background noise and genuine leak events. Although traditional acoustic methods – based on the propagation of mechanical waves – are capable of delivering good results in water leak detection, they are time-consuming, and their effectiveness in accurately locating leaks is influenced by several factors, including: the size, type, and depth of the pipe; soil characteristics and groundwater level; the type and size of the leak; system pressure; background noise; and the sensitivity and frequency range of the equipment [4, 5, 6]. In this context, Ground Penetrating Radar (GPR) and thermal imaging are increasingly used to map underground water flows and locate leakage hotspots, particularly in areas where excavation is either prohibited or risky.

Such technologies are invaluable in archaeological settings, allowing for precise interventions with minimal

physical impact on the site. Moreover, Internet of Things (IoT)-enabled systems can provide continuous data on moisture levels, water pressure, and structural health, enabling a proactive approach to water management and site preservation. To complement these technologies, integrated water infrastructure planning must be tailored to the unique needs of heritage environments. This involves replacing outdated or corroded pipelines with non-invasive trenchless technologies, installing permeable pavements to improve surface water drainage, and using smart valves that automatically shut off water in case of a detected leak. Historical cities like Rome, Istanbul, and Jerusalem have begun experimenting with such systems, balancing the dual demands of urban modernization and cultural preservation. In parallel, public-private partnerships and heritage conservation funds must be mobilized to ensure that sufficient financial and technical resources are available for implementing these advanced systems. Ultimately, the preservation of archaeological sites and historical cities in the face of water leakage depends on the intelligent fusion of traditional conservation methods with cutting-edge technology. By investing in advanced monitoring and infrastructure efficiency, we can mitigate the destructive impact of water leaks, prolong the life of ancient structures, and ensure that future generations inherit these invaluable testaments to human history. A strategic, data-driven approach – grounded in science, technology, and cultural sensitivity – is essential for protecting the past while navigating the challenges of the present and future.

II. THE PROJECT

The TEAMWIRE project (TEchnologies and Advanced Monitoring for Water Infrastructure and Resource Efficiency), coordinated by the University of Malta in collaboration with the Institute of Heritage Science (ISPC) of the Italian National Research Council (CNR), is a 24-month research and innovation initiative funded under the 2023 Call for Proposals for R&I Projects in the Fields of Energy and Water. The project aims to promote environmental sustainability by implementing innovative technologies capable of detecting underground leaks at an early stage. This approach not only helps to reduce water losses but also prevents potential structural damage caused by prolonged, undetected leaks.

TEAMWIRE addresses a major challenge faced by Mediterranean regions such as Malta, namely the need for cost-effective, non-invasive monitoring and maintenance of underground water and sewer networks. Factors such as water scarcity, aging infrastructure, and increasing urbanization demand new tools to reduce water losses while preserving surface and subsurface heritage.

Moreover, the project introduces the use of electromagnetic technologies – specifically Ground Penetrating Radar (GPR) – on a large scale for the first time in Malta, to detect leaks in sewer pipelines. These

advanced methods will contribute to the development of a prototype system for quality control within water and sewer networks, enabling frequent, remote, and continuous monitoring of network integrity.

Although the project's core objective focuses on enhancing the efficiency of water infrastructure, its technological approach holds significant potential for applications in archaeologically sensitive contexts. Water infiltration near or beneath archaeological sites can cause irreparable damage, especially in environments where rising damp or capillary action leads to moisture accumulation within walls, floors, and foundations, triggering salt crystallization and even microstructural collapse. The TEAMWIRE project introduces a monitoring strategy that supports early detection of such risks without invasive excavation, making it highly compatible with cultural heritage protection strategies. By adopting the TEAMWIRE protocol in such contexts, it becomes possible to apply a non-invasive monitoring system for early detection of hidden leaks before they reach critical levels, making it highly compatible with cultural heritage protection strategies and supporting preventive conservation and the safeguarding of archaeological sites.

This approach is especially suited to contexts where traditional excavation or intrusive inspection methods are prohibited, such as in museums, ancient churches, or open-air archaeological parks. The integrated use of GPR and TDR allows for high-resolution subsurface imaging and moisture profiling, while GPS ensures accurate georeferencing of findings for infrastructure mapping, risk assessment, and real-time monitoring of underground pipelines. Specifically, GPR – a non-destructive technique (NDT) – uses electromagnetic (EM) impulses to investigate subsurface conditions in archaeological sites and historic structures affected by moisture. It can be used to locate and evaluate the extent of damage and to support the development of restoration plans before irreversible deterioration occurs [7]. Furthermore, GPR facilitates rapid and non-invasive estimation of soil physical properties, supports advanced data interpretation, and provides valuable information on the materials investigated within archaeological and cultural heritage contexts [7].

