Modelling Approaches for Contamination Detection in Drinking Water Distribution Networks: A Comprehensive Review

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Abstract: Ensuring the safety and integrity of drinking water distribution networks is paramount for public health and well-being. With the increasing complexity of urban infrastructure and emerging threats, the need for robust contamination detection systems has become imperative. This review paper presents a comprehensive overview of modelling approaches for contamination detection in drinking water distribution networks. We categorize the literature based on the theoretical frameworks, computational methodologies, and practical applications employed in this field. The types and sources of contaminants are discussed and highlighting the diverse nature of potential threats to water quality. The study of modelling frameworks utilized for contamination detection, including deterministic and stochastic models, network hydraulics, and water quality simulations are carried out.. The mechanisms governing contaminant transport within distribution networks, elucidating the factors influencing dispersion and propagation are reviewed. Furthermore, the sensor placement optimization strategies are explored for maximizing detection coverage and minimizing response time. This review provides a comprehensive synthesis of modelling approaches for contamination detection in drinking water distribution networks, serving as a valuable resource for researchers, practitioners, and policymakers striving to safeguard public health and water security.

***Key words**: Drinking water, contamination, water distribution network, modelling.*

1. Introduction

1.1 Importance of water quality on human health

Every man, woman, and child have the human right and necessity to have access to clean water to drink and basic sanitation. (Millennium Development Goal) To preserve their health and dignity, people require access to clean water and proper sanitation. Better access to water and sanitation is crucial for ending the cycle of poverty since it enhances people's capacity to work, attend school, and maintain good health. (CAWST, 2009)

Water quality plays a vital role in human health, affecting various aspects of well-being and functioning. Here are some key points highlighting the importance of water quality on human health. Access to clean and safe drinking water is fundamental for maintaining health. Contaminated water can contain harmful microorganisms, chemicals, heavy metals, and other pollutants that can cause a range of waterborne diseases such as cholera, typhoid, dysentery, and gastroenteritis. Water is essential for transporting nutrients throughout the body and aiding in digestion and metabolism. Contaminated water can compromise nutrient absorption and contribute to malnutrition and related health issues. Common contaminants such as arsenic, lead, mercury, and pesticides can accumulate in the body over time and contribute to chronic health conditions, including neurological disorders, cardiovascular disease, and cancer. Improving water quality through filtration, disinfection, and treatment reduces the risk of waterborne diseases, particularly in vulnerable populations such as children, the elderly, and individuals with compromised immune systems. Safe water supply and sanitation are essential for preventing outbreaks of diseases like diarrhea, hepatitis, and cryptosporidiosis. Water quality also has significant implications for ecosystems and biodiversity. Access to clean water is closely linked to social equity, economic development, and poverty alleviation. Improving water quality and sanitation infrastructure can enhance productivity, reduce healthcare costs, and contribute to sustainable development goals related to health, education, and poverty reduction. Water distribution Networks (WDNs) are one of the most important infrastructures for modern society. Due to accidental or malicious reasons, water contamination incidents have been repeatedly reported all over the world, which not only disrupt the water supply but also endanger public health. To ensure the safety of WDNs, water quality sensors are deployed across the WDNs for real-time contamination detection and source identification. (Zhou et al., 2021)

Primary contamination in drinking water is due to improper storage of water supply, water storage and leakage of pipes and secondary contamination is due to manmade such as improper handling, storage, distribution and serving methods (Tambekar et al., 2005). This leads to the serious water borne diseases. Around 2.2 million people die of basic hygiene related diseases like diarrhoea every year.as per WHO 2001 report, water hygiene behaviour on storage and handling affects the quality of drinking water.

- The global water crisis claims more lives through disease than any war claims through guns. Drinking water quality, in most cases microbiological contamination is the main concern since it is responsible for the majority of illnesses and deaths related to drinking unsafe water.
- As per report of CDC an estimated 801,000 children younger than 5 years of age perish from diarrhea each year, mostly in developing countries.
- This amounts to 11% of the 7.6 million deaths of children under the age of five and means that about 2,200 children are dying every day as a result of diarrheal diseases.
- Unsafe drinking water, inadequate availability of water for hygiene, and lack of access to sanitation together contribute to about 88% of deaths from diarrheal diseases.

