

A 24/7 Cloud-Hosted Solution Evaluation for Anomaly Detection and Localization of Large-Scale Water Distribution Networks in Singapore [†]

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Abstract: In this study, a novel cloud-hosted software solution, titled as Anomaly Leak Finder (ALF), has been developed in collaboration with PUB, Singapore's national water agency, to enhance leak detection and localization in four major water distribution networks (WDNs) in Singapore. The large networks which span over 1000 km of underground pipelines are monitored 24/7 with 90+ smart sensors. Leveraging on near real-time hydraulic time-series data, ALF employs data-driven prediction (DDP) and physics-based simulation (PBS) models to minimize the total non-revenue water (NRW) losses by detecting and localizing hidden pipe leak events before they become disruptive events.

Keywords: smart water grid; anomaly detection and localization; water distribution networks; hydraulic model calibration; deep learning



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1. Introduction

In today's era of advanced water management, the efficient operation of water distribution networks (WDNs) is critical to ensure sustainable resource utilization. This is particularly evident in urban contexts, where the demand for water is high and the need to minimize non-revenue water (NRW) losses is paramount. In collaboration with PUB, Singapore's national water agency, a novel and pioneering cloud-hosted software solution, titled as Anomaly Leak Finder (ALF), has been developed to detect and localize hidden pipe leaks in four major WDNs in Singapore which span over 1000 km of underground water pipelines and are equipped with over 90 smart sensors, enabling 24/7 monitoring of hydraulic parameters such as flow, pressure, tank water level, and pump flow.

This paper presents the integrated solution embedded into ALF that empowers PUB engineers to leverage daily monitoring hydraulic data to perform proactive leak detection and localization in the near real-time (NRT) context. By employing novel data-driven prediction (DDP) models and physics-based simulations (PBSs), anomalies in flow and pressure dynamics are swiftly detected and clustered to form system events as indicative of hidden pipe leaks in the underground water pipelines. By performing daily model updating and calibration, ALF ensures that the baseline predictions from DDP and PBS models align closely with the observed hydraulic data to minimize the number of false-positive events. Besides detecting hidden leaks, ALF also enables PUB engineers to identify and mitigate various anomalies early, including data offsets, anomalous pressure due to

water usage changes, and sensor failures. Holistically, ALF technology will continue to evolve over time by assimilating the engineering inputs from all stakeholders involved in the daily monitoring of the WDNs in Singapore. In the following, an overview of ALF's tech-knowledge will be presented, followed by sharing the recent NRT evaluation of ALF to detect and localize hidden pipe leaks in the month of February 2024.

2. ALF Tech-Knowledge

Digital-twin establishes the tech-knowledge foundation for ALF [1] by having both DDP and PBS models to monitor the daily operations of the WDNs in Singapore and providing feedback to the engineers on their level of synchronization over time. The DDP models primarily leverage on the Extended Kalman Filter Deep Belief Network (EKF-DBN) technique to perform 24 h forecast of the flow and pressure dynamics in the modelled networks to detect the following types of anomalies:

- **Data offset:** A constant deviation between the 24 h prediction and monitored hydraulic time-series profiles, where the minimum deviation is at least 0.5 m. See Figure 1a for an example.
- **Anomalous pressure behavior:** Correlation between the 24 h prediction and monitored hydraulic time-series profiles is less than 70%; this behavior could be due to sudden change in the local water usage pattern. See Figure 1b for an example.
- **Network operational change:** Uninformed operations taking place in the network due to emergency events causing sudden flow variations across the entire network. See Figure 1c for an example of a sudden increase in the tank outflows into the modelled network.
- **Hydraulic outlier event:** Low-pressure or high-flow outliers detected by at least a single sensor installed in the network, as indicative of a likely hidden pipe leak event. See Figure 1d for an example of detecting low-pressure outliers at the local station level.

