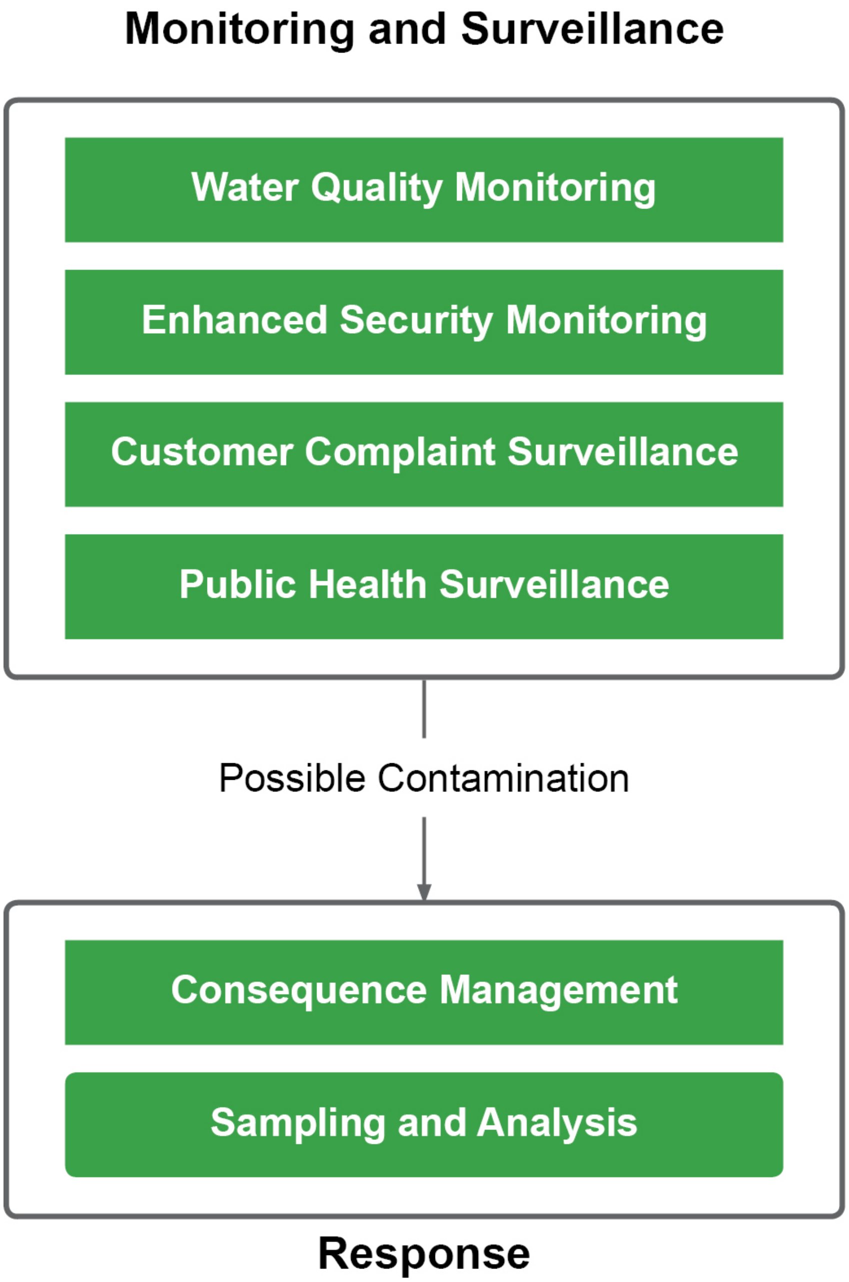
United States
Environmental Protection
Agency

Water Security Initiative: System Evaluation of the Cincinnati Contamination Warning System Pilot



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Executive Summary

The goal of the US Environmental Protection Agency's (EPA) Water Security Initiative (WSI) is to design and demonstrate an effective monitoring system for timely detection and response to drinking water contamination threats and incidents. A contamination warning system (CWS) integrates information from multiple monitoring and surveillance components to alert a water utility to possible contamination and guides response actions through consequence management.

System design objectives for an effective CWS are: operational reliability, spatial coverage, contaminant coverage, alert occurrence, timeliness of detection and response, and sustainability. Metrics were defined for each of these design objectives to provide a basis for the technical evaluation of the Cincinnati CWS. Evaluation techniques used to quantitatively or qualitatively evaluate each of the metrics include analysis of empirical data from routine operations, drills and exercises, modeling and simulations, forums, and a benefit-cost analysis. This report describes the analysis of data collected from the Cincinnati CWS during the evaluation period from January 2008 through June 2010.

The major outputs from the evaluation of the Cincinnati pilot include:

1. *Cincinnati Pilot System Status*, which describes the post-implementation status of the Cincinnati CWS following the installation of all monitoring and surveillance components.
2. *Component Evaluations*, which includes analysis of performance metrics for each component of the Cincinnati CWS.
3. *System Evaluation*, which integrates the results of the component evaluations, modeling and simulations, and a benefit-cost analysis.

The reports that present the results from the evaluation of the system and each of its six components are available in an Adobe portfolio, *Water Security Initiative: Comprehensive Evaluation of the Cincinnati Contamination Warning System Pilot* (USEPA 2014a).

Contamination Warning System Design

A multi-component design was adopted to meet the CWS design objectives. Such a system integrates information from multiple monitoring and surveillance tools common to the drinking water industry and public health sector that collectively provide timely and comprehensive detection capabilities. The monitoring and surveillance components of the Cincinnati CWS are:

- **Water Quality Monitoring (WQM)** comprises 15 stations located throughout the distribution system that measure chlorine residual, pH, total organic carbon, conductivity, turbidity and temperature. Data from each monitoring station is transmitted in real time over a communication network to an operations and control center where the data is continuously analyzed for anomalies by an automated event detection system.
- **Enhanced Security Monitoring (ESM)** includes the equipment and procedures that detect and respond to security breaches at critical distribution system facilities that provide access to finished water. Security equipment such as cameras, motion activated lighting, door contact alarms, ladder and window alarms, area motion sensors, and access hatch contact switches generate alerts when key facilities are breached.
- **Customer Complaint Surveillance (CCS)** enhances the collection, and automates the analysis, of calls from customers reporting water quality concerns, which may be indicative of a water

quality issue in the distribution system. Work orders and interactive voice response menu selections are monitored by an automated event detection system.

- **Public Health Surveillance (PHS)** involves the analysis of health-related data to identify disease events that may stem from drinking water contamination. Public health data analyzed in the Cincinnati CWS include 911 calls, emergency medical service data, Drug and Poison Information Center calls and hospital admission reports.

