Development of an Intelligent Framework for Leak Detection and Localization in Water Distribution Systems

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1.1 Executive Summary

Date: October 17, 2023
Applicant: California State University, Fresno
Applicant city, county, and state: Fresno, Fresno County, California
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Applicant Category: Category B

California State University, Fresno (Category B) proposes this project in partnership with the City of Lakewood, CA (Category A), and TagoIO Software Company. **The main objective of this project is to develop a comprehensive framework for leak detection and localization in water distribution systems.** Specifically, we want to apply our expertise to first: analyze and detect anomalies from hydraulic and simulated data due to the presence of a leak in the system. Second: we want to test different clustering techniques to determine an optimal sensor placement that yields the most representative hydraulic and quality measurements related to leak detection and localization. Third: we aim at using the sensors' information to apply a deep learning approach to localize leaks at different spatial resolutions. The partners of this project have expressed their interest in working together to provide hydraulic network data (City of Lakewood, CA) and software tools (TagoIO) for real-time data processing, visualization, and analysis. **This project will focus on advancing the knowledge of leak detection and localization using measured and simulated hydraulic parameters by:** (1) analyzing the measured data sets reported by Advanced Metering Infrastructure (AMI) devices and comparing them to simulated hydraulic data to improve the different types of anomalies affecting the current leak detection applications, (2) evaluating different clustering applications to identify the layout that optimizes leak localization results, (3) using hydraulic and quality data sets to evaluate their performance in identifying leaks, and (4) applying the results from the previous steps to feed an existing deep learning neural network to train the measurements with and without the presence of leaks. The proposed steps form a comprehensive framework that will undergo testing with our utility partner. Moreover, any water company interested in enhancing its water distribution system management and operation can implement this framework to achieve substantial improvements in water supply reliability and drought management activities to reduce losing potable water due to leaks.

Federal funds are primarily requested to support personnel for model/tool application tasks and test the products using water utility measured and simulated data, and project dissemination. Non-federal cost-share contributions are committed by the applicant organization California State University, Fresno. This project is in accordance with the requirements published by the Bureau of Reclamation's Notice of Funding Opportunity - section C.4.2. Eligible Project Types, **1. Modeling:** modeling tool projects should be for the improvement of water supply reliability, and **3. Data:** eligible projects may include improvements to data analysis.

Project length and completion date:
Two years from June 1, 2024 to May 31, 2026.

Federal Facility:
The proposed project is not located in a Federal Facility.

1.2 Technical Project Description

1.2.1 Applicant Category

California State University, Fresno (CSUF) (Category B) in partnership with the City of Lakewood (Category A) plans to apply a comprehensive leak detection and localization model to improve the water supply reliability in drinking water distribution systems. CSUF is a university located in California, acting in partnership with the agreement of the City of Lakewood. The City of Lakewood is located in the state of California and is a local authority whose members include an organization with water delivery authority, defined as a Category A applicant by the current Notice of Funding Opportunity. A letter from the City of Lakewood, CA confirming the partnership with CSUF and agreeing to the content of this application is attached as Exhibit 1.

1.2.2 Detailed Project Description

Municipal Water Distribution Systems (WDSs) are responsible for supplying potable water to their serving communities. Due to the aging conditions of the water infrastructure, significant amounts of water can be lost when potable water flows from the production to the consumption points. Extreme climate change events pose an increasing burden to the operation of these aged water systems to maintain adequate service levels while reservoirs decrease due to prolonged droughts. In the western United States, droughts can last for months and water managers constantly promote water conservation plans and seek more efficient water usage (Bolorinos et al., 2020; Klasic et al., 2022). Accurate modeling of WDSs as hydraulic networks represents real-world conditions. As part of the management and operation of WDSs, identifying and localizing the presence of leaks is critical to saving potable water. Consequently, applying an existing framework that consists of two main components, leakage identification, and localization, represents a fundamental necessity for climate-constrained drinking water distribution systems.

Despite extensive research on model-based and data-driven approaches for leak detection, there are limiting factors preventing the wide adoption of a procedure to find leaks and reduce non-revenue water (NRW) in water systems. Among these factors, water utilities are hesitant to deploy sensors across the network that may provide crucial information for leakage management. Furthermore, some utilities that have installed a considerable amount of sensors, do not leverage the full potential of this information due to mainly the inaccuracies produced by the presence of noise in the data acquisition systems (e.g., malfunctioning, vandalism, uncalibrated equipment). The proposed project aims at filling the following gaps found in the recent literature on leak detection and localization:

(a) Analysis of Noise Effects on Measured Data: most research works have modeled the presence of noise using a probability density function sample to affect simulated data. While this approach may provide a general understanding of the leakage models in the presence of noise, more research is needed on the sources of noise and its corresponding effects in identifying leaks in water systems.

(b) The Inclusion of Time of Leaks: a key component of a comprehensive leak detection and localization framework must include the start time of leaks. The project will identify and apply an anomaly detection framework to the leak identification stage.

(c) Optimal Sensor Placement: the geographic location of sensors and heuristic optimization techniques dictate most of the information retrieved from sensors. There is a need to apply different clustering techniques to simulate-optimize the sensors' coverage and customize this method by testing different networks' topological and hydraulic characteristics.

(d) Additional Hydraulic and Quality Data Sets: pressure and flow rate are the two most common measurements presented in the literature for the analysis of no-leak and leak scenarios. However, the project will include additional hydraulic and quality values to analyze their effects on leak identification and localization models.

Accurate outputs from the hydraulic model are critical information for utility operators and planners. However, inaccuracies in the reported measured data are part of the equipment and data acquisition systems. To obtain accurate values, hydraulic models should be fed with reliable real-time data, including flow rate at the reservoirs' entrances and exits, pressure from valves connected across the system, pump characteristics, storage tank levels, and water quality values.

1.2.3 Goals

The project's main objective is **to apply a comprehensive framework for leak detection and localization in water distribution systems (Figure 1).** Specifically, we aim at using existing models as part of a framework to analyze reported gaps in the literature about the (i) optimal sensors' location, (ii) anomaly detection analysis to identify the start time of one and multiple simultaneous leaks, (iii) noise analysis in measured data, and (iv) application of a deep neural network using measured and simulated hydraulic and quality data to forecast and identify no-leak from leak scenarios.

