MODELING STRATEGIES TO IDENTIFY WATER DISTRIBUTION SYSTEM SAMPLING LOCATIONS

Background

The delivery of safe, potable water to communities is the primary objective of drinking water utilities. However, the quality of the water can deteriorate as it is transported from the treatment plant through the distribution system to the customers due to interactions with the pipe walls and constituents in the water itself. Additionally, drinking water distribution systems can be vulnerable to intentional or accidental contamination incidents. Since these systems consist of thousands of pipes and service connections over large geographic regions, utilities cannot financially afford to install continuous online monitoring sensors everywhere in the system. Thus, drinking water utilities collect samples throughout the distribution system to evaluate the quality of the water to protect the health of the community. Sampling can be conducted to meet regulatory needs, to aid in the operations and maintenance of the system, to respond to customer complaints, and to investigate possible contamination incidents.

If a water contamination incident is suspected following an alert from a water quality monitoring sensor or customer complaint, samples could be taken to support response actions. Sampling could be used to confirm that a contamination incident has occurred or is occurring in the distribution system and to identify the type or concentration of a contaminant. The contamination injection location (or source), the extent of the contamination plume, and the required decontamination area could also be identified by sampling. Identifying the contamination source is important to stop more contamination from entering the system. Knowledge of the source would also help define the extent of contamination. By determining the extent of contamination, the percentage of the population exposed to contamination, or unaffected areas of the system can be identified. Accurate determination of the source and extent of contamination is challenging because there can be limited available measurements and significant uncertainty in system hydraulics, contaminant reaction dynamics, and incident details. Decision makers might have a difficult time implementing an effective response action if there is a large uncertainty associated with the contamination incident. Thus, it is important to develop techniques that can characterize a contamination incident quickly to mitigate the effects.

Modeling Uncertainties

Decision makers can use water distribution modeling tools to plan and inform sampling strategies. In order to achieve confidence in the modeling results, model uncertainty must be addressed. Water distribution system models have various sources of uncertainty in the hydraulic modeling parameters, including

- infrastructure representation (e.g., incorrect pipe diameters, missing pipes)
- customer demands (e.g., changes due to public health notices – do not use, boil water)
- operational controls (e.g., valve settings, pump curves)
- initial conditions (e.g., tank levels, pump statuses)

Additionally, water quality modeling parameters also have uncertainty associated with them, including

- contaminant type (e.g., biological, chemical)
- contaminant reaction dynamics
- amount of contaminant injected
- contaminant injection location
- time of the contaminant injection
- duration of the contaminant injection

Identifying the parameters that affect contaminant transport within the distribution system can be useful to select sampling locations to decrease the uncertainty in the extent of contamination.

Hart et al. (2019) investigated uncertainty in the contamination plume when modifying the following water quality modeling parameters:

- customer demands
- isolation valve status

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- bulk reaction rate coefficient
- contaminant injection start time
- contaminant injection duration
- contaminant injection location
- contaminant injection rate

The uncertainty in the injection location parameter had the most effect on the extent of contamination compared to the other parameters. More than half of the locations contaminated only small areas of the system and only a few locations contaminated a large area of the system. Figure 1 shows an example of how the extent of contamination is affected by the uncertainty in the injection location. The contaminant injection rate, reaction coefficient, and injection duration were the next most significant parameters after the injection location, since they also affected the total area contaminated in the system. Increasing the injection rate provided more contaminant that could spread further into the system before becoming too diluted. High reaction rate coefficients decreased the concentration below the contamination threshold more quickly. Increasing the injection duration ensured that the contaminant remained in the system longer and therefore increased the area affected.

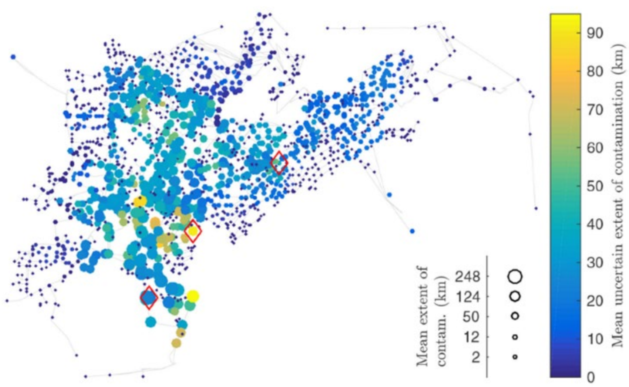

Figure 1. Map of the water distribution system in which the nodes are sized by the average extent of contamination of an injection occurring at the node and colored by the uncertainty. Nodes outlined with red diamonds are used as example injection location [from Hart et al. (2019)].