If any of these four monitoring and surveillance components detects an anomaly, an alert is generated and investigated according to documented procedures. If contamination is considered Possible at the conclusion of that investigation, **Consequence Management** procedures are initiated in an attempt to determine whether contamination is Credible. Additionally, procedures under the **Sampling and Analysis (S&A)** component guide the field investigation, sample collection and laboratory analysis for chemicals, radionuclides, pathogens and biotoxins through a laboratory network. Positive laboratory results are generally sufficient to Confirm a contamination incident.

Methodology

Several methods were used to evaluate the performance of the Cincinnati CWS. Data was tracked over time to illustrate the change in performance as the CWS evolved during the evaluation period. Statistical methods were also used to summarize large volumes of data collected over the evaluation period. Data was also evaluated and summarized for each reporting period over the evaluation period. In this evaluation, the term reporting period is used to refer to one month of data that begins on the 16th of the indicated month and ends on the 15th of the following month. Thus, the January 2008 reporting period refers to the data collected between January 16, 2008, and February 15, 2008. Additionally, 19 drills and two full-scale exercises designed around mock contamination incidents were used to practice and evaluate the full range of procedures, from initial detection through response.

Because there were no contamination incidents during the evaluation period, there is no empirical data to fully evaluate the detection capabilities of the Cincinnati CWS. To fill this gap, a computer model of the Cincinnati CWS was developed and challenged with a large ensemble of simulated contamination incidents in a simulation study. An ensemble of 2,015 contamination scenarios representing a broad range of contaminants and injection locations throughout the distribution system was used to evaluate the effectiveness of the CWS in minimizing public health and utility infrastructure consequences. The simulations were also used in a benefit-cost analysis, which compares the monetized value of costs and benefits and calculates the net present value of the CWS. Costs include implementation costs and routine operation and maintenance labor and expenses over a 20-year lifecycle for the CWS. Benefits included reduction in consequences (illness, fatalities and infrastructure contamination) and dual-use benefits to routine system operation.

Design Objective: Operational Reliability

For a CWS to consistently detect extremely rare contamination incidents, it must achieve a high degree of operational reliability, which is defined as the availability and production of data of acceptable quality and quantity for reliable event detection. Operational reliability of the Cincinnati CWS was evaluated through data completeness and availability.

Data completeness was 95% for the CWS over the entire evaluation period. Issues with WQM equipment during the early stages of deployment contributed significantly to lost data. ESM, CCS and PHS regularly had months of 100% data completeness, with only intermittent periods of data loss. After the components were optimized by June 2009, data completeness for the CWS regularly exceeded 95%.

Average availability for the individual CWS components during the evaluation period ranged between 73% and >99%, as shown in **Table ES-1**. The single greatest contributor to downtime was issues related to the WQM event detection system (CANARY), which was particularly significant during the early portion of the evaluation period. As problems with CANARY were resolved, the availability of the WQM component, and the entire CWS, increased. Had CANARY been fully operational during the evaluation period, the WQM component would have been available for 89% of the time, rather than the 73% availability observed during the evaluation period.

Table ES-1. CWS Component Availability

Component	Availability
WQM	73% (89%)[1]
ESM	97%
CCS	>99%
PHS	90%

[1] The value in parenthesis (89%) represents WQM component availability when downtime caused by the CANARY event detection system is excluded.

The CCS component had the highest availability at >99%, followed closely by ESM at 97%. The PHS tools deployed specifically for this project, 911 and emergency medical service surveillance, were available 90% of the time; however, the PHS tools that were in place prior to the pilot were mature systems that were available >99% of the time.

Availability of the entire CWS was evaluated in terms of percentage of time when one, two, three or four components were concurrently available. Overall, downtime of multiple components was rare. Three of the four components were available >99% of the time, and all four surveillance components were available 78% of the time. The longest periods of multi-component downtime were 26 hours for two components and 8 hours for three components, which were well below the average residence time of contaminated water in the distribution system during simulated contamination scenarios (5.3 days). This indicates that even with multiple components unavailable for a period, it is still likely that a significant contamination incident will be detected by the CWS. For more information, see Section 4.0.

Design Objective: Spatial Coverage

The Cincinnati CWS monitoring and surveillance components were selected and designed to provide redundant coverage throughout the distribution system in order to maximize the potential of the system to detect contamination regardless of injection location. Through a multi-component design, the Cincinnati CWS achieved broad spatial coverage of the study area, which includes the most populous region of the Greater Cincinnati Water Works (GCWW) service area, with approximately 760,000 customers and covering 294 square miles. Area coverage ranged from 72% for WQM to 100% for CCS, PHS and S&A. Population coverage was greater than area coverage, ranging from 84% for WQM to 100% for PHS and S&A.

Results from the simulation study were evaluated to determine the number of contamination scenarios originating from each of the 94 pito zones that were detected by the CWS. (A pito zone is a small region of the distribution system, ranging from 0.3 to 15 square miles, in which water quality and pressure are fairly constant.) This analysis showed that 100% of the scenarios originating from 51 pito zones and

94.1% of scenarios originating from another 38 pito zones were detected by the CWS. The 44 scenarios that were not detected were spread across 43 pito zones, indicating that there is no spatial trend to undetected scenarios. The primary reason that these 44 scenarios were not detected is that they produced low consequences, which generate weak signals and thus are difficult to detect regardless of where the injection occurs. In summary, all regions of the distribution system were effectively covered by the CWS. For more information, see Section 5.0.

Design Objective: Contaminant Coverage

The design of the Cincinnati CWS ensured the system had robust detection capabilities for a variety of contaminants, including nuisance chemicals, toxic chemicals and biological agents. Seventeen contaminants were selected to represent a wide range of contamination threats, and during simulation studies all were found to be detectable by at least one monitoring and surveillance component at a concentration equal to or less than the critical concentrations necessary to cause significant public health or infrastructure consequences.

Table ES-2 presents the ratio of critical concentration to detection threshold for each contaminant across the components. A ratio of 1.0 or greater indicates that the component can detect the contaminant at or below the critical concentration. Conversely, ratios less than 1.0 indicate that the component would not detect the contaminant until the concentration exceeds the critical concentration that would result in adverse public health or infrastructure consequences.