The TEAMWIRE project introduces a highly modular and scalable system that surpasses current commercial technologies. Unlike traditional methods, which are slow and require experienced operators, the TEAMWIRE system enables near-instantaneous leak detection over long pipe segments - up to 10 km per day - thanks to its efficient data acquisition and processing capabilities.

The innovation lies not only in the integration of TDR and GPR but also in the automated decision-support platform that allows real-time visualization and analytics. This will help water utilities move toward predictive maintenance strategies and long-term infrastructure

planning.

III. METHODOLOGY

The integrated methodology proposed in this project aims to significantly reduce inspection times, increase accuracy, and lower operational costs compared to traditional leak detection methods, such as electro-acoustic surveys. This is achieved through the combination of hardware and software innovations. The hardware component consists of three main sensing modules: TDR, GPR, and GPS.

The TDR module is a low-cost and portable technology capable of detecting changes in the dielectric properties of the soil caused by water leaks. It consists of a portable instrument which interacts a low-cost elongated sensing element (up to 100 m long) usually buried with the pipe. One end of the sensing element remains accessible through a manhole or through an inspection well. The TDR module is able to localize leaks with an accuracy of less than 1 meter and is suitable for all pipe materials when paired with a buried sensing element, through which the signal generated by the TDR instrument propagates. For localizing the position of the leak, the operator connects the TDR instrument to the connection point.

The GPR module allows us to obtain a 3D subsurface image of the pipe and surrounding materials, thanks to the data acquired by moving the GPR system along the observation line. Moreover, it can discriminate the simultaneous presence of several pipes, even quite close to one another, and can also provide refined details on the geometric configurations. This method helps us to confirm the presence of leaks identified by the TDR and assessing the physical condition of the infrastructure.

Finally, the high-precision GPS module enables accurate geolocation of all measurement data, supporting detailed mapping and documentation of the inspection process.

The software component, custom-developed for the project, will manage data acquisition and allow real-time monitoring. It will be compatible with third-party sensors, enabling broader utility in various water management contexts.

IV. EXPECTED IMPACT

By the end of the project, TEAMWIRE is expected to achieve Technology Readiness Level 7 (TRL 7), meaning the proposed system will be demonstrated as a fully functioning prototype in a real-world operational environment. The impact of TEAMWIRE extends across several sectors: (i) for utility providers, the system offers a more efficient way to detect and repair leaks, which will help reduce water losses and cut operational costs; (ii) from an environmental perspective, early detection of leaks – especially in sewer pipelines – can significantly reduce groundwater contamination, contributing to the preservation of vital water resources; (iii) for policy