Sampling for Extent of Contamination

Affected drinking water utilities can take samples within the distribution system to determine the source and extent of a contamination. Rodriguez et al. (2021) presented an optimization framework to reduce the uncertainty about the contamination incident as quickly as possible by selecting the best sampling locations to determine the source and extent of the contamination. Step 1 built a database of simulation results from potential contamination scenarios with different characteristics (e.g., injection location, amount, duration, customer demands, and reaction coefficients). Step 2 updated the probability of the contamination scenarios based on available measurements following the possible alert of a contamination incident. Step 3 calculated the probability that a node was contaminated using the precomputed simulation results and the contamination scenario probabilities from Steps 1 and 2, respectively. Step 4 categorized nodes based upon their probability of contamination given a specific confidence level. Step 5 assessed the number of nodes that were categorized as uncertain in terms of contamination, and if the number was close to zero, the process stopped. Otherwise, Step 6 used an optimization-based approach to determine the best locations to take additional samples. Step 7 obtained new sample measurements and returned the process back to Step 2. A node's probability of contamination was adjusted as more sample measurements were obtained and the uncertainty in the contamination source and extent were reduced. The optimization formulations presented solved for multiple optimal sampling locations simultaneously and efficiently, even for large systems with a large uncertainty space. The efficiency and effectiveness of the framework was demonstrated in two case studies.

Figure 2 shows node probability maps after each sampling cycle of four samples each for one of the case studies. Approximately 30% of the nodes were highly unlikely to be contaminated when the initial alarm was triggered, while the remaining 70% remained uncertain as to whether they were contaminated. By cycle 2 with a total of eight measurements, the level of uncertainty in the extent of contamination had been greatly reduced, and by cycle 3 with a total of 12 measurements, the extent of contamination was almost completely characterized. To identify sampling locations quickly and optimally, a broad set of contamination scenarios, including hydraulic patterns to reflect significant decreases in the overall demand due to public health notices (e.g., do not drink, do not use), should be precomputed. However, new contamination scenarios can be included during the sampling process to account for scenarios generated based on real-time data or other system knowledge during an actual incident.

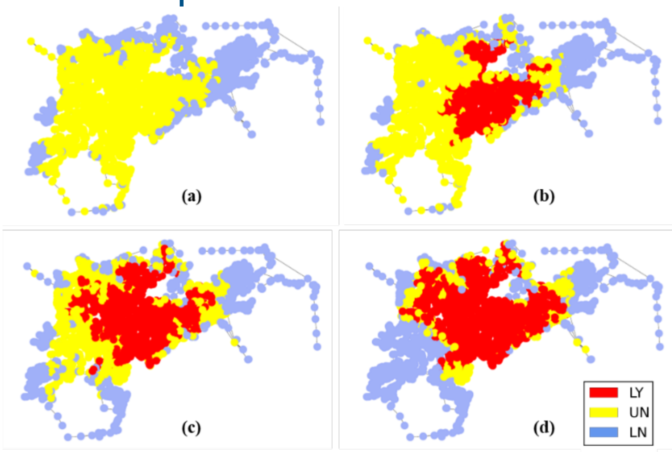

Figure 2. Nodal probability maps in which LY (red) is likely contaminated, UN (yellow) is uncertain if contaminated, and LN (blue) is likely not contaminated for different sampling cycles: (a) alarm is triggered (cycle 0 – no measurements); (b) after four measurements (cycle 1); (c) after eight measurements (cycle 2); and (d) after twelve measurements (cycle 3) [modified from Rodriguez et al. (2021)].