Table ES-2. Ratio of Critical Concentration to Detection Threshold

Contaminant	WQM	CCS	PHS	S&A
Nuisance Chemical 1	4.76	20.0	–	2.00×10^4
Nuisance Chemical 2	33.3	–	–	2.00×10^4
Toxic Chemical 1	225	5.86	458	1,470
Toxic Chemical 2	463	50.5	3,640	3.39×10^4
Toxic Chemical 3	185	22.8	1,640	3.69×10^6
Toxic Chemical 4	104	4.03	290	5.80×10^4
Toxic Chemical 5	57.6	–	668	6,680
Toxic Chemical 6	352	–	850	4.08×10^4
Toxic Chemical 7	1.97	–	950	57.0
Toxic Chemical 8	0.0333	–	300	6.60×10^7
Biological Agent 1	265	88.2	4,500	2.25×10^4
Biological Agent 2	1,310	–	3,940	4.93×10^5
Biological Agent 3	2.40	–	2.40×10^4	24.0
Biological Agent 4	3.57	–	4.54	90.7
Biological Agent 5	7.87	–	10.0	20.0
Biological Agent 6	9.70	–	1.74	5.79×10^4
Biological Agent 7	0.582	–	1.64	3.30×10^5

Results from the simulation study demonstrate that the Cincinnati CWS was able to detect 98% of simulated contamination incidents from an ensemble of 2,015 scenarios involving 17 contaminants and injection locations throughout the entire distribution system. These results demonstrate the value of a multi-component CWS, in which the detection capabilities of the monitoring and surveillance components are complementary and provide broad contaminant coverage. The majority of the 44 scenarios that were undetected involved a contaminant that does not cause acute health effects and is detectable by only a single component. Small, isolated contamination incidents that produced limited consequences were more difficult to detect than incidents producing widespread consequences. For more information, see Section 6.0.

Design Objective: Alert Occurrence

One of the goals of the Cincinnati CWS design is to minimize the number of invalid alerts without compromising the ability of the system to detect real water quality anomalies or public health incidents. Valid alerts are valuable in that they provide early warning of unusual water quality conditions in the distribution system. However, too many invalid alerts can divert personnel from other duties and may ultimately lead to the perception that the CWS is unreliable and therefore unsustainable. The alert rates for all four monitoring and surveillance components decreased during the transition from the optimization phase to the real-time monitoring phase, as is evident from the average number of alerts per reporting period for each of these phases shown in **Table ES-3**.

Table ES-3. Invalid Alerts per Reporting Period During Optimization and Real-time Monitoring

	Average Number of Invalid Alerts per Reporting Period	
Component	**Optimization**	**Real-time Monitoring**
WQM	33	17
ESM	82	23
CCS	17	14
PHS	25	15
System	**152**	**69**

Invalid alerts occurred frequently, with more than 150 alerts during most reporting periods in the first year of operation. However, once the system was optimized by improving the quality of the underlying data (i.e., through improved maintenance of equipment) and updating event detection system configurations to reflect normal variability in the data, the number of invalid alerts was substantially reduced to 69 per reporting period. While most alerts were determined to be invalid, the CWS did detect 84 valid alerts, with more than half caused by unusual system operating conditions or public health events (unrelated to drinking water).

The Cincinnati CWS was designed to include a variety of surveillance tools to increase contaminant coverage as well as the reliability of the system for utility managers that need to decide whether or not contamination may be Possible. Through this multi-component design, weaknesses in the detection capabilities of one component are offset by the strengths of another. Furthermore, co-occurring alerts from multiple components can increase the utility manager’s confidence that the alerts are valid and indicative of a potential water quality issue. The results of the simulation study demonstrate that alert clusters are common for simulated contamination incidents. Specifically, alert clusters occurred in 86% of simulation scenarios detected by the CWS, with three or more components alerting in 50% of the simulated contamination scenarios. In contrast, alert clusters were rare in the empirical data (which did not include any contamination incidents). In fact, a cluster of three component alerts occurred only once in the empirical data, and consisted of invalid alerts. The prevalence of valid alert clusters in the simulated data and the paucity of valid alert clusters in the empirical data would suggest that valid alert clusters involving alerts from multiple components are likely the result of a real water quality issue in the distribution system. For more information, see Section 7.0.

Design Objective: Timeliness of Detection and Response

For a CWS to have the maximum potential to reduce consequences of a contamination incident, it must detect the incident early enough to allow sufficient time to implement response actions under the consequence management plan.

Given that there were no real contamination incidents during the evaluation period, simulated contamination scenarios were used to evaluate this design objective. Results from the simulation study show median detection times less than 7 hours for WQM, CCS and PHS, while ESM typically detected the incident before the start of contaminant injection. During the investigation, the median time for Possible determination was 5.5 hours, just under 6.5 hours for Credible determination, and just under 9.5 hours for Confirmed determination. CCS alerts were almost always generated shortly after the first exposure to contaminated water. While PHS alerts are also driven by exposures, the results showed more variability in the time of PHS alerts due to the delay between exposure and symptom onset. The timing of WQM alerts was strongly dependent on the hydraulic travel time from the injection location to the WQM station. When multiple components detect a simulated contamination incident, threat level escalation and implementation of response actions occurred much more quickly compared to scenarios in which just one component detects contamination.

For simulated contamination scenarios that produced a significant number of fatalities, the response stemming from detection by the CWS facilitated a large reduction in the number of fatalities when compared to the same scenario without CWS detection and response capabilities in place. **Figures ES-1** and **ES-2** show representative scenarios for a biological agent and toxic chemical, respectively, and depict key timeline metrics and primary consequences.