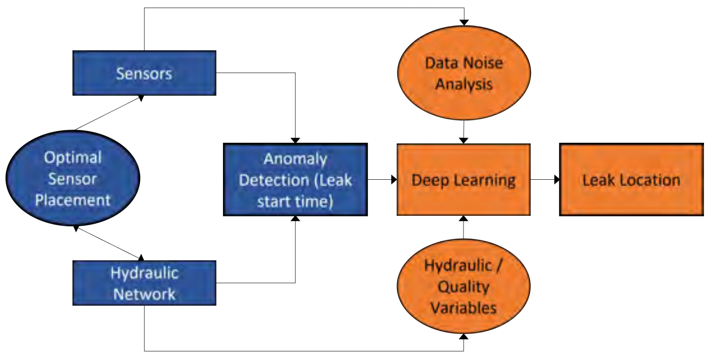
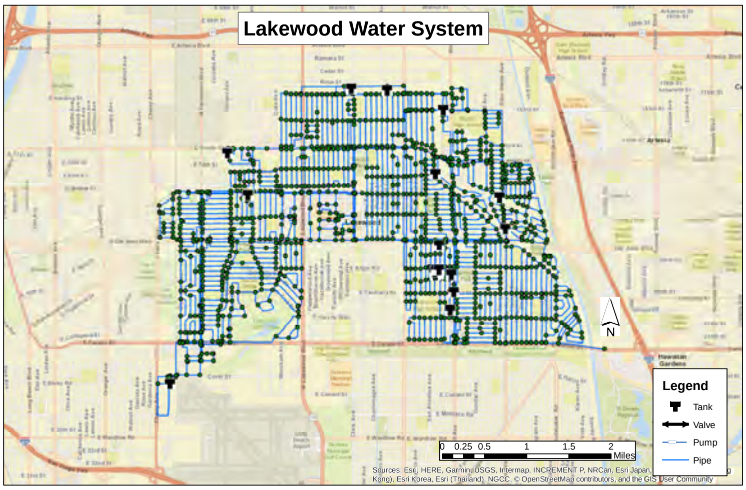


Figure 1: Proposed Leak Identification-Localization Framework

1.2.4 Project Location

The project focuses on weather-constrained water distribution systems. Historically, California has suffered from severe drought periods. Hence, we have partnered with the City of Lakewood, CA (Figure 2a) to develop and test our leak identification and localization framework on their water distribution system (Figure 2b).

(a)



(b)

Figure 2: (a) City of Lakewood, California, and the United States; (b) City of Lakewood water distribution system.

1.2.5 Data Management Practices

The input hydraulic models are connected to GIS databases that accurately represent the geographic location of the water network components. Any spatially explicit data or model will be developed in industry standard formats. Our team is also committed to fostering open access to the models that result from the project. The team has experience working with open-source programming languages, such as Python and the Water Network Tool for Resilience (WNTR) package (Klise et al., 2018), which are the two main components of the model. Furthermore, the developed models will be useful for any water distribution system that has a hydraulic model and sensors installed in the network.

The input data needed to test our models are owned by the City of Lakewood, California. However, the proposed models can also use synthetic data to evaluate their performance. Consequently, researchers and practitioners can use our models with their own data sets or synthetic inputs to test the capabilities of our leak detection framework.

1.3 Evaluation Criteria

1.3.1 Evaluation Criterion A - Water Management Challenge(s)

A.1. Describe the water management challenge(s). Describe in detail the water management challenge is occurring within your project area. Describe the severity of the challenge to be addressed with supporting details. For example, will your project address water supply shortfalls or uncertainties, the need to meet competing demands for water and the lack of reliable water supplies for municipal, agricultural, tribal, environmental or recreational water uses, complications arising from drought, conflicts over water, or other water management issues?

During the last ten years, the State of California and most of the Western USA have faced severe and prolonged drought events that have triggered multiple municipal water conservation programs. Some conservation policies enforced by water utilities in Southern California included restrictions on outdoor watering to reduce the per capita consumption from 125 to 80 gallons per day. While these conservation policies aimed at alleviating the problem immediately, **the presence of leaks in water systems across California is a major problem for utilities as losing potable water may exacerbate the effects of extreme weather events on the available water resources.** Decreasing the volume of water lost due to leaks has been proven to help the long-term management and operations of water distribution systems (WDSs) worldwide. A recent study found that it is feasible to reduce water losses by 34.7% (A. Rupiper et al., 2022). **Our project will benefit water utilities in California with the development of a leak identification and localization framework.** The presence of leaks in WDSs is the main source of water losses, pipe-bursting events, and potential sources of contamination. The management challenge to be addressed by this project is the identification and localization of background leaks, which due to their size, are not visible and pose a serious burden to the WDS supply reliability. Therefore, a comprehensive leakage management program implemented by water utilities in California will provide a valuable management tool for finding leaks and reducing non-revenue water.

A.2. Describe the concerns or outcomes if this water management challenge is not addressed?

The aging conditions of water infrastructure make the components of water distribution systems prone to bursts and background or invisible leaks. **The volume of non-revenue**

water in a constrained climate environment, especially affecting the Western USA, will continue to grow and may become a problem that prevents water utilities to supply potable water at adequate pressure and quality conditions to their customers. Furthermore, losing hundreds of gallons of potable water due to leaks also affects the financial sustainability of water utilities as losing potable water will inflate non-revenue water reports.

A.3. Explain how your project will address the water management issues identified in your response to the preceding bullet. In your response, please explain how your project will contribute to one or more of the following water management objectives and provide support for your response: a. water supply reliability for municipal, agricultural, tribal, environmental or recreational water uses, b. management of water deliveries, c. water marketing activities, d. drought management activities, e. conjunctive use of ground and surface water, f. water rights administration, g. ability to meet endangered species requirements, h. watershed health, i. Restore a natural features or use a nature-based feature to reduce water supply and demand imbalances, the risk of drought or flood, or to increase water supply reliability for ecological values, j. conservation and efficiency, or k. other improvements to water supply reliability.