1.2 Need of Contamination Detection in Drinking Water Distribution Networks

The primary concern is safeguarding public health. Contaminants in drinking water can pose serious health risks, leading to illnesses, diseases, and even fatalities. Early detection allows for swift response and mitigation measures to prevent widespread exposure to harmful substances. Water utilities are subject to strict regulations and standards to ensure the quality and safety of drinking water. Regular monitoring and detection of contaminants are necessary to comply with regulatory requirements and avoid penalties or legal consequences for non-compliance. Water distribution networks are vulnerable to various threats, including accidental spills, deliberate sabotage, natural disasters, and terrorist attacks. Contamination detection systems enable rapid response and mitigation actions during emergencies, minimizing the impact on public health and infrastructure. Contaminants in water can also corrode or degrade infrastructure components, such as pipes, pumps, and storage tanks, leading to costly repairs, interruptions in service, and compromised system reliability. Detection of contaminants helps mitigate potential damage to infrastructure and maintain the integrity of the distribution network. Identifying and assessing potential sources of contamination, as well as understanding the pathways and mechanisms of contaminant transport within distribution networks, are essential for effective risk management. Detection systems provide valuable data for risk assessment and decision-making to prevent and mitigate contamination incidents. Early detection and prompt response to contamination incidents can result in significant cost savings by minimizing the extent of contamination, reducing the need for extensive remediation efforts, and avoiding potential legal liabilities and reputational damage.

Water distribution networks play a critical role in delivering safe and potable water to communities, industries, and agriculture. However, despite advancements in water treatment and infrastructure, these networks are vulnerable to various contamination risks that can compromise the quality and safety of drinking water. Contamination incidents can have severe consequences for public health, the environment, and economic stability. Therefore, understanding the sources, pathways, and potential impacts of contamination in water distribution networks is essential for effective risk management and mitigation strategies.

1.3 Sources of Contamination:

Water Contamination can occur at three different stages:

- At source (can be controlled by treatment before supply),
- During distribution (can be controlled by proper monitoring and maintenance of system ,
- At user hand (can be controlled by proper sanitation measures and awareness)

Contaminants in water can originate from a diverse range of sources, including industrial discharge, agricultural runoff, wastewater effluent, chemical spills, natural disasters, and deliberate sabotage as shown inn fig 1. Industrial activities, such as manufacturing, mining, and chemical processing, may release hazardous substances into water bodies or sewage systems, posing risks of chemical contamination. Similarly, agricultural practices involving fertilizers, pesticides, and animal waste can introduce pathogens, nutrients, and organic pollutants into surface and groundwater sources.

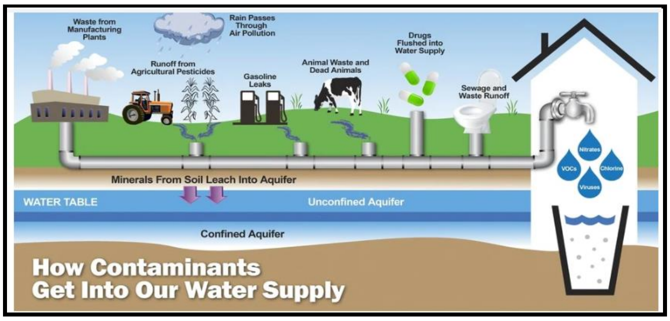

Fig-1 Sources of contamination

Source: https://www.freshwatersystems.com/blogs/blog/contaminants

Once introduced into the water distribution network, contaminants can propagate through various pathways, including infiltration into pipes, cross-contamination at distribution nodes, and backflow events from consumer premises. Aging infrastructure, pipe breaks, leaks, and unauthorized connections can create entry points for contaminants, allowing them to infiltrate the network and spread to different parts of the distribution system. Additionally, hydraulic transients, changes in flow patterns, and operational disruptions can exacerbate contamination risks by facilitating the movement of pollutants within the network.