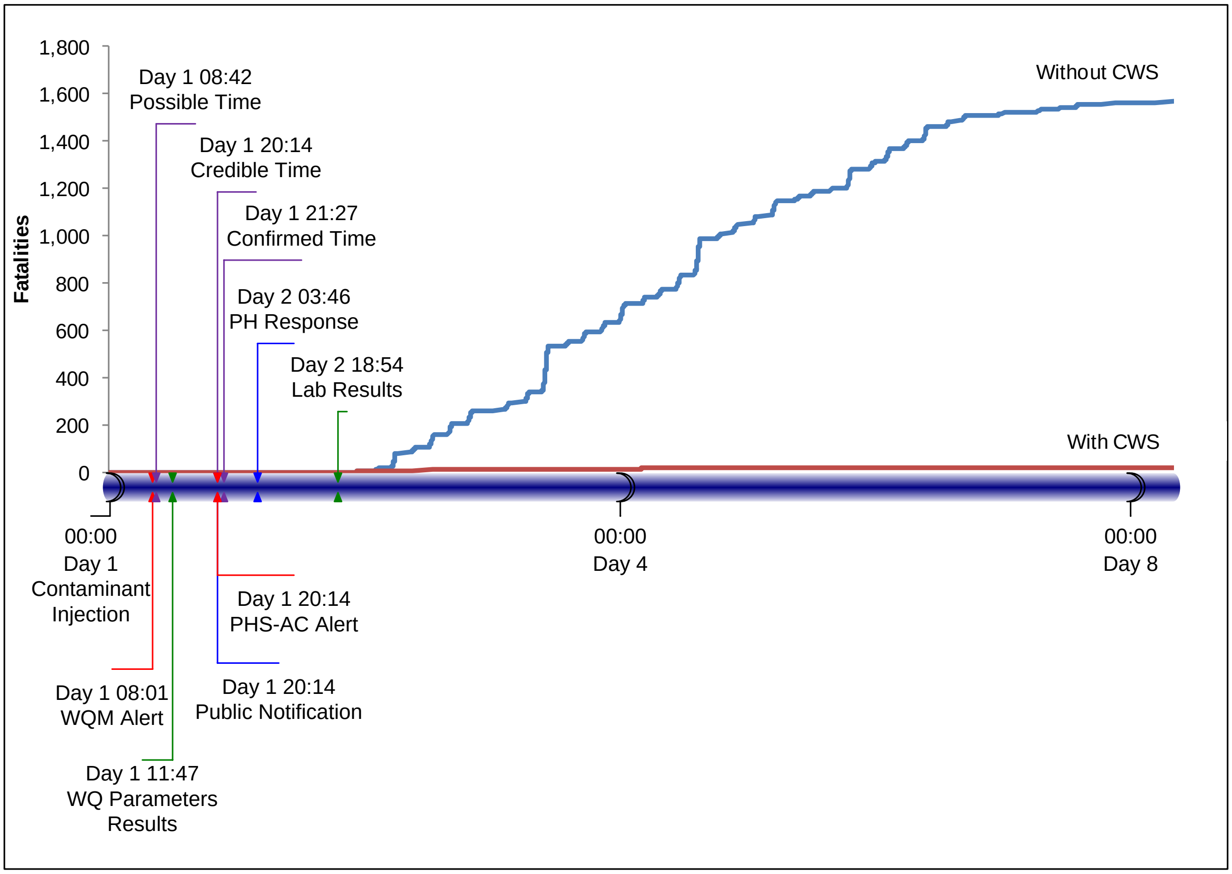

Figure ES-1. Timeline and Consequences for a Contamination Scenario Involving Biological Agent 4

The CWS reduced the number of fatalities by 99% in the scenario involving Biological Agent 4. This reduction in consequences was largely attributable to the public notification being issued early in the response process, which dramatically reduced the number of individuals exposed to the contaminant. Additionally, prophylactic treatment provided as part of the public health response prevented a large number of potential fatalities.

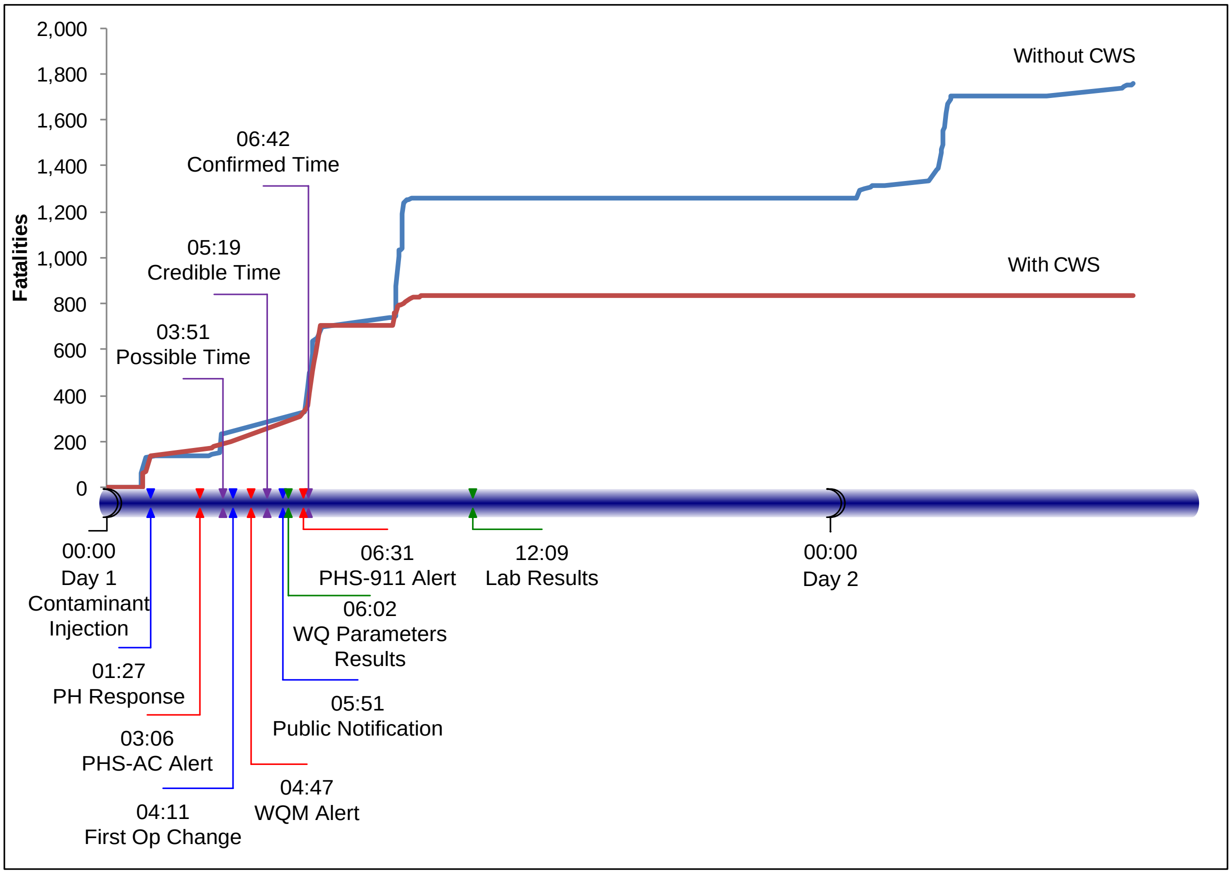

Figure ES-2. Timeline and Consequences for a Contamination Scenario Involving Toxic Chemical 6

The CWS resulted in a 55% reduction in fatalities in the scenario involving Toxic Chemical 6. This reduction in fatalities is primarily due to the public notification, which sharply reduced the number of exposures after individuals complied with the public notification. A typical scenario involving a toxic chemical unfolds quickly, with PHS alerts occurring early in the scenario due to the rapid onset and progression of symptoms, which differs from typical scenarios for biological agents. For more information, see Section 8.0.