Our project will use real-time data and a hydraulic model to test leak identification and localization methods. **The project will improve water management by *a.* supporting water supply reliability for municipal uses by identifying and reporting the location of leaking pipes.** When detecting the presence of leaks, the water utility can deploy its crews to find and replace damaged pipes. The project outcomes will provide an immediate effect on reducing the volume of potable water lost to leaks. Furthermore, the project will provide a model that can be continuously used by the water utility, improving its *j.* conservation and efficiency activities. The application of this project can alleviate ongoing conservation campaigns launched by water utilities during prolonged droughts. A leak management program may also allow water utilities to serve as role models for customers to promote water conservation actions and improve the efficiency of the potable water delivery process.

We will implement a framework consisting of modules that work sequentially to identify and localize leaks in water distribution systems. Each module is described as follows.

(i) Optimal Sensor Placement: application of a previously developed clustering algorithm (Pesantez et al., 2019; Pesantez, Berglund, & Kaza, 2020) to maximize the hydraulic coverage of the sensors installed in the hydraulic network.

(ii) Anomaly Detection Analysis: the project will analyze measured data to pinpoint the presence of one and multiple simultaneous leaks. The output of this step is the start time of the leaks.

(iii) Noise Analysis: to evaluate the robustness of our method, we will analyze different sources of noise that affect measured data reported by the sensors.

(iv) Deep Neural Network (DNN): our project will implement a Convolutional Neural Network (CNN) as part of a DNN architecture to obtain the geographic area of the distribution system where leaks may exist and report their magnitude.

Identifying leaks is a crucial step to improve the water supply reliability of a water system. Based on recent estimates, leak management may cost $277/acre-feet to US water utilities, which is considerably lower than other water management practices

(A. Rupiper et al., 2022). This project will develop a comprehensive leak detection framework that can be used by any water utility. Therefore, in an effort to find leaks, managers can apply the model with their own hydraulic/quality measurements and hydraulic network to get a better idea about the presence and location of leaking pipes. Even if some water utilities have yet to install sensors across the network, they can leverage the Optimal Sensor Placement module of the project to evaluate several scenarios with simulated data.

1.3.2 Evaluation Criterion B - Project Benefits

B.1. Describe how the need for the project was identified. Was the proposed project identified using a collaborative process with input from multiple and diverse stakeholders?

The City of Lakewood, CA has expressed its interest to collaborate with our research efforts. Located in Southern California, Lakewood has been greatly affected by the long-lasting drought events that constantly hit California and the southwest. Prolonged droughts in the West pose a burden on the reliability of water distribution systems and utilities are forced to implement aggressive conservation policies. Therefore, the water utility wants to implement our research products to improve its water system efficiency. The City of Lakewood will participate in this project by providing its hydraulic network and sensor measurements which are the backbone for testing our models.

The City of Lakewood, CA master plan recommended in 2017 that the city may consider the application of a leak detection approach (https://www.lakewoodcity.org/Government/City-Documents/Water-Department-Documents). It was also reported that 89% of the recorded pipeline breaks occurred in pipes with a 4" diameter. In most water systems, pipe breaks are the result of small leaks that increased with pressure and flow rate fluctuations and heavy continuous traffic. Therefore, a leak identification and localization framework that focuses on small-size leaks is of utter importance to improve water system reliability.

B.2. Describe how the tool, method, or information will be applied and when will it be applied.

- Will the tool or information be used immediately or will additional work need to be done before the tool will be used?

  The leak identification and localization framework will be readily available for water resources managers. The tool includes codes that use the hydraulic network and sensors' measurements as the only input needed for computation. No additional work is needed for the tool to be used.

B.3. Describe, in detail, the extent of benefits that can be expected to occur upon implementation of the project, and provide support for your responses.

- Who will use the tool or data developed under this proposal and how will they benefit from the project? Support could include but is not limited to letters from stakeholders expressing support for the project and explaining how they will benefit.

  The results will be readily available for the City of Lakewood, CA. The City of Lakewood can use and continuously improve the model by adding sensor measurements. Identifying leaks may reduce the volume of non-revenue water and prevent bursts from happening due to the pressure fluctuations and aged conditions of water infrastructure. Letters of support are included at the end of the document.

- How will the project improve water management decisions?

Water utilities bear a significant cost in repairing pipe bursts, which disrupt the regular functioning of drinking water systems and put a financial burden on the utility (A. Rupiper et al., 2022). Our leak detection model can aid water managers in identifying background leaks in specific regions of interest. **This model can assist water managers in replacing pipes that have minor or background leaks before they burst due to the pressure fluctuations of the water distribution system.** It can also help water managers allocate resources to decrease the number of leaks in their system, while also reducing the volume of non-revenue water.

- Describe if the results of your project will be applicable elsewhere. What additional work would need to be done to make the project results transferable to others?

  The framework proposed in this project will also be available to other water distribution systems that can analyze their networks with their own hydraulic and quality measurements or with simulated data to evaluate the potential applications of our model. Our framework will provide guidance on how to input data for other interested water managers. While the framework can be used elsewhere, the unique conditions of each water distribution system may yield different results and additional work would focus on those system-specific characteristics. Also, water managers elsewhere can use a generic version of the model with their own water system and synthetic hydraulic and quality values to get a better idea of their system conditions.

- To what extent will the project address the water management challenges described in E.1.1.?

  The extent of the application of our project can be objectively quantified by comparing the volume of non-revenue water prior to and post-leak detection implementation. Our model identifies the presence of leaks and reports the geographical area where the leaking pipes may be found. Once our results are discussed with the water utility, they can plan pipe-replacement activities. Once the replacement is performed, the utility may update its non-revenue water volume. We envision that with a continuous application of our model, new leaks will be found, and the water distribution system may improve its overall operation.

B.4. Explain how your project complements other similar efforts in the area where the project is located. Will your project complement or add value to other, similar efforts in the area, rather than duplicate or complicate those efforts? Are there other similar efforts in the area that have used a similar methodology successfully which can be complimented? Applicants should make a reasonable effort to explore and briefly describe related ongoing projects. Consider efforts by any Federal, state, local agency, or non-governmental organizations.