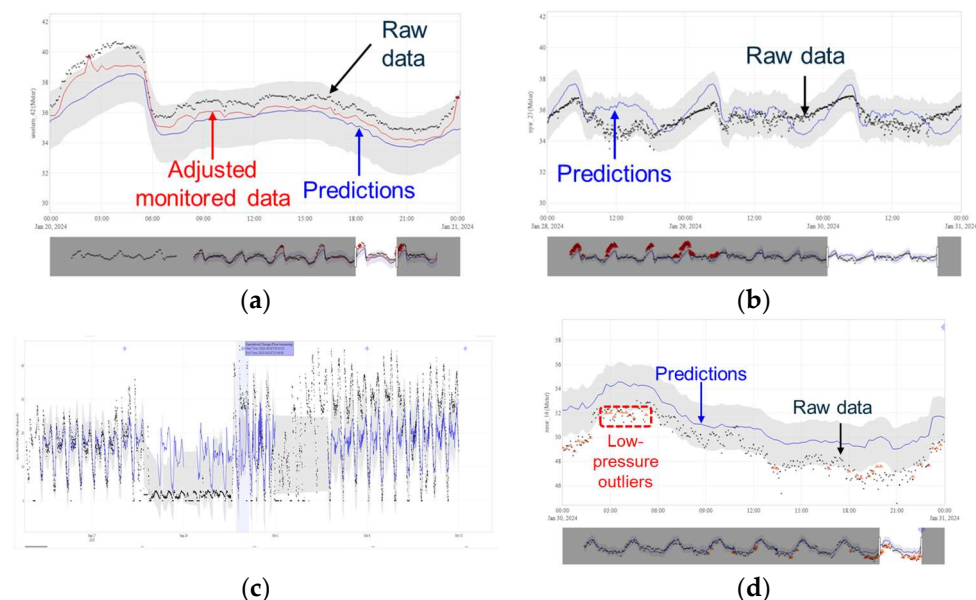


Figure 1. Types of anomalies detected by the ALF solution in the NRT context: (a) data offset, (b) anomalous pressure behavior, (c) network operational change, and (d) hydraulic outlier event.

Daily, the PBS models assimilate the NRT operational data which include, but are not limited to, pump operational statuses, tank stock levels, and any recorded boundary flows into the modelled system that is monitored by PUB's operational team. Automatic updating of the baseline hydraulic model will then be performed after the above-mentioned data assimilation in the NRT context, where the tank and pump outflows will be re-calibrated to model the most representative flow dynamics in the modelled network [2]. Figures 2a and

2b, respectively, illustrate the reasonably good fit obtained between the simulated and the associated monitored flow profiles for the tank outflow and pump outflow in Zone 3 of the pilot study in Singapore for a recent arbitrary period in Jan 2024.

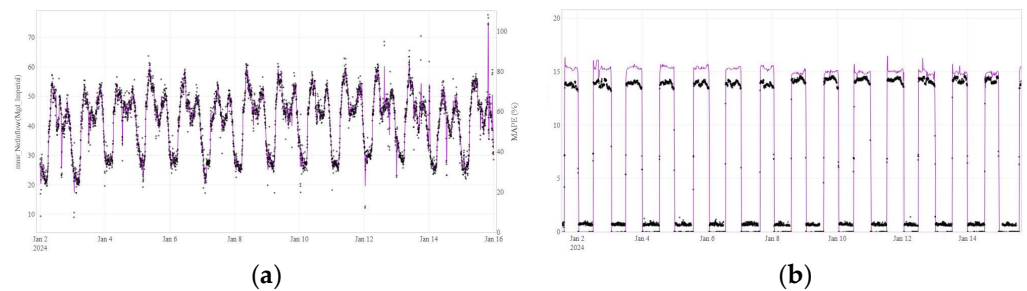


Figure 2. Daily model re-calibration of different flow dynamics: (a) tank outflows into the network and (b) pump outflows inside the network.

Overall, the hydraulic model re-calibration process on a daily basis ensures that the PBS model can adequately represent the hydraulics of the modelled network in the NRT context and complement the daily baseline predictions by the DDP models for the same hydraulic parameters. The advantage of this complementary process, as part of digital twin fidelity, will be demonstrated in the next section.

3. ALF NRT Evaluation

Likewise, on a daily basis, the corresponding performances for the PBS and DDP models, as measured by the mean absolute percentage error (MAPE) or mean absolute error (MAE), are tracked and then reported for the corresponding network zones (Zones 1–4) in Singapore. Figure 3a–d illustrate the distribution of the MAPE scores for Zones 1–4 for the month of February 2024. It can generally be observed that both PBS and DDP are in close synchronization in the NRT context, in terms of the percentage of modelling results in the three main categories of good (<5%), fair (5–10%), and bad (>10%) MAPE ranges.