Design Objective: Sustainability

A key design objective for the CWS is to develop a sustainable system that provides an acceptable benefit-cost trade-off. The full cost of the CWS is comprised of three broad categories: initial deployment costs, lifecycle operations & maintenance (O&M) expenses and equipment renewal and replacement costs. There is also a small cost offset due to the salvage value of equipment at the end of the lifecycle. The breakdown of these costs for the Cincinnati CWS over a 20-year lifecycle is shown in **Table ES-4.**

Table ES-4. Total Lifecycle Cost of the Cincinnati CWS

Cost Element	Total Cost
Deployment Costs	$11,936,000
Lifecycle O&M Costs	$4,598,000
Renewal and Replacement Costs	$2,569,000

Cost Element	Total Cost
Salvage Value	($127,000)
Lifecycle Cost	**$18,976,000**

A benefit-cost analysis was performed to evaluate whether the monetized benefits of a CWS were greater than the total lifecycle cost of the Cincinnati Pilot. Thirty scenarios, three scenarios each for ten contaminants, were evaluated during the benefit-cost analysis. **Table ES-5** shows the benefits, in millions of dollars, for the scenario with median consequences for each contaminant. The monetized benefits exceeded the total lifecycle cost of the CWS for 23 (77%) of the scenarios and was more than 100 times the cost of the CWS in 19 (63%) of the scenarios. The primary driver of monetized benefits for most scenarios was the reduction in public health consequences of water contamination.

Table ES-5. Benefits Attributable to the Cincinnati CWS due to the Reduction in Consequences from a Contamination Incident

Contaminant ID	Total Value
Nuisance Chemical 1	$6 million
Toxic Chemical 1	$462 million
Toxic Chemical 5	$72 million
Toxic Chemical 6	$2,605 million
Toxic Chemical 7	$252 million
Toxic Chemical 8	$252 million
Biological Agent 3	$145,027 million
Biological Agent 4	$9,789 million
Biological Agent 5	$30,097 million
Biological Agent 6	$14 million

Despite demonstrating significant monetized benefits in this analysis, the probability of water contamination is very low. Thus, the business case for deploying a CWS depends largely on dual-use benefits realized through the Cincinnati CWS. For example, GCWW was able to utilize WQM sensors to optimize chlorine residuals throughout the distribution system, reducing the overall chlorine dose and associated costs. Several non-monetizable benefits were realized across multiple CWS components including the ability to detect a wide range of distribution system water quality issues. Additionally, the Cincinnati CWS demonstrated benefits to business practices, such as improved communication and coordination within the utility and its external partners. Overall, the investment in the CWS improved the response posture of GCWW and the local partners for “all hazards.”

Management and personnel from GCWW and local partners demonstrated a strong willingness to maintain the CWS beyond the pilot. This was demonstrated in the high rate of alert investigations (greater than 90%) after the CWS was optimized. Furthermore, active participation in drills and exercises indicated a willingness to adopt the CWS components and procedures. Finally, GCWW is considering upgrading the WQM component and continues to engage local partners through the Public Health Users Group. For more information, see Section 9.0.

Summary and Conclusions

Evaluation of the Cincinnati pilot produced a comprehensive assessment of the multi-component CWS design deployed under WSI. Through layers of redundancy built into the CWS and each of its components, the system achieved a high degree of operational reliability during the evaluation period.

The multi-component Cincinnati CWS achieved comprehensive contaminant and spatial coverage through the implementation of a variety of data streams and monitoring points throughout GCWW's distribution system. Analysis of simulation study results showed a 98% detection rate for 2,015 simulated contamination scenarios, which emphasizes the value of a multi-component CWS, in which the detection capabilities of the monitoring and surveillance components are complementary and provide broad contaminant coverage. For the contaminant coverage and timeliness of detection capabilities, weaknesses in the capabilities of one component are offset by the strengths of another. Moreover, simulation study results emphasized that timely detection and threat level determination lead to quicker implementation of response actions and a significant reduction in consequences.

The overall success of a CWS depends not only on reliable data, but also requires the commitment of utility personnel and external partners who are aware of the possible causes of changes in observed water quality data, customer complaints, or trends in public health data. In Cincinnati, this was accomplished and demonstrated by a strong commitment of utility personnel and local partners to maintain the CWS. The overarching goal of the CWS – to improve situational awareness such that potential water quality issues in the distribution system can be quickly detected and proactively addressed – was achieved during the Cincinnati pilot through deployment of a multi-component monitoring and surveillance system combined with "all-hazards" response planning.

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Section 1.0: Introduction

The purpose of this document is to describe the evaluation of the Cincinnati contamination warning system (CWS) pilot, the first such pilot deployed under the United States Environmental Protection Agency's (EPA) Water Security Initiative (WSI). The following subsections of the introduction present the CWS design objectives, the overall objectives of the evaluation and the organization of this report.

1.1 Contamination Warning System Design Objectives

The Cincinnati CWS was designed to meet six overarching objectives, which are described in detail in *WaterSentinel System Architecture* (USEPA, 2005) and are presented briefly below:

- **Operational Reliability**. The objective of this aspect of CWS design is to achieve a sufficiently high degree of system availability such that the probability of missing a contamination incident becomes exceedingly low. This design objective is met through redundancies built into the CWS and each of its components. Metrics evaluated under this design objective include: data completeness and availability.
- **Spatial Coverage**. The objective of this aspect of CWS design is to monitor the entire population served by the drinking water utility. This design objective depends on the location and density of monitoring points in the distribution system and the hydraulic connectivity of each monitoring point to downstream regions and populations. Metrics evaluated under this design objective include: area coverage and population coverage.
- **Contaminant Coverage**. The objective of this aspect of CWS design is to provide detection capabilities for all priority contaminants. This design objective is further defined by binning the priority contaminants into 12 classes according to the means by which they might be detected (USEPA, 2005). Use of these detection classes to inform design provides more comprehensive coverage of contaminants of concern than would be achieved by designing the CWS around a handful of specific contaminants. Contaminant coverage is largely determined by the specific data streams analyzed by each monitoring and surveillance component. Metrics evaluated under this design objective include: contaminant detection threshold and contamination scenario coverage.
- **Alert Occurrence**. The objective of this aspect of CWS design is to minimize the rate of invalid alerts (alerts unrelated to drinking water contamination or other unusual water quality conditions) while maintaining the ability of the system to detect real incidents. This design objective depends on the quality of the underlying data as well as the event detection systems that analyze that data for anomalies. Metrics evaluated under this design objective include: invalid alert occurrence, valid alert occurrence and alert co-occurrence.
- **Timeliness of Detection and Response**. The objective of this aspect of CWS design is to provide initial detection of a contamination incident in a timeframe that allows for the implementation of response actions that result in significant consequences reduction. Metrics evaluated under this design objective include: detection time, response time and consequence reduction.
- **Sustainability**. The objective of this aspect of CWS design is to provide benefits to the utility and partner organizations while minimizing the costs. This can be achieved by leveraging existing systems and resources that can readily be integrated into the design of the CWS. Furthermore, a design that results in dual-use applications that benefit the utility's day-to-day

operations while also providing the capability to detect intentional or accidental contamination incidents, will also improve sustainability. Metrics evaluated under this design objective include: net present value, dual-use benefits and willingness to maintain the CWS.