The proposed project complements previous research on leak identification and localization through the development and application of novel models to be tested by the City of Lakewood, CA water network. A recent analysis of water lost to leaks in the state of California highlighted that leak identification and localization as part of water loss reductions must be conducted with utility-specific data (A. Rupiper et al., 2022). Furthermore, our work adds value to previous research projects (Soldevila et al., 2022; Basnet et al., 2023) by developing an optimal sensor placement method, including different sources of noise on the measured data, and the effects of water quality values on the leak detection framework.

Several recent studies have shown the potential for leak reduction as a management tool for water utilities. California is leading the efforts to report water losses and plan for leak management practices across the United States (A. M. Rupiper et al., 2021; A. Rupiper et al., 2022). However, there is yet a need for models that use real hydraulic and measurement conditions. We propose to use a water network from Southern California to test our leak identification and localization framework. Our work will provide water utilities with a framework that can be implemented as part of their leak management strategies.

Ongoing Efforts on Leak Detection: A Brief Review

As water infrastructure ages, the volume of water lost due to leaks and bursts threatens the reliable service of potable water to our communities. Multiple research works have reported the capabilities of model-based analysis to pinpoint the area where a leak may be present. This approach allows utilities for effective planning by decreasing the search area before crew deployment (Puust et al., 2010; Gupta & Kulat, 2018; Hu et al., 2021). Leakages in water systems cause multiple adverse effects on WDS operation. Researchers also propose multiple data-driven models where the analysis focuses on hydraulic measurements reported by data acquisition equipment of different-magnitude leaks (Wu & Liu, 2017; Soldevila et al., 2022; Tariq et al., 2022). To consolidate multiple models using the same hydraulic network and data sets, the Water Distribution Systems Analysis research community launched a worldwide competition: the Battle of the Leakage Detection and Isolation Methods (BattLeDIM) (Vrachimis et al., 2022). Researchers and practitioners presented their solutions to find the start time and location of leaks on a water system based on simulated hydraulic measurements and a hydraulic network (L-Town). The dataset presented in the BattLeDIM included hydraulic measurements (e.g., pressure and flow rate) reported by multiple sensors, which do not represent the current status of most water networks worldwide that prefer deploying water quality over hydraulic sensors (Liu et al., 2019; E. Z. Berglund et al., 2020). The solution presented by the team led by PI Pesantez was awarded third place (Daniel et al., 2022; Vrachimis et al., 2022). Hence, we want to build on top of those methods to test our models using real data from the City of Lakewood, California.

Recent approaches have applied deep neural networks for leak detection (Guo et al., 2021; Jun & Lansey, 2023) and localization (Soldevila et al., 2022; Basnet et al., 2023). The vast majority of used deep neural networks consist of Convolutional Neural Networks (CNNs). In general, CNNs use hundreds of simulated pressure and flow rate as the input data to train a model with a defined output, such as the normalized residuals between observed and measured data. The models use a "no-leak" and a "leak" scenario to calculate these residuals as the difference between those two conditions. Then, the supervised learning methods aim at finding the network location responsible for the discrepancy between measured and simulated hydraulic data.

Pressure and more recently flow rate has been widely used by researchers to solve this inverse engineering problem for leak localization (A. Berglund et al., 2017; Basnet et al., 2023). However, there are gaps in the literature about the analysis of **water quality values** in the presence of leaks. Also, there are multiple limitations listed by researchers about the leak localization step including the definition of candidate areas or nodes and more importantly, **the application of these methods to real water distribution systems.**

1.3.3 Evaluation Criterion C - Project Implementation

C.1. Briefly describe and provide support for the approach and methodology that will be used to meet the objectives of the project. You do not need to repeat the full technical project description included in Section D.2.2.4 under the Technical Project Description. However, you should provide support for your chosen methodology, including use of any specific models, data, or tools.

Based on the identified gaps described in the "Ongoing Efforts on Leak Detection: A Brief Review" subsection, our project will apply a framework for leak identification and localization in water distribution systems. The framework comprises multiple sequential modules including: 1) the application of a previously developed optimal sensor placement based on clustering analysis (Pesantez, Berglund, & Mahinthakumar, 2020); 2) an anomaly detection analysis that uses measured hydraulic and quality parameters (Palla & Tayeb, 2021)) (leak identification); 3) the analysis of different sources of noise in measured data; and, 4) the application of a classifier using deep neural networks for localizing the geographic area where leaks occur (leak localization). The chosen methodology is described below.

The application of the leak identification and localization framework largely depends on the information reported by sensors. Sensor placement should be identified such as the hydraulic coverage of each sensor is maximized. We plan to use a clustering method, i.e., the K-means clustering algorithm (kMCA) previously applied by PI Pesantez for the creation of District Metering Areas in water systems (Pesantez et al., 2019). kMCA will identify the centroids of each cluster as the points in the system where the hydraulic coverage is maximum. Then, the clusters' centroids will be used for sensor placement locations. Although the centroids' location may not match the actual location of the sensors, the analysis will still assess the impact of sampling hydraulic parameters as if the sensors were situated in the identified centroids.

In the proposed novel end-to-end model, a synergistic integration of leak diagnosis and anomaly detection is achieved, harnessing the power of adaptive fusion techniques. This sophisticated framework combines two crucial components, namely anomaly detection and leak diagnosis, in a cohesive and dynamic manner. Anomaly detection plays a pivotal role in safeguarding the model's integrity against erroneous assessments when encountering unknown anomalies. This capability ensures that the system remains resilient and avoids the perilous pitfall of misclassifying unknown anomalies as benign. By effectively discerning and distinguishing these anomalies, the model is expected to achieve an exceptional level of discernment and adaptability in its decision-making process. On the other hand, leak diagnosis empowers the end-to-end model to delve even deeper into the intricacies of the system's behavior. Through this diagnostic capacity, the model can ascertain the precise nature and typology of the encountered system leak. This sophisticated analysis provides invaluable insights into the underlying issues that may be affecting the system's performance, enabling targeted and precise troubleshooting strategies to be employed.

The analysis of the sources of noise in the measured data is among the novelties of our work. As recently highlighted by Basnet et al. (2023), the inclusion of a comprehensive noise analysis including different probability density functions may improve leak localization methods by providing a wide range of training data to the supervised learning step explained below. As the presence of noise in measured data is unavoidable, its analysis and modeling provide valuable tools for a comprehensive leak detection framework.

