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An Innovative Model-Based Methodology for Rapid Response to Drinking Water Contamination Events †

Sotirios Paraskevopoulos [1,2,*], Stelios G. Vrachimis [3], Marios S. Kyriakou [3], Mirjam Blokker [1,2], Patrick Smeets [1], Demetrios G. Eliades [3], Marios Polycarpou [3,4] and Gertjan Medema [1,2]

[1] KWR Water Research Institute, 3433 PE Nieuwegein, The Netherlands; mirjam.blokker@kwrwater.nl (M.B.); patrick.smeets@kwrwater.nl (P.S.); gertjan.medema@kwrwater.nl (G.M.)
[2] Department of Water Management, Delft University of Technology, Mekelweg, 2628 CD Delft, The Netherlands
[3] KIOS Research and Innovation Center of Excellence, University of Cyprus, Aglantzia 2109, Cyprus; vrachimis.stelios@ucy.ac.cy (S.G.V.); kiriakou.marios@ucy.ac.cy (M.S.K.); eliades.demetrios@ucy.ac.cy (D.G.E.); polycarpou.marios@ucy.ac.cy (M.P.)
[4] Electrical and Computer Engineering Department, University of Cyprus, Aglantzia 2109, Cyprus
* Correspondence: s.paraskevopoulos@tudelft.nl; Tel.: +31-0617278778
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Abstract: In a desktop exercise, a water utility's emergency response to suspected wastewater contamination in a drinking water network was compared with a model-based approach using PathoINVEST. This tool simulates contamination scenarios and assists with locating the source of contamination using sampling results. The sampling procedure used a portable sensor that offers rapid (20 min time-to-result) screening of fecal contamination. Preliminary results show that the model-based approach is able to find the contamination source faster and with fewer samples than current practices. Integrating modeling and rapid sensor tools in emergency responses improves decision-making and public health protection in drinking water networks.

Keywords: drinking water contamination modeling; source identification; emergency response

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1. Introduction

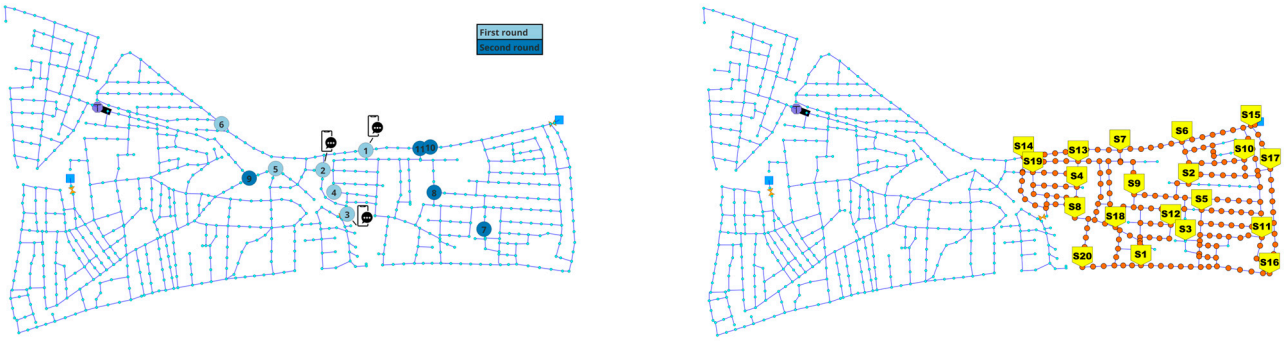
Ensuring drinking water safety is crucial due to potential health risks from contamination events, which may result from natural disasters, human errors, or malicious attacks [1]. Despite advancements in monitoring and remediation technologies, there is a challenge in using real-time modeling tools effectively during crises. Typically, water utilities respond to contamination based on past experiences and manual protocols, with modeling experts contributing at a later stage, often using outdated information. Moreover, current testing protocols such as RT-PCR necessitate that samples be transported to a laboratory for analysis (approximately 4 h). Rapid and effective decision-making is crucial during such events; delays or inaccuracies can lead to increased health risks, economic losses, and loss of public trust [1–3].

This paper compares traditional and model-based strategies in responding to wastewater contamination in drinking water networks (DWNs), focusing on improving decision-making with real-time tools and sensors. We analyze a case study in the Netherlands using the L-Town digital DWN testbed and the PathoINVEST tool, part of the Horizon 2020 Pathogen Contamination Emergency Response Technologies (PathoCERT) project. The tool is based on the open-source software EPANET-Matlab toolkit, and one of its functionalities is to simulate contamination events and suggest sampling locations to find the contamination source [4–6].