Contamination incidents in water distribution networks can have significant impacts on public health, environmental quality, and socio-economic well-being. Exposure to microbial pathogens, toxic chemicals, heavy metals, and other pollutants in drinking water can lead to acute and chronic health effects, including gastrointestinal illnesses, respiratory problems, neurological disorders, and cancer. Moreover, contamination events can disrupt water supplies, necessitate emergency responses, and impose financial burdens on water utilities, governments, and affected communities. In extreme cases, large-scale contamination incidents can trigger public health crises, loss of confidence in water systems, and social unrest.

Contamination risks in water distribution networks pose multifaceted challenges that require proactive management and mitigation efforts. By identifying potential sources, understanding pathways of contamination, and assessing the potential impacts on public health and the environment, stakeholders can develop robust strategies to prevent, detect, and respond to contamination incidents effectively. Collaboration among water utilities, regulatory agencies, researchers, and community stakeholders is essential for enhancing the resilience and sustainability of water distribution systems in the face of evolving contamination threats.

2. Objectives

- To make a comprehensive review of the body of research on modelling approaches for detecting contamination in drinking water distribution systems
- To sort the different modelling approaches—data-driven models, physics-based models, machine learning algorithms, and sensor technologies—into different groups according to their methods.
- To determine and emphasize the best practices for detecting contamination while integrating various modelling techniques, real-time monitoring platforms, and cutting-edge sensor technology.
- To examine case studies and examples that demonstrate successful approaches to improving pollution detection in various drinking water distribution network scenarios.

3. Literature Review

Contamination occurrences in water distribution networks pose a major threat to public health and the availability of clean water (WDN). Efficiently and precisely determining the source of contamination (CSI) can aid in the development of corrective measures to mitigate consequences. Though many machine learning (ML) methods have been proposed for fast detection, there is an urgent need for methods to capture complex spatial dynamics in WDNs. Li Z. et al proposed a gated graph neural network (GGNN) for CSI in the WDN, which integrates spatiotemporal water quality data along with flow directionality between network nodes. The GGNN has good prediction accuracy even with restricted sensor coverage, according to the authors' evaluation across a range of contamination conditions. Interestingly, directed connections dramatically improve the accuracy of GGNN CSI, highlighting the significance of flow dynamics and network architecture in ML-based WDN CSI methods. In particular, the technique uses only two hours of sensor data to reduce the contamination source to five spots with an accuracy of 92.27%. [2]

The complexity and difficulty of managing modern water distribution networks (WDNs) stems from factors such growing urbanization, fluctuating consumer needs, aging infrastructure, operating expenses, and insufficient water resources. Depending on how long they take to solve or consider, management issues in such complex networks can be categorized as short-, medium-, or long-term. Mathematical models have been utilized by researchers, water utility managers, and operators to analyse and improve the performance of water infrastructure at the lowest possible operational cost and to handle the management issues related to WDNs. Bello O. et al. provided an in-depth analysis of the key mathematical models and management issues that are addressed at different stages of WDNs. It also covers the primary strategies for handling these management issues in order to satisfy customer expectations while maintaining the necessary pressure levels for sufficient water quantity and quality. [3]

Water distribution networks (WDNs) are susceptible to contamination events that can significantly affect public health and water supply. As a result, online water quality sensors are being used more frequently to identify contamination events in real time. Although reliable extraction of spatial characteristics in water quality signals remains problematic, the authors have integrated multivariate time series water quality data at numerous sites for contamination identification using machine learning. Li Z. et al suggested generative adversarial networks (GANs) as the foundation for a contamination detection technique. In order to take into account both the temporal information of water quality indicators and the geographical correlation between sensor locations, the GAN model was built. A WDN was used to test the suggested approach for a range of distinct contamination events. When compared to the minimum volume ellipsoid benchmark method, the results demonstrated the suggested GAN approach's good detection performance for a range of contamination amplitudes. Additionally, the GAN method demonstrated its robustness and potential for practical application to real-time contamination events with a variety of characteristics by achieving high accuracy for a range of contamination events with varying amplitudes and numbers of anomalous water quality parameters, as well as water quality data from multiple sensor stations. [4]