A deep neural network (DNN) will be applied to train on hundreds of simulated hydraulic and quality values. We will use the well-known EPANET (US EPA, 2020) software to simulate pressure, flow rate, and quality values with different demand patterns. The simulated data along with the previously defined clusters will feed a DNN to perform binary classification as normal and abnormal events (Pesantez et al., 2022). Abnormal events may be due to the presence of leaks. Once an abnormal event is identified, DNN's output reports the cluster where the abnormal event occurs. The cluster represents the leak's possible geographical location.

C.2. Describe the work plan for implementing the proposed scope of work. Such plans may include, but are not limited to: a. an estimated project schedule that shows the stages and duration of the proposed work, b. milestones for each major task, c. start and end dates for each task and milestones, and d. costs for each task

Planned Work

Our project will apply a framework for leak identification and localization in water distribution systems. The framework comprises multiple sequential modules including the application of an optimal sensor placement analysis (Task 1), an anomaly detection analysis (Task 2), and the application of a deep neural network with the inclusion of noisy data for leak localization (Task 3).

Task 1: Optimal Sensor Placement

This task will use graph theory and hydraulic modeling to find the optimal clustered configuration that maximizes the hydraulic coverage of a defined number of sensors. The clustering approach presented in Pesantez et al. (2019) and Pesantez, Berglund, & Mahinthakumar (2020) will be applied to partition a water distribution network into a fixed number of clusters. The k-means clustering algorithm (kMCA) will be applied to group nodes using different surrogate nodal distances calculated as shown in Equation (1).

$$d_k = \alpha x_k + \beta y_k + \gamma z_k \tag{1}$$

where α, β, and γ are the weighting coefficients of the different hydraulic, geometric, or quality values (x, y, z) of link k to be evaluated in the sensor placement optimization process; d_k is the surrogate nodal distance that will be used by (kMCA).

The objective function to be optimized is the pressure variation among clusters. Minimizing the variation in pressure across clusters has a twofold effect. If a water network has deployed few sensors, the analysis from some clusters can be extrapolated to those that lack sensors. Second, a more uniform pressure distribution will make the pressure drop more visible due to leaks. Hence, the optimization will follow Equation (2).

$$Minimize\ CVP = \frac{\sqrt{\frac{1}{N_{Clusters}-1}\sum_{i=1}^{N_{Clusters}}(P_i - P_{avg})}}{P_{avg}} \tag{2}$$

where CVP is the coefficient of variation of pressure among clusters; $N_{Clusters}$ is the number of clusters that will be evaluated based on the number of sensors and the network's size; P_i is the average pressure of nodes within the i_{th} cluster; and P_{avg} is the mean of the average pressure across all clusters.

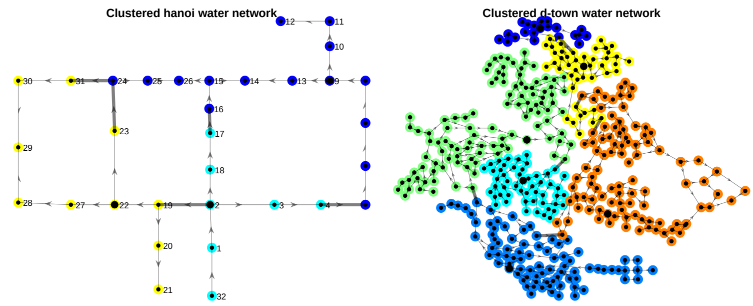
Once the clusters are defined, the sensors will be placed at each cluster centroid. Figures 3a and 3b show a previous implementation of the clustered-based approach for demand similitude with the Hanoi and D-town water networks (Pesantez et al., 2019).

Task 2: Anomaly Detection Analysis

The proposed end-to-end model capitalizes on a cohesive interplay between anomaly detection and leak diagnosis, where the former serves as a protective shield against unknown anomalies, and the latter serves as a powerful investigative tool to discern and classify the specific type of system fault. This seamless integration bestows the model with a profound understanding of the system's health, enhancing its overall robustness, adaptability, and efficacy.

Task 3: Application of Deep Neural Networks

Artificial neural networks (ANN) as supervised learning algorithms for classification problems have been recently used in leak detection problems. As presented in Pesantez, Berglund, & Kaza (2020) for forecasting methods, ANN can effectively learn the patterns of non-linear



(a) (b)

Figure 3: Hydraulic network partitioned into clusters to determine the sensor placement at each cluster centroid for the (a) Hanoi and (b) D-town water networks.

input data to predict the correct output. Furthermore, ANNs can be enhanced by the implementation of deep neural networks, specifically, Convolutional Neural Networks (CNN), where multiple kernels define the best weight values in the learning process (Samek et al., 2021). Instead of a fully connected neural network where all inputs are connected to the nodes in the hidden layers, CNN uses multiple pooling layers to analyze each input data point prior to feeding the hidden layers (Figure 4). The convolution process reduces the number of parameters and improves the neural network accuracy (Gu et al., 2018).

The input data comprises the simulated hydraulic and quality parameters such as pressure, flow rate, and water quality. The size of the input arrays depends on the number of sensors; hence, the project will evaluate a different number of sensors to improve the CNN output. The variable of interest is represented as the residual or the difference between simulated and measured or observed data. A noise analysis using different probability density functions will be performed to improve the neural network performance. The method uses a common split ratio of 70:30 to train and test the data set.

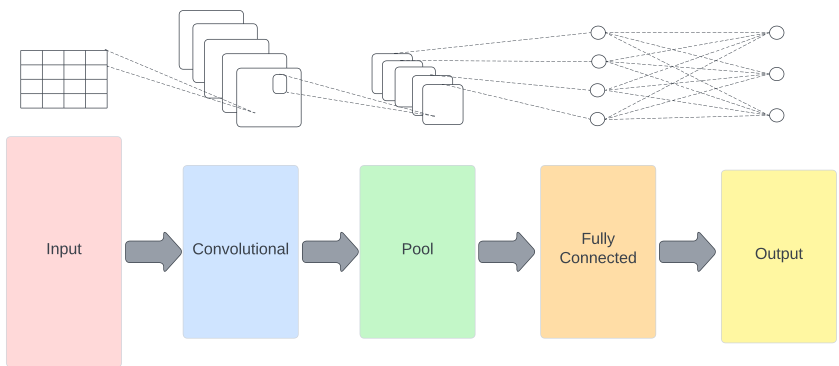


Figure 4: Convolutional Neural Network (CNN) architecture. Convolutional layers apply multiple filters to the input variables to find the optimal hyperparameters. Then, the pooling layer reduces the size of the convolutional output by sub-sampling. Finally, the pooling layer output is fed into a fully connected neural network for classification purposes.

