

iOLE—Human-Centered Software Design for Leakage Detection in Water Distribution Networks [†]

Ivo Daniel ^{1,2}, David Steffelbauer ³, Ella Steins ^{1,2}, Jonas Schorr ⁴, Sophie Persigehl ⁴, Enrique Campbell ³, Johannes Koslowski ³ , Jens Kley-Holsteg ⁵, Bernd Lindemann ⁵ and Andrea Cominola ^{1,2,*} 

¹ Smart Water Networks, Technische Universität Berlin, 10623 Berlin, Germany; ivo.daniel@tu-berlin.de (I.D.); steins@tu-berlin.de (E.S.)

² Einstein Center Digital Future, 10117 Berlin, Germany

³ KWB—Kompetenzzentrum Wasser Berlin, 10825 Berlin, Germany; david.steffelbauer@kompetenz-wasser.de (D.S.); enrique.campbell@kompetenze-wasser.de (E.C.); johannes.koslowski@kompetenz-wasser.de (J.K.)

⁴ Urban Impact Berlin GmbH, 10178 Berlin, Germany; jonas@urbanimpact.agency (J.S.); sophie@urbanimpact.agency (S.P.)

⁵ Gelsenwasser AG, 45891 Gelsenkirchen, Germany; jens.kley-holsteg@gelsenwasser.de (J.K.-H.); bernd.lindemann@gelsenwasser.de (B.L.)

* Correspondence: andrea.cominola@tu-berlin.de

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Abstract: Leakages in water distribution networks still pose major challenges to water utilities. Despite numerous technological advances, the adoption of digital leakage detection technology remains a slow process. Here, we present the project iOLE—intelligent Online LEakage detection, where we aim to increase the applicability of automated leak detection in practice through enhanced user experience and detection robustness. iOLE employs a human-centered design approach that involves the feedback of potential users during its development process to maximize subsequent user acceptance. To this end, we design a graphical user interface, combine model-based and data-driven leakage detection, and conduct a comprehensive robustness analysis.

Keywords: leakage detection; water distribution networks; human-centered design



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1. Introduction

With over 120 billion cubic meters of lost water per year globally, leakages in drinking water distribution networks (WDNs) continue to be a major challenge for water utilities, potentially resulting in various cascading effects, including operational disruptions, environmental hazards, property damage, and sanitary issues [1]. As a result, there has been an increasing focus on leakage management within the scientific community, leading to the development of numerous digital applications for leakage detection [2]. Existing solutions span from (i) *model-based* approaches that employ hydraulic models comparing simulated data to sensor data to (ii) *data-driven* approaches that analyze time series data using mathematical models, and (iii) *hybrid* approaches combining elements from both categories [3].

Despite these technological advancements, the practical approaches employed by water utilities still primarily rely on the use of in situ acoustic devices in combination with periodic water audits, altogether falling short of ensuring continuous system monitoring and leaving significant potential for further leakage reduction [3]. The adoption of leakage detection technology may further be hindered by a reluctance of water utility companies to introduce new and potentially risky technologies whose readiness levels and robustness have not yet been fully proven in an operational environment [4]. For instance, both model-based and data-driven approaches offer advantages and risks with respect to the

objectives of leakage detection and isolation, namely (i) a short time to detection (TTD) of any occurring leak, (ii) a low number of false positive (FP) detections, and (iii) accurate leak localization quantified as the distance between the detected leak location to its actual location. In the case of model-based approaches, more spatial information about the WDN is available through a hydraulic model; however, relying on a hydraulic model for leakage detection introduces additional uncertainties related to the input parameters of the hydraulic model itself and their calibration. Data-driven approaches, on the other hand, having merely access to sensor data and locations, may not be able to compete with the accuracy of model-based approaches—especially with respect to the leak location. While the recent BattLeDIM competition has aimed at comparing the performance of various algorithms on a benchmark dataset [5], we are unaware of any investigation that comprehensively and comparatively analyzes the robustness of both model-based and data-driven leakage detection approaches. Providing this information might further encourage more water utilities to uptake digital leakage detection technology.

Moreover, within the scientific context, the focus of any study mostly revolves around the functionality of the therein proposed methodology. However, a key aspect to a utility's decision for technology uptake lies in the usability of said technology, alongside its functionality and robustness. While user experience plays a central role in consumer-centered digital applications, we are unaware of any study that considers the effect of usability on the uptake of digital technologies in the water utility sector.

In this work, we introduce the project iOLE—intelligent Online LEakage detection. iOLE aims at developing a digital leakage detection software technology and dashboard that are practical and follow a user-centric approach, while accommodating for the greatest possible variety of utility settings. Here, we present the two main components of iOLE, i.e., (i) the robustness of model-based and data-driven leakage detection with a holistic approach, considering both aleatoric and epistemic uncertainties, and (ii) the user experience by active involvement of water utility companies in the co-development of our user interface through interactive workshops and feedback sessions.

2. iOLE—Intelligent Online LEakage Detection

Software development in iOLE is centered around three principles: (i) *user experience*, ensuring user acceptance of the software tool, (ii) *automation*, guaranteeing practicability during continuous application, and (iii) *integration*, focusing on meeting the technical requirements of utilities regarding functionality and robustness.

2.1. A Leakage Detection Solution Combining Model-Based and Data-Driven Leakage Detection and Isolation Algorithms

While both model-based and data-driven leakage detection and isolation methods carry individual advantages and disadvantages with respect to each utility-specific case study, their combined application may yield great benefits. By combining two award-winning leakage detection algorithms developed by our consortium in previous research, i.e., the data-driven leakage identification module of LILA [6] and the model-based dual model [7], we aim to simultaneously lower technical barriers and maximize leakage detection robustness. For instance, when a precise hydraulic model is available, accurate leakage detection may benefit from a model-based approach, while a data-driven approach is more effective when no hydraulic model is available or the uncertainties regarding its inputs are considerably high. Through the combination of both algorithms, iOLE can cover a wider range of scenarios, altogether increasing its applicability for a greater number of water utilities.