Events that cause contamination to occur in water distribution systems might be caused by deliberate acts, accidents, or even naturally occurring events. When a contamination incident happens, people may consume harmful substances that have infiltrated the network, worsened their health and potentially having an impact on the economy. Water networks are becoming smarter and more resilient to these kinds of catastrophes due to developments in sensor and actuator technologies. The theoretical, modelling, and computational advancements in the field of contamination event identification for water distribution systems were comprehensively reviewed by Demetrios G et al. Three primary tasks make up research: "Event Detection and Isolation," "Emergency Event Management," and "Preparedness." Within a coherent mathematical framework based on systems theory, the main research subjects from each task are outlined and their unresolved issues are highlighted. [5]

The safety of home drinking water is impacted by pollutant incursion in water distribution networks, and sensors are installed to identify such intrusions. Numerous studies have concentrated on optimizing sensor placement since the quantity and positioning of sensors directly impact the detection efficiency. Because different nodes have different effects on the water distribution networks after contaminant intrusion—that is, different risk levels of contaminant intrusion at nodes, optimizing sensor placement is a crucial mitigation strategy that is required to reduce the serious consequences of contaminant intrusion.

The following procedures are part of the multi-objective sensor placement optimization strategy that Hu et al. suggested, which is based on contamination risks: (1) Based on the influence of the contamination events, four distinct categories of contamination probability are identified. The Pareto fronts, which are based on several assumptions for the contamination probability distribution, are then obtained by solving a multi-objective optimization problem. (2) A multi-criteria decision analysis is used to rank and cluster the Pareto fronts, resulting in the best scheme for each cluster under various preferences. (3) The effects of the pollutant entry on the network are compared between the best strategies. The proposed method is empirically analysed using the D-town network model. All sensor placement schemes show a high true detection rate of contamination when node-to-node variation in the contamination probability is enabled, according to the results. For a fixed number of sensors, the contamination probability based on the number of impacted pipes can provide the best location for the sensors to reduce the effect of pollutant infiltration on the pipeline network. (Hu et al., 2022)

The technology for detecting contamination aids in protecting and managing surface water quality. It's critical to promptly identify abrupt contamination episodes from dynamic differences in online water quality monitoring data caused by different interference causes. Liao et al. have proposed a framework named “Prediction - Detection - Judgment” with a method framework of “Time series increment - Hierarchical clustering - Bayes' theorem model”. Time to detection is used as an evaluation index of contamination detection methods, along with the probability of detection and false alarm rate. The proposed method is tested with available public data and further applied in a monitoring site of a river. Results showed that the method could detect the contamination events with a 100% probability of detection, a 17% false alarm rate and a time to detection close to 4 monitoring intervals. Timely detection guarantees that contamination incidents can be responded to and handled in a timely manner. The suggested index time to detection assesses the timeliness of the approach. The site application also shows that the framework suggested in this study is feasible, workable, and has the potential to be widely used. (Liao et al., 2024)

Numerous techniques have been used in the literature to enhance contamination source identification (CSI) performance, and new research indicates that deep learning models offer a lot of promise for solving the CSI problem. Large amounts of training samples must frequently be gathered in order for deep learning-based CSI techniques to be successful. In practice, there are rarely many contamination occurrences in a single WDN, particularly when the WDN is brand-new. Unfortunately, the majority of CSI techniques now in use in the literature concentrate on the analysis of training and applying models on the same WDNs, and CSI knowledge acquired from one WDN cannot be used to another WDN. To this purpose, this research offers a cross-network CSI solution that may transfer the CSI knowledge obtained from one WDN to another WDN, based on the application of graph convolutional networks. Empirically, Zhou et al. demonstrated that the suggested cross-network CSI technique may attain equivalent accuracy even trained on a different WDN in the task of contamination source identification, based on a benchmark WDN. [6] (Zhou et al., 2021)