Project Timeline

The team will work together to sequentially complete the proposed framework. PI Pesantez will be responsible for managing the project and delivering outcomes. The team will meet monthly to assess the tasks conducted and plan accordingly the next activities. The team will specifically evaluate the milestones described in this document at the end of each quarter. The total duration of the project is two years. The timeline for the entire project is shown in Table 1.

The project includes tangible milestones that are detailed below to ensure the timely development of the leakage identification and localization framework.

(i) Optimal Sensors Location: analysis of different nodes based on clustering techniques to identify distinct locations that yield more discernible observations due to the presence of leaks.
Milestone 1: Multiple sensors' location and quantity that yields the most accurate leak identification and localization results.

(ii) Anomaly Detection Analysis: the simulated and observed hydraulic and quality data will be used to train an anomaly detection model to identify the start time of one and multiple simultaneous leak events.
Milestone 2: A list of the start times for all leak events to be studied in the hydraulic network testbeds.

(iii) Noise Analysis: the application of different modeling techniques to add and evaluate the effects of different types of noise on the simulated hydraulic and quality data.
Milestone 3: A graphic and tabular description of the different types of noise added to the simulated data.

(iv) Deep Neural Network: exploratory analysis of multiple deep neural network architectures trained with different combinations of observed and simulated hydraulic and quality values.
Milestone 4: A deep neural network architecture to localize leaks using historical or simulated hydraulic and quality values.

The estimated timeline with start and end dates for each task and milestone of this project is presented in Table 1. The project will include three meetings with an initial kickoff and two workshops with the beneficiary (water utility) for transferring-knowledge activities. The final product of this project is an open-source model available via accessible repositories like GitHub.

Table 1: Estimated Project Schedule, Tasks and Costs

Project Task	Year 1				Year 2				Cost ($)*
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
Task 1: Optimal Sensor Placement	■	■	■						$14,000
Task 2: Anomaly Detection Analysis			■	■	■				$12,000
Task 3: Noise Analysis		■	■	■					$6,000
Task 4: Deep Neural Network Application and MCS				■	■	■	■		$24,000
Kick-off meeting and Information Transfer	■				■			■	$1,000
Final Report and Manuscript(s)						■	■	■	$6,000

* Tasks costs were determined as an approximation of time required by senior personnel.

C.3. Provide a summary description of the products that are anticipated to result from the project. These may include data, metadata, digital or electronic products, reports, and publications. Note: using a table to list anticipated products is suggested.

Table 2: Description of the anticipated products.

Item	Anticipated Products Description	Format
Optimal Sensor Layout	The geographic location to place sensors that maximize hydraulic coverage for leak identification and localization	Map document (GIS)
Start time and duration of abnormal events	Time stamps when abnormal events occurred and their estimated duration	Database (xlsx)
Noise analysis of measured data	A model to evaluate the presence of noise in data measurements	Python script (py)
Leak(s) location	The geographic areas within the water network that contains one or multiple leaks	Map document (GIS)
Leask identification and Localization Model	The complete framework that compiles each module to identify and localize leaks	Python script (py)

C.4. Who will be involved in the project as project partners? What will each partner or stakeholder's role in the project be? How will project partners and stakeholder be engaged in the project and at what stages? If you are a Category B applicant, be sure to explain how your Category A partners will be engaged in the project.

We plan to apply an existing sequential model for leak identification and localization using data from our partner, the City of Lakewood. The City of Lakewood's role in this project will include sharing data from pressure and flow rate sensors and an updated version of the water system's hydraulic model. The outputs and findings of this project will be informed to the City of Lakewood for their expert opinions and recommendations.

C.5. Identify staff with appropriate credentials and experience and describe their qualifications. Describe the process and criteria that will be used to select appropriate staff members for any positions that have not yet been filled. Describe any plans to request additional technical assistance from Reclamation or via a contract. Please answer the following:

C.5.a. Have the project team members accomplished projects similar in scope to the proposed project in the past either as a lead or team member?

Jorge E. Pesantez, Ph.D. is an Assistant Professor in the Department of Civil and Geomatics Engineering at California State University, Fresno. He has worked on the modeling and simulation of water distribution systems and data analysis of water and energy demands. His scientific contributions have been selected as the Editor's choice of the month by the ASCE Journal of Water Resources Planning and Management. Pesantez led a team formed by faculty from TU Berlin, Germany, and US researchers that developed "LILA: a comprehensive Leak Identification and Localization Analysis framework." LILA ranked third in a worldwide competition on leakage management organized by the Water Distribution Systems Analysis Committee (https://battledim.ucy.ac.cy/) (Daniel et al., 2022).

Shahab Tayeb, Ph.D. is an Associate Professor of Electrical and Computer Engineering, holding various industry certifications in networks and cybersecurity. His research utilizes deep learning frameworks to detect anomalies. He has authored 50+ refereed research papers, and his research findings have been highlighted by local, regional, and national agencies, including the National Science Foundation. He has also been the recipient of several scholarships and national awards, including a US Congressional Commendation for STEM mentorship.

Fayzul Pasha, Ph.D., PE. As a Professional Engineer and Professor in Water Resources Engineering, Dr. Pasha's work focuses on quantitative analysis in water resources planning and management specifically in energy–water nexus. During nineteen (19) years of his research and professional career, Dr. Pasha has developed numerous models and performed different quantitative analyses for sustainable decision making in integrated water resources management especially in the fields of water distribution systems, hydropower planning, water conservation, energy efficiency, efficient use of water in energy generation and distribution, ecosystem restoration, and agricultural water and drainage management. Dr. Pasha uses statistical methods, numerical techniques, optimization theories, geoprocessing (GIS), and machine learning approaches for model development and analysis. Dr. Pasha has earned his Ph.D. from the University of Arizona and authored more than 90 technical articles. He can be reached at 559-278-2464 or by email at mpasha@csufresno.edu.