Regulatory Sampling for Emergencies

While sampling locations can be determined following an alert of a possible contamination, drinking water utilities already have established routine sampling locations within the distribution system for operational and regulatory purposes. Since utilities are already used to taking samples at these locations, they might begin an investigation of a contamination incident there first. Haxton et al. (2021) evaluated the effectiveness of routine, regulatory sampling locations for emergency response scenarios. They also investigated the performance of emergency response sampling locations for regulatory purposes. For the systems assessed in the paper, the sampling locations identified for one purpose (regulatory or emergency response) detected less scenarios when evaluated against the opposite purpose. The average performance was reduced by 3%–4% when emergency response locations were used for regulatory goals, while the performance was reduced by 7%–10% when regulatory response locations were used for emergency response. Figure 3 illustrates the sampling locations and the contribution each sampling location had on scenario detection for the emergency response scenarios. This work highlighted that regulatory sampling locations could provide value in responding to an emergency for the system evaluated.

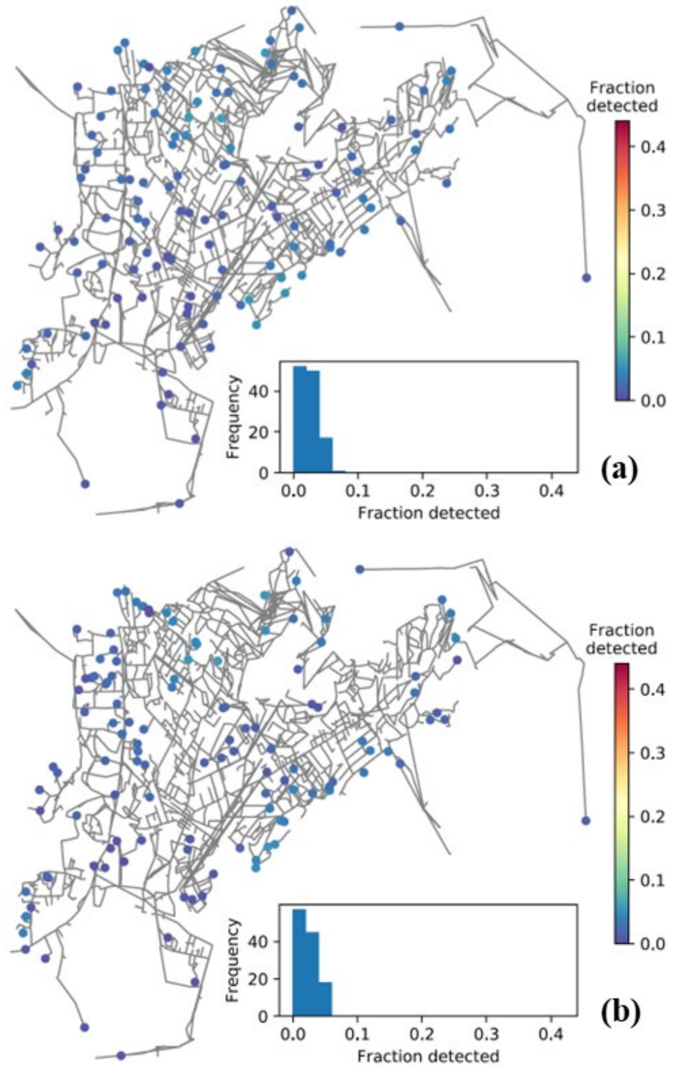

Figure 3. Fraction of detected scenarios using 120 sampling locations for (a) emergency response optimization and (b) regulatory optimization, evaluated for emergency response conditions. Each figure includes the total fraction detected and a histogram showing the frequency of sampling locations for each fraction detected [modified from Haxton et al. (2021)].

Drinking water distribution modeling tools can support water utilities in making decisions with regards to sampling locations during emergency response situations. During an emergency, prioritizing the use of limited personnel and resources is critical to (1) determining the nature and extent of contamination within a system and (2) determining the effective mitigation strategies to address the emergency. While having an up-to-date emergency response plan with available sampling locations identified is desired, these sampling locations might not be predefined for all systems. However, systems will likely have designated locations already established for complying with regulatory requirements. The approaches discussed here can be applied to help utilities understand how effective manual samples would be for their system and to improve the sampling location selection process. If a system does not have an emergency response plan, then regulatory sampling locations could provide a good basis for an initial round of sampling during a suspected emergency, allowing utility personnel to be quickly dispatched to get preliminary data related to contamination extent.

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