For water distribution networks (WDNs), Rathore et al. suggested an operational management strategy that can both locate and identify leaks and reduce contamination brought on by them. The creation of a contamination mitigation control plan is the main focus of this endeavour. Usually, a leak causes a decrease in network pressure, which raises the possibility of contamination. The leakage in the WDN is found and localized via a leakage localization technique. Contamination mitigation control is turned on when a network leak is found. The contamination mitigation control optimizes the flow and pressure settings of the pumps to reduce the danger of contamination. The complete architecture is evaluated on two large-scale benchmark water networks: L-town, a municipal network, and the Smart Water Infrastructure Laboratory at Aalborg University in Denmark [7] (Rathore et al., 2023)

One of the most difficult research problems in water distribution systems analysis is the issue of contamination event detection in water distribution systems. Housh & Ostfeld used a range of techniques, including as statistics, heuristics, machine learning, and optimization techniques, in their attempt to detect events. Alarms are obtained independently for every water quality indicator, which is a feature shared by a number of current event detection systems. Using a statistically oriented model for discrete choice prediction, which is estimated using the maximum likelihood method for integrating the individual alarms, is a prominent element of the currently proposed approach. Using evolutionary algorithms, the discrete choice model is jointly calibrated in a training data set with other elements of the event detection system framework. It is shown that the fusing process of individual indicator probabilities, which is neglected in many current models of event detection systems, is an essential component of the system that might be modeled by utilizing a discrete choice model to enhance its performance. [8]

A thorough assessment of ten cutting-edge semi-supervised anomaly detection (AD) techniques for leakage identification in water distribution networks (WDNs) was given by Tornyeviadzi et al. The semi-supervised AD algorithms are evaluated on LeakDB, a benchmark consisting of distinct leakage scenarios that additionally account for the many sources of uncertainty that occur in WDNs. The effectiveness of semi-supervised AD techniques is assessed using three performance metrics (PR AUC Score, Identification Lag Time), which taken together represent the many aspects of leakage identification in WDNs. Furthermore, two weighting methodologies are offered by the TOPSIS MCDM tool, which is used to concurrently take into account all performance measures while assessing the effectiveness of semi-supervised AD algorithms. This thorough comparative analysis's findings demonstrate that Local Outlier Factor (LOF) is LeakDB's top semi-supervised AD technique overall. The capacity of proximity-based semi-supervised AD algorithms to identify leak occurrences around typical operational data points makes them clearly superior to linear and probabilistic AD systems. Lastly, general advice on the application of semi-supervised AD techniques for leakage identification is covered, along with the effect of uncertainties on the performance of the semi-supervised AD models. [9]

Over the last twenty years, many academics have proposed a number of approaches for locating sensors in water distribution networks with various goals. Researchers disagree on the goals, methods, and other details of sensor placements, despite the fact that many different approaches have been created. The approaches of sensor placement have been broadly divided into two groups, single objective and multi-objective, and have been contrasted using various criteria. The approaches that are currently accessible are critically reviewed in order to identify future research needs for sensor network design for real-world networks. [10]

The management of disinfectant concentrations across the network greatly depends on the modelling of chlorine residual in water supply systems. Both bulk and wall chlorine consumption are currently described by first order decay kinetics. Nevertheless, more sophisticated methods have been suggested; one such method is the parallel, two-reactant second order decay model (2R model), which has been shown to produce more accurate results when simulating bulk decay of chlorine in lab experiments. With the release of the EPANET Multi-Species Extension (EPANET MSX), it is now possible to simulate chlorine residuals in water supply systems using any other formulation or the 2R model. The effectiveness of the 2R model and first- and nth-order decay kinetics were evaluated in the current work for full-scale modelling of chlorine in a transmission system. The three studied kinetic models may all reach a comparable degree of accuracy, according to the results, if the wall decay coefficient is calibrated correctly. Despite having better modelling capabilities, the stand-alone EPANET MSX was harder to use than the regular EPANET application because it lacked a graphical user interface that would have allowed profiles of the system's chlorine concentration to be seen. These restrictions were overcome by using the EPANET Java web application, which supports 3D. By utilizing EPANET MSX's expanded capabilities, this tool, in conjunction with improved characterisation and estimation of the bulk and wall decay components, enables more realistic and precise modelling of chlorine in water supply systems. [11]