The project team will collaborate with the City of Lakewood, California to test the leak identification and localization models. Mr. Michael Santillan will be the point of contact and our main collaborator at Lakewood. The data needed to test our models include a hydraulic model of the water distribution system, pressure, flow rate, and water quality data collected from sensors and data acquisition equipment across the network. The transfer of knowledge activities will have the participation of Lakewood and other interested water utilities.

C.5.b. Is the project team capable of proceeding with tasks within the proposed project immediately upon entering into a financial assistance agreement? If not, please explain the reason for any anticipated delay.

Yes, the team is capable of developing the project as defined in the project timeline.

1.3.4 Evaluation Criterion D - Dissemination of Results

D.1. Describe how the tools, frameworks, or analyses developed under the proposed scope of work will be disseminated, communicated, or made available to water resources managers who may be interested in the results.

- If the applicant is not the primary beneficiary of the project (e.g., universities or research institutes), describe how project results will be communicated to project partners and interested water resources managers in the area.

  The products of this project will be communicated to the partners using two types of channels. For results that use network-specific data, we will share those results using a protected sharing drive. The models trained with synthetic data and their corresponding documentation will be uploaded to two open main repositories: Zenodo and GitHub. Zenodo will be the repository for the reports and documents we prepare with preliminary results. GitHub will host all the scripts developed in this project. Communications with our stakeholders are also planned for the transferred-knowledge activities of this project as shown above. We will hold one kickoff meeting and two workshops with the City of Lakewood, California to receive input about the model outputs and provide details about the use of the models. In addition to the described communication activities, we plan to present the results of our project at scientific conferences at the regional and national levels. The results of this project will also be published in peer-reviewed journals.

- Describe how the project results will be shared with other water managers in the West that could use the information to support water management objectives.

  We will present the results of the project at two venues. The first one is the American Society of Civil Engineers Environmental and Water Resources Institute (EWRI) summer meeting. The second one is the American Water Works Association Water Infrastructure annual conference. We foster open-source platforms for our codes and models. The model and synthetic data will be readily available to water managers via an open repository.

1.3.5 Evaluation Criterion E - Presidential and Department of the Interior Priorities

Please address only those priorities that are applicable to your project. It is not necessary to address priorities that are not applicable to your project. A project will not necessarily receive more points simply because multiple priorities are addressed. Points will be allocated based on the degree to which the project supports one or more of the priorities listed, and whether the connection to the priority(ies) is well supported in the application.

- E.O. 14008 emphasizes the need to prioritize and take robust actions to reduce climate pollution; increase resilience to the impacts of climate change; protect public health; and conserve our lands, waters, oceans, and biodiversity.

  - If applicable, describe how the project addresses climate change and increases resiliency. For example, does the project help communities respond to or recover from drought or reduce flood risk?

    Leak detection is one of the key challenges affecting water supply reliability. The proposed framework provides water utilities with a tool to localize leaks and prevent potable water from being lost due to leaks. As part of the resiliency of water systems, it is of utter importance that water distribution systems managers apply leakage management strategies to not only minimize water losses but prevent contamination of the system due to the low pressures generated by the presence of leaks. The proposed project will assist water managers to improve the overall functioning conditions of their water systems.

- How will the project build long-term resilience to drought? How many years will the project continue to provide benefits? Please estimate the extent to which the project will build resilience to drought and provide support for your estimate.

  Conservation efforts are key responses to the prolonged droughts that affect the entire country and specifically, Western USA. A leak detection framework based on current metering infrastructure technologies (e.g., smart meters, pressure, and quality sensors) and computing technology (eg., complex neural networks) is a perfect fit to build a portfolio of long-term resilience strategies. Furthermore, as machine learning methods use vast amounts of data to train, the extent of the proposed project can be improved in time with additional historical data. Lastly, as mentioned by current works (A. Rupiper et al., 2022), identifying and localizing leaks is an essential tool to build resilience for our water systems.

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TagoIO

August 29, 2023

Tago LLC
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Jorge E. Pesantez
Assistant Professor of Civil Engineering
Department of Civil and Geomatics Engineering
California State University Fresno
2320 E. San Ramon Ave.
Fresno, CA 93740

Re: WaterSMART Applied Science Grant

Dear Dr. Pesantez,

TagoIO is fully supportive of working with partners such as California State University Fresno to provide our platform for the visualization stage of the proposal "Development of an Intelligent Framework for Leak Detection and Localization in Water Distribution Systems." To that end, TagoIO, a company that specializes in supporting the development of IoT using its IoT cloud platform, will make available to the California State University Fresno team of researchers our web platform for six months, which represents an estimated amount of $ 5,400 as an In-Kind contribution to this project.

We look forward to collaborating with the California State University Fresno team in this and other projects related to water resources management.

If you have any questions, please contact me at customersupport@tago.io.

Sincerely,

Fabio

Fabio Rosa

CEO , TagoIO

fabioer@tago.io

(269) 281 6214

August 17, 2023

Jorge E. Pesantez
Assistant Professor of Civil Engineering
Department of Civil and Geomatics Engineering
California State University Fresno
2320 E. San Ramon Ave.
Fresno, CA 93740

Re: WaterSMART Applied Science Grant

Dear Dr. Pesantez,

I am writing this letter to express our enthusiastic support to participating in the prospective proposal from the California State University Fresno Department of Civil and Geomatics Engineering titled, "Development of an Intelligent Framework for Leak Detection and Localization in Water Distribution Systems." We firmly believe that this project holds immense potential in revolutionizing leak detection in water distribution systems and thereby ensuring the reliability of potable water across the Western United States.

As representatives of the City of Lakewood Water Utility, we recognize the significance of this project and its potential impact on water utilities. To that end, we are fully dedicated to providing the necessary input data from our water distribution system. We understand the importance of such data in the development of an applicable and effective tool for leak detection, and we are committed to contributing our resources to ensure the success of this endeavor. Moreover, we are eager to actively participate in the development of this project by offering valuable technical feedback based on our extensive experience and knowledge in the field. Our input will be aimed at making the project readily adaptable to a diverse range of water distribution systems and their unique operational conditions. We firmly believe that our collective expertise will play a pivotal role in shaping the outcome of this project and bringing practicality to the proposed framework.