1.2 Evaluation Objectives

The purpose of WSI was to pilot and evaluate a drinking water CWS. The lack of established design standards for the relatively new CWS concept precluded an evaluation of system performance in absolute terms. Instead, the Cincinnati CWS was evaluated to characterize how well it met the design objectives described above. Several sources of information were used to conduct this evaluation, including data collected during routine operation, drills and exercises, and computer simulations.

Evaluation of the Cincinnati CWS pilot was performed at both the system and component level. This report presents results from the evaluation of the integrated CWS. Six additional reports, which are listed in Section 11, present the results from the detailed evaluation of each of the primary CWS components. Both the system and the components were evaluated against the design objectives using the same general metrics. However, the system evaluation considers the performance of the integrated CWS and characterizes metrics that are applicable only to the system as a whole, such as the potential reduction in consequences of a contamination incident. Furthermore, the CWS evaluation report does not present a detailed analysis of the performance of individual components, which can be found in the component evaluation reports.

1.3 Organization of this Report

This document contains the following sections:

- **Section 2: Overview of the Cincinnati CWS**. This section provides a brief overview of each component of the Cincinnati CWS and presents a summary of significant milestones and modifications made to the CWS during the evaluation period of the pilot.
- **Section 3: Methodology**. This section describes the data sources and techniques used to evaluate the Cincinnati CWS.
- **Sections 4 through 9: Evaluation of CWS Performance relative to the Design Objectives**. Each of these sections addresses one of the design objectives listed in Section 1.1. Each section introduces the metrics that will be used to evaluate the CWS relative to that design objective. Each of these metrics is discussed in a dedicated subsection that defines the metric, provides an overview of the evaluation method, and presents the results.
- **Section 10: Summary and Conclusions**. This section provides an overall summary of Cincinnati CWS performance and discusses limitations and applications of the results.
- **Section 11: References**. This section lists all sources and documents cited in this report.
- **Section 12: Abbreviations**. This section defines all abbreviations used in this report.
- **Section 13: Glossary**. This section provides definitions for terms used in this report.
- **Appendix A: Cincinnati Contamination Warning System Model**. This appendix describes the Cincinnati CWS model used in the simulation study as well as the design of the study itself.
- **Appendix B: Benefit-Cost Analysis Methodology**. This appendix describes the methodology and assumptions used to evaluate the net present value of the Cincinnati CWS.

Section 2.0: Overview of the Cincinnati CWS

The overall architecture of the Cincinnati CWS is presented in **Figure 2-1**, which shows two operational paradigms: 1) monitoring and surveillance and 2) response. Monitoring and surveillance consists of the following four components: enhanced security monitoring, water quality monitoring, customer complaint surveillance and public health surveillance.

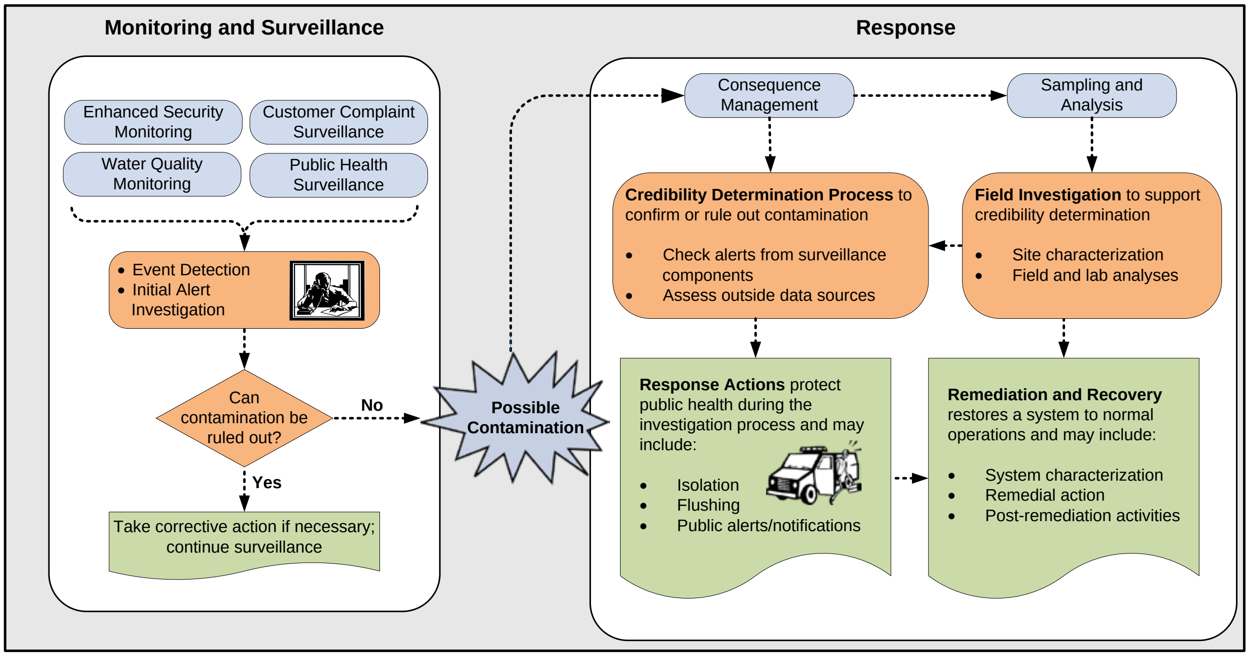

Figure 2-1. CWS Architecture

The purpose of routine monitoring and surveillance is to detect unusual water quality conditions that may be indicative of possible drinking water contamination. The monitoring and surveillance components are not designed to detect specific contaminants, but rather changes from baseline conditions that warrant further investigation (or in the case of enhanced security monitoring, detect unauthorized access to a drinking water distribution system facility). If the conclusion from the initial investigation is that the alert is valid, CWS operations transition to response. During response, the investigation of the Possible contamination incident continues under consequence management in an attempt to determine whether or not contamination is Credible. Additionally, procedures under sampling and analysis are used in an attempt to confirm the incident and identify the contaminant. Consequence management also guides response actions that are intended to protect utility infrastructure and the public from potentially contaminated drinking water while the investigation proceeds.