Kuwait, one of the nations with the highest water-risk rankings in the world, urgently needs fresh, cutting-edge approaches and procedures to maximize and save its water infrastructure. The issues facing Kuwait's water distribution system include water usage, water quality, and network design optimization. This study is a step toward developing an EPANET-based model for various Kuwaiti water network segments. EPANET-based models are widely utilized in water systems applications globally. An EPANET model was created and examined for a particular region of Kuwait. Mabrok et al. assessed the water age as well as the quality of the water in the selected area. A number of plausible scenarios with varying population vocations were taken into consideration. The emphasis was placed on how the habitation stages of a given area affect the water age and quality in water distribution networks. Since partial occupation might impair water quality, as the water network analysis revealed, several scenarios should be considered during the water network design phase. [12] (Mabrok et al., 2022)

Although karst aquifers are widely used as dependable sources of drinking water, their inherent qualities—such as concentrated recharge and high groundwater flow velocities—as well as the escalation of human demands render them extremely susceptible to pollution. An efficient method for determining intermittent groundwater pollution and guaranteeing safety conditions in drinking water delivery systems is the continuous monitoring of karst springs. In order to characterize contamination events in a carbonate karst aquifer of a mountainous and rural area of Spain, Fernández-Ortega et al. focused on improving groundwater protection insights through an integrated methodological approach based on real-time measurements of continuous water parameters coupled to bacterial analysis.

The findings demonstrated the many dynamics of flow, sedimentation, and mixing that dictate how human-caused faecal contamination affects the karst groundwater that each spring drains. The procedures that are being discussed regulate the fluctuating impact of allogenic recharge, resulting in significant variations in the reaction times, maximum turbidity values, and bacterial activity that are connected with the outlets under investigation. The results of this study demonstrate the value of the applied methodological framework in laying the groundwork for the effective global adoption of early-warning systems to prevent public health problems. [13]

The ability to provide high water quality distribution from sources to consumers is a foremost objective in water distribution systems security. Different techniques based on physical, chemical, and other methods constitute a variety of solutions for the layout, design, and operation of water networks, all aimed at decreasing the risk of supplying contaminated water to consumers. R. Lifshitz et al. presents a new analysis approach based on clustering insights of water distribution networks connectivity for enhancing its security. Clustering is utilized herein for dynamically exploring the system behaviour. Through clustering formations, addition of network components such as pipes and tanks for the layout problem, and valves for its operation – contamination spreading is controlled and contained. The developed methodology is demonstrated on several example applications, showing its capabilities to provide a decision support tool for contaminant control and containment in water distribution systems. [14]

4. Conclusion

Finally, by analysing numerous modelling approaches for the detection of contamination in drinking water distribution networks, the research topic "Modelling Approaches for Contamination Detection in Drinking Water Distribution Networks: A Comprehensive Review" dives into the crucial field of preserving public health. This study's thorough analysis of the body of literature has brought to light the wide variety of techniques used to improve the capacity to recognize and react to contamination events.

According to the thorough examination, sophisticated sensor technologies combined with data-driven and physics-based models have showed promise in raising the precision and effectiveness of contamination detection. It has become apparent that integrating machine learning algorithms, network simulations, and real-time monitoring systems is a workable way to improve the drinking water distribution networks' overall resilience. The evaluation also emphasizes how critical it is to take into account the dynamic nature of water distribution systems, the inherent ambiguities in data on water quality, and the necessity of a multifaceted strategy that combines proactive and reactive actions. The results underscore the importance of ongoing research and development in this domain to tackle changing obstacles and remain ahead of possible hazards to the quality of water.