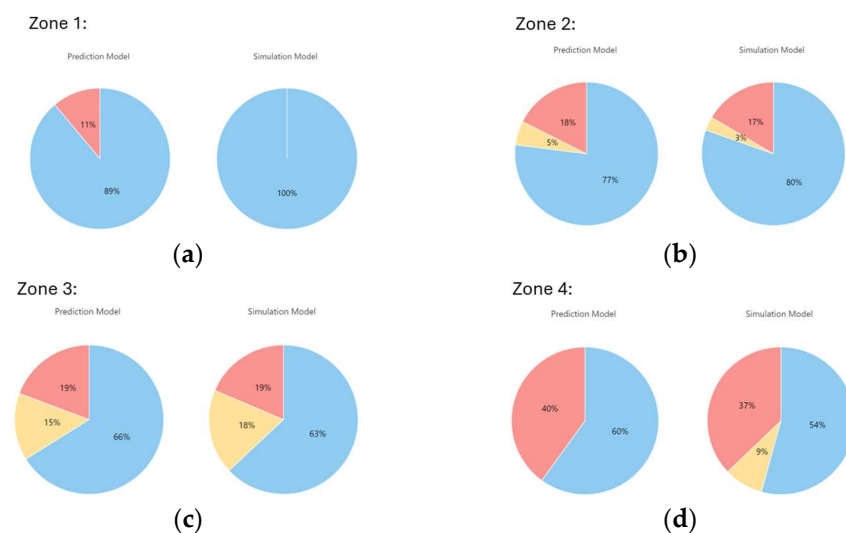


Figure 3. Distribution of MAPE scores for respective modelled zones in Singapore for Feb 2024: (a) Zone 1, (b) Zone 2, (c) Zone 3, and (d) Zone 4. Note different colors represent different MAPE ranges: blue, <5%; yellow, 5–10%; red, >10%.

The following describes an actual example of using both the PBS and DDP models to detect and localize a true hidden leak event in the Zone 3 network of the pilot study in Singapore. Figure 4a shows that both models complement each other by detecting low-pressure outliers during the time range between 30 and 31 January 2024. PUB's field

team were then informed of the alert to investigate the localized hotspot pipelines which are within 500 m pipeline distance from the detected pressure station. In mid-February 2024, PUB's field team then confirmed that they discovered the hidden leak source (see Figure 4b), which is around 220 m pipeline distance from the detected pressure station, hence resulting in a detection lead-time of almost two weeks.

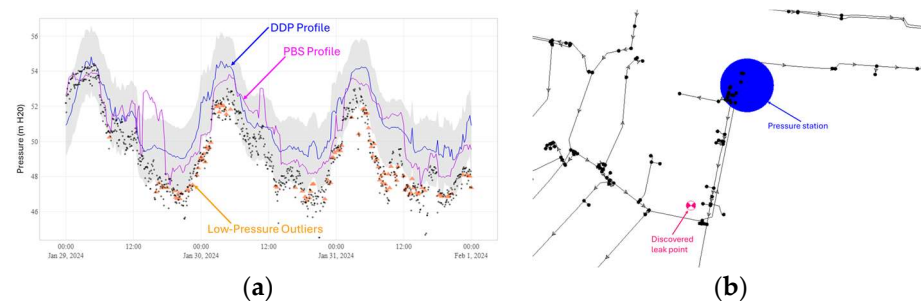


Figure 4. Actual example of detecting and localizing a hidden leak source in the NRT context in Singapore's Zone 3 network using both DDP and PBS models: (a) detection of low-pressure outliers and (b) localization of the leak point causing detected low-pressure outliers.

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Conflicts of Interest: Authors Alvin Wei Ze Chew, Ashley Zhang, Fred Cao, Rony Kalfarisi, Xue Meng and Jocelyn Pok was employed by the company Bentley Systems Singapore Pte Ltd. Author Zheng Yi Wu was employed by the company Bentley Systems Inc. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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