The six components that make up the Cincinnati CWS are described in more detail in the following subsections.

2.1 Enhanced Security Monitoring

Enhanced security monitoring (ESM) is one of the four monitoring and surveillance components of a CWS. This component includes the systems, equipment and procedures for detecting and responding to security breaches at distribution system facilities such as pump stations, elevated storage tanks and reservoirs that are vulnerable to contamination. At GCWW, ESM capabilities were installed at 12 distribution system facilities. ESM data streams consist of 59 pieces of physical security equipment such as motion sensors, video cameras and magnetic proximity switches, which are monitored using associated response procedures. ESM alerts are transmitted over the utility's Supervisory Control and Data Acquisition (SCADA) network to the control facility at the main treatment plant where they are displayed on a SCADA interface.

The status of the ESM component is monitored 24/7, 365 days a year via the SCADA user interface. A physical security breach that generates an alert initiates an investigation to determine whether or not the intrusion presented an opportunity to contaminate drinking water. The investigation includes a review of video clips (if available) and a physical site inspection to verify an intrusion. If video or on-site evidence corroborates the security breach and potential access to the drinking water, contamination is considered Possible. A detailed evaluation of the ESM component of the Cincinnati CWS can be found in *Water Security Initiative: Evaluation of the Enhanced Security Monitoring Component of the Cincinnati Contamination Warning System Pilot* (USEPA, 2014b).

2.2 Water Quality Monitoring

Water quality monitoring (WQM) is one of the four monitoring and surveillance components of a CWS. This component consists of a network of monitoring stations located throughout a drinking water distribution system, a data management system, and procedures for responding to alerts. At GCWW, there are 15 WQM stations with sensors representing a total of 82 data streams installed throughout the distribution system, as well as a monitoring station at each of the two treatment plants. The data from the two treatment plant monitoring stations are not used to detect contamination, but instead to facilitate the investigation and validation of alerts produced by any of the 15 monitoring stations in the distribution system. Specifically, data from the two monitoring stations located at the treatment plants provides a benchmark for water quality in the distribution system. The parameters monitored include free chlorine residual, specific conductivity, oxidation reduction potential, pH, temperature, total organic carbon and turbidity.

Data from the remote WQM stations are polled every two minutes and transmitted via digital cellular to a centralized SCADA system. The SCADA system collects and displays the data from all monitoring stations in real time. Simultaneously, the data is transmitted to an event detection system, which is an algorithm that continually analyzes water quality data, along with metadata such as sensor alerts and data quality flags, to monitor for changes in water quality triggered by abnormal conditions. If abnormal conditions are detected, a visual and audible alert is generated.

The status of the WQM component is monitored 24/7, 365 days a year via the SCADA user interface. Unusual water quality that generates a WQM alert initiates an investigation to determine the cause of the alert. The investigation considers plausible causes, and may include a site inspection to verify that the equipment is functioning properly. If all reasonable explanations and likely benign causes are ruled out, contamination is considered Possible. A detailed evaluation of the WQM component of the Cincinnati CWS can be found in *Water Security Initiative: Evaluation of the Water Quality Monitoring Component of the Cincinnati Contamination Warning System Pilot* (USEPA, 2014c).

2.3 Customer Complaint Surveillance

Customer complaint surveillance (CCS) is one of the four monitoring and surveillance components of a CWS. This component involves monitoring customer complaints about water quality to identify degradation of distributed water quality, potentially including contamination. Customers may detect contaminants with characteristics that impart an odor, taste, or visual change to the drinking water or that result in instantaneous symptoms such as a mild dermal irritation.

Three independent data streams are monitored: Interactive Voice Response (IVR), work request and work order systems. The IVR allows customers to self-select whether they are calling about a water quality concern by pushing the corresponding number on the phone (i.e., push 5 for a water quality concern). A customer service representative may generate a work request if, after interviewing the caller, (s)he believes that additional investigation of the complaint is warranted by a water quality specialist. Upon review, the specialist may convert the work request into a work order to initiate the requested follow-up action. A custom event detection system analyzes each data stream independently in real time. If the event detection system detects an anomaly, automated email alerts are generated. While the work request data stream was monitored and maintained through January 2009, GCWW disabled alert generation for this data stream as part of the transition to real-time analysis. After a year of receiving alerts, GCWW deemed the data stream to be redundant with the work order data stream. The work request data stream is included only in analyses that cover the optimization period up until the transition to real-time analysis.

The status of the CCS component is monitored by call center personnel during normal business hours and by a dispatcher during off hours. When a CCS alert is generated, the complaints are first examined to determine whether they are spatially clustered and/or have similar complaint descriptions. If so, the investigator reviews other information such as distribution system work and operations for possible benign causes of the alert. If the investigators conclude that the calls are unrelated, the investigation into possible contamination is closed, and regular procedures for customer complaint follow-up are implemented. If the complaints are clustered and there is no benign explanation for the complaints, contamination is considered Possible. A detailed evaluation of the CCS component of the Cincinnati CWS can be found in *Water Security Initiative: Evaluation of the Customer Complaint Surveillance Component of the Cincinnati Contamination Warning System Pilot* (USEPA, 2014d).

2.4 Public Health Surveillance

Public health surveillance (PHS) is one of the four monitoring and surveillance components of a CWS. This component involves monitoring health seeking behaviors in an effort to detect the early signs of a public health incident in a community. Most of the priority contaminants considered under WSI can cause serious health effects to individuals exposed to a sufficiently high dose. Presumably, some of the symptomatic individuals would seek healthcare, and in sufficient numbers, these health seeking behaviors can produce a PHS alert.

In the Cincinnati CWS pilot, the following public health surveillance data streams are monitored: 911 calls, emergency medical service logs, Cincinnati Drug and Poison Information Center (DPIC) calls, emergency department (ED) visits (including both hospital and urgent care facilities) and reporting from astute clinicians. This diverse set of data streams has the potential to detect contaminants that produce rapid onset of symptoms following exposure, as well as those with delayed symptom onset. However, for this evaluation only the PHS systems that were installed for the pilot are included in analyses. Operational reliability was evaluated for only the 911 and EMS data streams, while alert occurrence was evaluated for the 911, EMS and DPIC data streams.