To sum up, this thorough analysis offers insightful information to water management scholars, practitioners, and policymakers, stimulating additional cooperation and creativity in the search for reliable and efficient contamination detection techniques for drinking water distribution networks. In the end, the objective is to protect communities' health and safety by reducing the hazards brought on by waterborne pollutants in a constantly shifting environment.

References

[1] T. P. Lambrou, C. Anastasiou and M. Polycarpou, "A Low-Cost Sensor Network for Real-Time Monitoring and Contamination Detection in Drinking Water Distribution Systems," *IEEE Sensors Journal,* vol. 14, no. 8, pp. 2765 - 2772, 2014.

[2] Z. Li, H. L. C. Z. and G. , "Gated graph neural networks for identifying contamination sources in water distribution systems," *Journal of Environmental Management,* 2024.

[3] O. Bello, A. M. Abu-Mahfouz, Y. Hamam, P. R. Page, K. B. Adedeji and O. Piller, "Solving Management Problems in Water Distribution Networks: A Survey of Approaches and Mathematical Models," *Water,* vol. 11, no. 562, 2019.

[4] Z. Li, H. L. C. Z. and G. , "Generative adversarial networks for detecting contamination events in water distribution systems using multi-parameter, multi-site water quality monitoring," *Environmental Science and Ecotechnology,* 2023.

[5] S. G. V. a. b. A. M. a. b. I. T. a. b. M. M. P. a. b. Demetrios G. Eliades a, "Contamination event diagnosis in drinking water networks: A review," *Annual Reviews in Control,* 2023.

[6] Y. Z. J. J. K. Q. and Y. D. , "Graph convolutional networks based contamination source identification across water distribution networks," *Process Safety and Environmental Protection,* 2021.

[7] S. S. R. R. M. C. S. K. and R. W. , "Leakage diagnosis with a contamination mitigation control framework using a graph theory based model," *Annual Reviews in Control,* 2023.

[8] M. Housh and A. O. , "An integrated logit model for contamination event detection in water distribution systems," *Water Research,* 2015.

[9] H. M. Tornyeviadzi and H. M. R. S. , "Semi-supervised anomaly detection methods for leakage identification in water distribution networks: A comparative study," *Machine Learning with Applications,* 2023.

[10] S. Rathi and R. Gupta, "Sensor Placement Methods for Contamination Detection in Water Distribution Networks: A Review," *Procedia Engineering,* vol. 89, pp. 181-188, 2014.

[11] L. Monteiro , D. Figueiredo , S. Dias, R. Freitas , D. Covas and . J. Menaia, "Modeling of Chlorine Decay in Drinking Water Supply Systems Using EPANET MSX," *Procedia Engineering,* vol. 70, pp. 1192-1200, 2014.

[12] M. A. Mabrok , . A. Saad and T. Ahmed , "Modeling and simulations of Water Network Distribution to Assess Water Quality: Kuwait as a case study," *Alexandria Engineering Journal,* vol. 61, no. 12, pp. 11859-11877, 2022.

[13] J. Fernandez-Ortega , J. Antonio Barbera and B. Andreo, "Real-time karst groundwater monitoring and bacterial analysis as early warning strategies for drinking water supply contamination," *Science of the Total Environment,* vol. 19, 2024.

[14] R. Lifshitz1 and A. O. F.ASCE2, "A Clustering Model for Contamination Spreading Control in Water Distribution," *World Environmental and Water Resources Congress,* p. 517, 2017.

[15] Z. Hu, W. C. ,. D. T. S. Y. and D. , "Multi-objective model for optimal sensor placement in water distribution systems considering contamination probability variation-based contaminant impact," *Journal of Cleaner Production,* 2022.

[16] Z. L. . M. Z. and Y. C. , "A "Prediction - Detection - Judgment" framework for sudden water contamination event detection with online monitoring," *Journal of Environmental Management,* 2024.