If you have any queries or require further information, please do not hesitate to reach out to me directly at (562) 866-9771 ext. 2701 or via email at dnguyen@lakewoodcity.org. Our team is eager to collaborate and contribute to this essential initiative in any way possible.

We are looking forward to being an integral part of this project and driving positive change in the water industry. Thank you for considering our participation.

Sincerely,

Derek Nguyen, Ph.D., P.E.
Director of Water Resources

Budget Narrative

Table 1.—Summary of Non-Federal and Federal Funding Sources

FUNDING SOURCES	AMOUNT
Non-Federal Entities	
1. Fresno State In-kind Match	$ 56,220
2. Fresno State Match - Indirect Costs	$ 22,489
3. TagoIO Third Party Match	$ 5,400
Non-Federal Subtotal	$ 84,109
REQUESTED RECLAMATION FUNDING	$ 83,824

1. Salaries and Wages

All labor rates proposed represent actual labor rates of the identified personnel with an anticipated 4% annual increase for faculty.

A. Key Personnel Salary

$70,885 ($36,742 Federal funding, $34,143 Cost share)

- PI/Project Manager Dr. Pesantez requests 7% effort/year for a total of $26,140 request funding with $13,070 federal funding and $13,070 cost sharing. Dr. Pesantez will work on the project year around, direct the program, and mentor one graduate and one undergraduate student to accomplish associated tasks and dissemination of research outputs.
- Co-Investigator Dr. Tayeb requests 3% effort/year for a total of $14,187 request funding with $7,004 federal funding and $7,183 cost sharing. Dr. Tayeb will work on the application of anomaly detection analysis and will also contribute to the writing of the project results. Dr. Tayeb will also mentor one graduate and one undergraduate student to accomplish anomaly detection tasks and dissemination of research outputs.
- Co-Investigator Dr. Pasha requests 6% effort/year for a total of $30,558 request funding with $16,668 federal funding and $13,890 cost sharing. Dr. Pasha will work on the application of Monte Carlo simulation with hydraulic modeling and will also contribute to the writing of the project results.

B. Other Personnel Salary

$10,720 ($10,720 Federal funding)

- Two graduate students to be named for hourly work as research assistants for 80 hours per year per student at $20.00/hour, with a total of $6,400 request funding. The graduate students will learn advanced hydraulic modeling and data analysis to identify abnormal points in the time series data.

- Two undergraduate students to be named for hourly work as research assistant for 60 hours per year at $18.00/hour, with a total of $4,320. request funding. The undergraduate students will work on literature review, data collection, running hydraulic models, and writing project reports.

2. Fringe Benefits

$25,990 ($3,913 Federal funding; $22,077 Cost share)

- Fringe benefits include all mandated federal and state/local payroll taxes, such as FICA, Workers‟ Compensation, Unemployment Insurance, and Medicare. Additional benefits for salaried employees include health, vision, dental, and life insurance, and may include optional 401K contribution. Fringe benefits are billed at the actual current rate for the Fresno State employees while rates for new hires are billed at the Foundation's current rates for Foundation employees. Fringe benefit rates for this grant are fringe benefits are charged at 68% for PI Pesantez, 54% for Co-PI Tayeb, and 65% for Co-PI Pasha for year 1 and 69%, 55%, and 67% for year 2 for faculty. all other faculty summer pay and stipends—10%; all student research assistants—2.23%.

3. Travel Costs

$5,000.00 (Federal funding)

- Domestic travel costs are included for one trip per year for PI Pesantez or other project members to present results at the American Society of Civil Engineers Environmental and Water Resources Institute Summer Conference, or the CSU Water conference. Each 5-day trip is budgeted at $2,500.00 to cover conference registration ($500.00), abstract fees ($100.00), airfare and ground transportation ($700.00), hotel (4 nights at $250.00), and per diem (4 days at $50.00). The total cost for each year is $2,500.00, and total cost of $5,000.00.

4. Equipment

None.

5. Supplies

None.

6. Contractual

Software developer consultant: $50.00/hr x 20 hour = $1,000.

$1,000.00 (Federal funding)

One consultant will be hired to assist with the implementation of the graphs and visualization of results with the water utility as needed. The consultant will use the web platform provided by TagoIO. We have conducted a preliminary price analysis and found average fees for graph-based developers are $50 per hour. The estimate would spend 20 hours of consultant work focused on the development of the visualization of hydraulic output data using the TagoIO web platform.

7. Construction

None.

8. Other

$7,900.00 ($2,500.00 Federal funding; $5,400.00 Cost share)

Publication fee: $2,500.00 is requested to pay for the open-access publishing fee to the ASCE Journal of Water Resources Planning and Management, AGU Water Resources Research, or IWA Journal of Hydroinformatics.

TagoIO Consulting Firm: $5,400.00 ($0.00 Federal Funds, $5,400.00 cost share)

The project budget includes in-kind services from a private consultancy firm. TagoIO Consulting offered its web platform for up to six months to the project to create visualization and data presentation of the project's output. Please refer to the attached document for the corresponding letter of commitment.

9. Direct Costs

$116,095 ($59,875 Federal funding; $56,220 Fresno State Cost share)

10. Indirect Costs

$46,438 ($23,950 Federal funding; $22,488 Fresno State Cost share)

11. Federal Funding Requested: $83,824

12. Total Fresno State Cost Shared Committed (including Third Party In-Kind): $84,109

13. Total Project Cost: $167,933

September 8, 2023

Jorge E. Pesantez
Assistant Professor of Civil Engineering
Department of Civil and Geomatics Engineering
California State University Fresno
2320 E. San Ramon Ave.
Fresno, CA 93740

Re: WaterSMART Applied Science Grant

Dear Dr. Pesantez,

This letter is to provide you with a quote for the visualization stage of your project "Development of an Intelligent Framework for Leak Detection and Localization in Water Distribution Systems," using the Tago web platform.

My work as a software developer will consist of creating visualizations with water demand, pressure, and flow rate data. To that end, the cost of my services ascends to $1,000.00 (one thousand dollars) to be paid with the reception of the developed product.

Let me know if you have any questions.

Sincerely,

Michael Skarbek
Software Developer