2. Methodology

2.1. Case Study

The case study used L-Town's DWN to simulate a 24 h enterovirus contamination. L-Town has 782 junctions, and 905 pipes, and serves approximately 30,000 people. The utility responded to water quality complaints at 09:30 a.m. (Figure 1a), forming a response team (lead by the Incident Commander). The team used data on water age and flow to hypothesize that the contamination started around 8 a.m. in the eastern part of the network. Emergency measures were then focused on identifying the contamination source and calculating infection risks using the QMRA framework [4].



(**a**) (**b**)

Figure 1. (**a**) The proposed sampling locations in two rounds (light and dark blue), and the customer complaints (smartphone); (**b**) the upstream potential contamination sources (orange circles), and the 20 most probable contamination sources (yellow labels). The light-blue squares are the network's reservoirs while the purple hexagon represents a tank.

2.2. Source Identification

2.2.1. Traditional Approach

The Incident Commander established two sampling rounds at 11 locations (Figure 1a). Instead of the usual RT-PCR method, they used the PathoTESTICK, a mobile sensor for the rapid, low-cost, on-site screening of contamination [7], assumed to detect viruses for this study. Each sampling iteration took about 20 min. The first sampling occurred at 10:30 a.m., an hour after receiving the initial complaints. The goal was to systematically identify the contamination source by ruling out clean sections of the network based on the sampling outcomes.

2.2.2. Model-Based Approach

The model-based approach involves PathoINVEST, a tool intended to help investigations during pathogen contamination events in the DWNs using realistic water demands, and the up-to-date modeling of reactions between different substances (pathogens, chlorine, organic compounds). The functionality that helps identifying the contamination source in a DWN employs a simplified version of the expanded sampling concept [8]. It analyzes potential sources and selects strategic sampling locations, marked with binary indicators for positive (1) or negative (0) results. A positive indicator suggests the contamination passed through that location. The initial step involves identifying all the potential contamination sources by locating upstream nodes from the complaint sites (Figure 1b). Next, experts selected 20 locations as the most probable contamination sources in the tool based on their knowledge. The same upstream nodes were also considered as sampling locations. To locate the contamination source, the DWN's hydraulics and quality dynamics were simulated across 20 scenarios corresponding to each hypothesized contamination source. This produced binary indicators for each sampling location based on whether the contamination was likely to have passed through at a specific timestep (Table 1). The simulations and subsequent team discussions took approximately 30 min, finishing by 10:00 a.m. The next step

included the recommendation of the first (most suitable) sampling location, utilizing the theory of entropy. This approach calculates the frequency of contamination presence (1) and absence (0) across all 20 scenarios for each sampling location. The location with the highest entropy, indicative of the greatest uncertainty regarding contamination, is prioritized for sampling. After entropy analysis, node *n241* exhibited the highest entropy, signaling it as the prime candidate for the first sample. The field team was instructed to take the first sample in the designated location at 10:00 a.m. The result was positive, and that allowed for the exclusion of simulated contamination scenarios that do not align with this outcome (Table 1). This iterative process continued until the potential contamination sources were narrowed to one, facilitating the identification of the actual source of contamination.

Table 1. Simulated binary signatures for a snippet of sampling locations and contamination sources at 10:00 AM. The selected sampling location is highlighted in green, based on entropy results. Scenarios misaligned with the positive result (marked in red) are discarded.

Scenario	n220	n223	n224	n239	n240	n241	n244	n245	n248	n249	n250
S1	1	0	0	0	0	0	0	0	0	0	0
S2	1	1	0	1	1	1	1	1	1	1	1
S3	0	0	0	0	0	0	0	0	0	0	0
S4	0	0	0	1	0	1	1	0	0	0	0

3. Expected Results

Preliminary results and assessments suggest that the model-based approach requires significantly fewer samples and less time to find the source of contamination compared to the traditional approach. We anticipate that the model-based approach will demonstrate superior efficiency and effectiveness, thereby reducing response time and subsequent potential health risks. This hypothesis is grounded in initial findings and the theoretical advantages of integrating real-time modeling tools with the presented experimental methodology in emergency response frameworks.

4. Conclusions

The incorporation of modeling and sensor technologies represents a pivotal advancement in managing DWN contamination events. While traditional knowledge and manual interventions remain valuable, the integration of modern, automated approaches promises significant improvements. Our study underscores the potential of these integrated strategies to enhance public health protection through more informed and timely decision-making. Detailed analyses will be conducted, further exploring the efficacy and implications of these methodologies.

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Conflicts of Interest: The authors declare no conflicts of interest.

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