2.2. Robust Leakage Detection Through Global Sensitivity Analysis

With iOLE employing both model-based and data-driven leakage detection, it is essential to determine the robustness for both approaches to different scenarios and their inherent uncertainties. Ultimately, through this process, we aim to generate interpretable detection results that incorporate and leverage both approaches to the maximum.

In general, the abovementioned uncertainties can be subdivided into aleatoric and epistemic uncertainties [8]. Aleatoric uncertainties arise from the inherent randomness of the system. These uncertainties are typically irreducible and are characterized by their unpredictability. Epistemic uncertainties, on the other hand, are thought to be reducible when additional information becomes available. The classification in aleatoric and epistemic uncertainties depends on the context and application.

Within iOLE, we first build a hierarchical framework to comprehensively identify and classify the potential sources of uncertainty to leak detection (Figure 1). We then implement a global sensitivity analysis using Sobol' indices to determine the influence of each source of epistemic uncertainty (and their combinations) over the scenarios given by the aleatoric uncertainties on leak detection performance, ultimately assessing leak detection robustness.

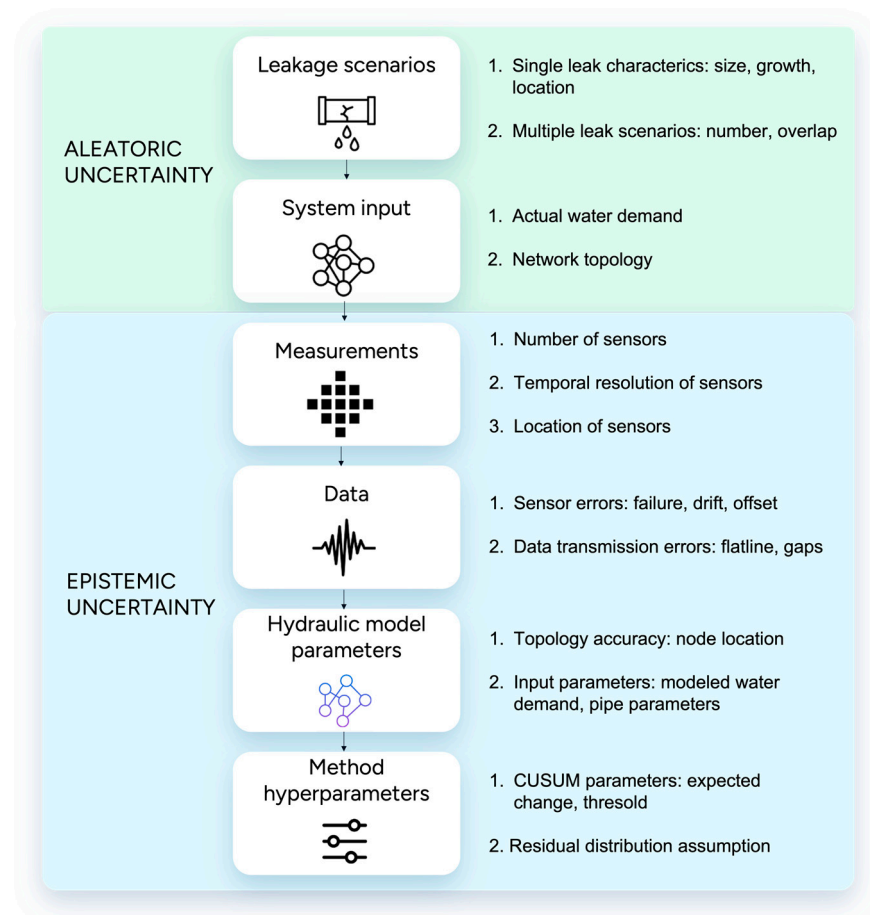


Figure 1. Hierarchical framework for classification of uncertainty sources and robustness analysis of leakage detection in water distribution networks.

2.3. Human-Centered Software Design: User Experience and Feedback

To further increase the applicability of iOLE solutions through increased user acceptance, we focus its software development on a human-centered design approach by incorporating the concept of user experience. This approach involves feedback loops with utility operators enacted in workshops and audits throughout the two-year project development. As a first step in the human-centered software design, we conducted a comprehensive market analysis among water utilities in Germany, identifying their com-

pany size, infrastructure size, and current leakage monitoring system. This analysis helps identify suitable stakeholders to be involved in co-design workshops and to gain a broad overview of the current status quo of the technologies currently used by water utilities.

A central aspect to improving the user experience within iOLE is the development of a dashboard with a graphical user interface (GUI) that enables the user to visualize iOLE's detection results as efficiently as possible to support further decision-making regarding the most effective deployment of technical and maintenance personnel. Furthermore, we conceptualize an automated program flow that minimizes manual interaction for data preparation, algorithm calibration, and final leak detection, while simultaneously ensuring maximum compatibility with existing utility assets. Both aspects are subject to evaluation within the stakeholder workshops.

3. Outlook

The iOLE project presented in this paper aims to increase the applicability of digital leakage technology by increasing the user experience and detection robustness. During the two-year development process, we are continuously involving stakeholders from the water sector within organized workshops, focusing on maximizing subsequent user acceptance of the developed software. As part of the funding program Digital GreenTech established by Federal Ministry of Education and Research (BMBF) in Germany, we ultimately aim at publicly releasing the iOLE software in an open-source format.

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