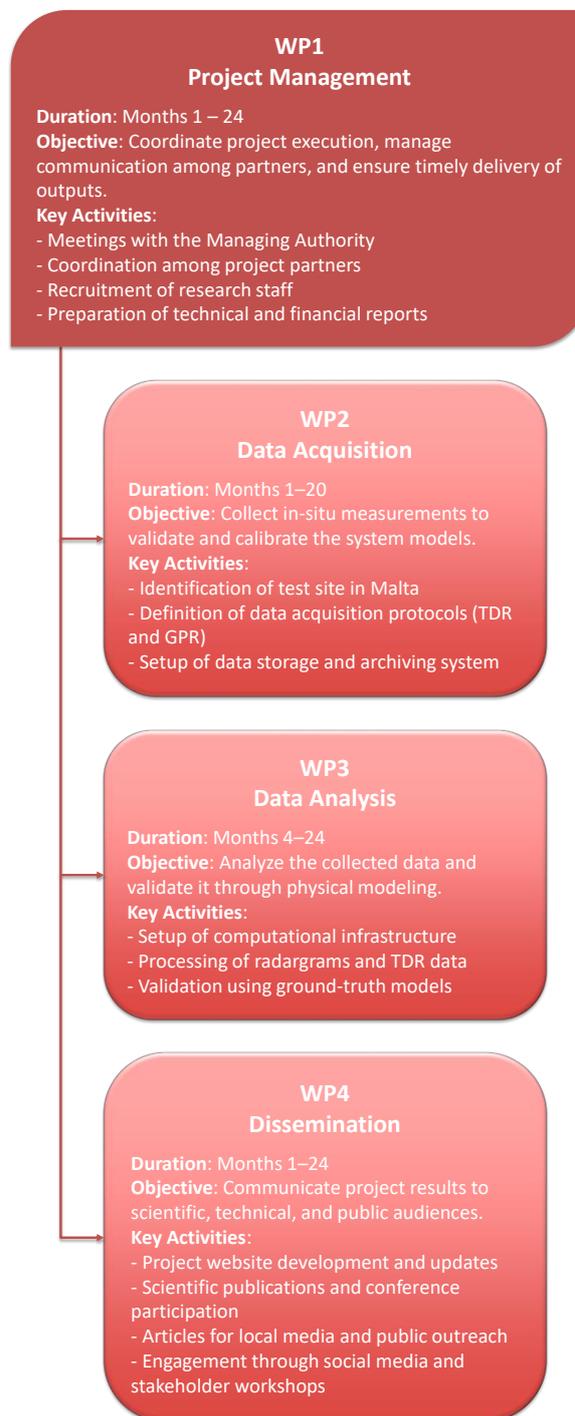


Fig. 1. Schematic overview of the Work Package structure and workflow.

makers, the project will provide new tools to support the development and implementation of leakage reduction strategies; (iv) for the research and industrial communities,

TEAMWIRE opens new opportunities for commercial exploitation and further investigation into scalable, smart monitoring technologies applicable to urban infrastructure systems.

To effectively achieve these objectives and reach TRL 7 by the end of the project, TEAMWIRE is structured into four interrelated Work Packages (WPs), each focused on a specific aspect of the development and implementation process (Fig. 1). This structured approach ensures that the project progresses in a coherent and efficient manner, from technical development to field validation and public outreach.

V. DISCUSSION

The integration of geophysical technologies, as demonstrated in the TEAMWIRE project, represents a promising advancement in the monitoring and maintenance of underground water and sewer infrastructures, particularly when these networks intersect with archaeologically sensitive areas. Traditional maintenance and detection methods, which often require invasive excavation, are typically unsuitable or outright prohibited in heritage zones. In contrast, the TEAMWIRE protocol combines Ground Penetrating Radar (GPR), Time Domain Reflectometry (TDR), and GPS technologies to detect early-stage water leaks in a non-invasive, continuous, and cost-effective manner.

Moreover, archaeological sites located above or near modern water and sewer pipelines may be affected by rising damp, material decay, and even structural instability when leaks remain undetected. These conditions are not only harmful to the physical integrity of the structures but also threaten the loss of valuable historical and archaeological information. The early identification of such issues through non-invasive techniques can prevent long-term damage, offering a proactive tool for managing both urban infrastructure and the protection of our archaeological past.

The ability to implement regular monitoring routines using geophysical methods offers clear advantages: minimizing the need for emergency interventions, reducing long-term maintenance costs, and, most importantly, preserving heritage sites from progressive degradation. In this context, the TEAMWIRE approach aligns closely with both sustainability goals and cultural heritage preservation strategies.

VI. CONCLUDING REMARKS

The future applications of the TEAMWIRE protocol on water and sewer pipes in areas of archaeological sites could significantly improve the preservation of cultural heritage. By preventing rising damp, condensation, and the propagation of leaks beneath historically significant structures, this technology addresses a critical yet often overlooked risk in archaeological conservation.

The TEAMWIRE protocol aims to support sustainable

water network management, reduce leakage rates, and enable proactive interventions that are particularly relevant in archaeologically sensitive environments where standard invasive methods are not acceptable. This integration of infrastructure monitoring with heritage protection reflects a broader shift towards interdisciplinary approaches in urban and environmental planning.

In this context, the city of Valletta – recognized as a UNESCO World Heritage Site – not only embodies exceptional historical and architectural value, but also presents unique conservation challenges due to its dense urban fabric and layered archaeological deposits. The implementation of the TEAMWIRE protocol in such environments could play a crucial role in preserving the city's cultural legacy, ensuring that interventions in modern infrastructure do not compromise the integrity of its heritage assets.

In conclusion, the deployment of non-invasive geophysical methods, as proposed in TEAMWIRE, represents a strategic solution for ensuring both the efficiency of water distribution systems and the long-term safeguarding of archaeological assets. The continued refinement and application of this protocol could establish a new standard for sustainable infrastructure management in cultural heritage contexts.

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