Each of the data streams listed above has a unique monitoring and notification strategy. Alerts from the 911 or emergency medical service data streams are automatically emailed to members of a PHS User Group, which includes members from the county and city health departments, DPIC, GCWW and law enforcement. Distribution of alerts to this diverse group facilitates information sharing from a variety of sources during the alert investigation. The DPIC call center is staffed 24/7, 365 days a year by trained personnel. ED data is monitored by EpiCenter, an automated syndromic surveillance tool that can send alert notifications to personnel at the county and city health departments. Reporting from astute clinicians is an informal surveillance method that relies upon the observations of healthcare providers to alert public health officials when they observe unusual symptoms or diseases in their patients.

Once an alert is received, it is reviewed by personnel from the health department or DPIC. If the reviewer believes that the alert is possibly related to drinking water contamination, they implement a process called the "communicator," which is an autodialing system used to send out a message to all members of the PHS User Group. Typically, a call is convened to review and evaluate the alert. If the PHS User Group concludes that the alert is a valid indicator of a public health incident, and if the causative agent could have been delivered via the drinking water supply, then contamination is considered Possible. A detailed evaluation of the PHS component of the Cincinnati CWS can be found in *Water Security Initiative: Evaluation of the Public Health Surveillance Component of the Cincinnati Contamination Warning System Pilot* (USEPA, 2014e).

2.5 Consequence Management

Consequence management (CM) is one of the two response components of a CWS. This component includes the plans and procedures that govern the investigation of and response to a Possible, Credible, or Confirmed contamination incident. These procedures are meant to minimize response and recovery timelines through a pre-planned, coordinated effort. Investigative and response actions initiated upon determination of a possible contamination incident are used to establish credibility, minimize public health and economic consequences and ultimately return the utility to normal operations.

The procedures that govern consequence management are documented in a Consequence Management Plan (CMP). The CMP consists of a series of decision trees that guide the investigation to determine if the contamination incident is Credible or Confirmed and the implementation of response actions to minimize consequences.

The threat level determination process in CM involves the collection of additional information related to the Possible contamination incident from a variety of sources, including all monitoring and surveillance components as well as sampling and analysis activities, which are discussed in Section 2.6. If there is sufficient information to corroborate the initial alert(s), contamination is considered Credible. If sampling and analysis activities identify a contaminant in a sample from the distribution system or if there is a preponderance of evidence from a variety of sources, contamination is Confirmed. A determination that contamination is Credible or Confirmed may result in elevated response actions.

Response actions taken during consequence management are intended to minimize public health consequences and contamination of utility infrastructure. A range of response actions is available to the utility, and the level of response action generally correlates with the threat level (i.e., more aggressive response actions will be considered when the contamination incident is considered Credible compared to Possible). While the response actions are situation-specific, potential response actions to contamination can be grouped into three categories: operational response, public notification and public health response.

Operational response typically involves the manipulation of distribution system control points (e.g., pumps, valves, tanks, etc.) to either limit the spread of potentially contaminated water or to purge it from the system. In general, operational responses are considered as early as the time when contamination is considered Possible. However, the impact of a specific operational response on utility operations, customers and the environment must be considered in the context of the threat level.

Public notification involves direct communication to the public and often includes instructions regarding use restrictions (e.g., Do not drink or Do not use). The intent of public notification is to limit exposure to potentially contaminated water. Because issuance of a use restriction has a serious impact on the public, the utility would implement such an action only if contamination were considered Credible or Confirmed.

Unlike the previous two response actions, public health response is not implemented by the utility, but instead by public health officials in response to a developing public health crisis. In fact, public health response may be implemented independent from the utility and any potential connection to contaminated water. Public health response might include mobilization of additional medical resources and issuance of prophylaxis. In extreme cases, public health or government officials may recommend temporary evacuations to remove the public from the source of exposure.

A detailed evaluation of the CM component of the Cincinnati CWS can be found in *Water Security Initiative: Evaluation of the Consequence Management Component of the Cincinnati Contamination Warning System Pilot* (USEPA, 2014f).

2.6 Sampling and Analysis

Sampling and analysis (S&A) is one of the two response components of a CWS. This component is a support function under CM that provides information to the threat level determination process and decisions regarding response, remediation, and recovery actions. S&A includes the capabilities, equipment and procedures for conducting site characterization (SC) and laboratory analysis (LA) during the investigation of a contamination incident. SC and LA are the two primary processes undertaken when S&A is activated in response to a possible water contamination incident.

SC involves the collection of information from a location in the distribution system to support the threat level determination process. SC activities include site approach and observation, field safety screening, rapid field testing of drinking water at the site and collection of samples for laboratory analysis. The location of a SC will be situation-specific; however, SC teams are often dispatched to the location of an alert from one of the four monitoring and surveillance components. SC activities performed at the location of an ESM alert are unique in that the investigation could show signs of tampering at a utility facility that would inform the threat level determination process. For all other sites, information to inform the threat level determination process may be limited to the results from field testing of water. Depending on the perceived hazards at the site, SC may be performed by either trained utility personnel or by Hazmat responders.

Samples collected from the field during SC are delivered to laboratories for further analysis. This involves transport of samples from the field to one or more laboratories using chain of custody procedures, laboratory and method mobilization, sample analysis, quality control (QC) procedures and reporting of the results. LA is pre-planned to identify laboratories and methods prior to an incident in order to streamline the process and reduce the time between sample collection and reporting. Because the identity of a potential contaminant is often unknown during a suspected, but unconfirmed, contamination incident, GCWW identified a baseline suite of analytes that would be included in any laboratory investigation into a contamination incident. Analytes outside of this baseline suite would be analyzed only if evidence was available to implicate a potential contaminant outside of the baseline suite.

A detailed evaluation of the S&A component of the Cincinnati CWS can be found in *Water Security Initiative: Evaluation of the Sampling and Analysis Component of the Cincinnati Contamination Warning System Pilot* (USEPA, 2014g).

2.7 CWS Evaluation Timeline

The Cincinnati CWS was fully deployed and operational by the end of 2007 and a detailed description of the CWS at this point in the project can be found in *Water Security Initiative: Cincinnati Pilot Post-Implementation System Status* (USEPA, 2008). **Figure 2-2** shows the significant activities that occurred during the pilot from January 2008 through June 2010. Two phases of the pilot occurred during this period, the optimization phase and the real-time monitoring phase.

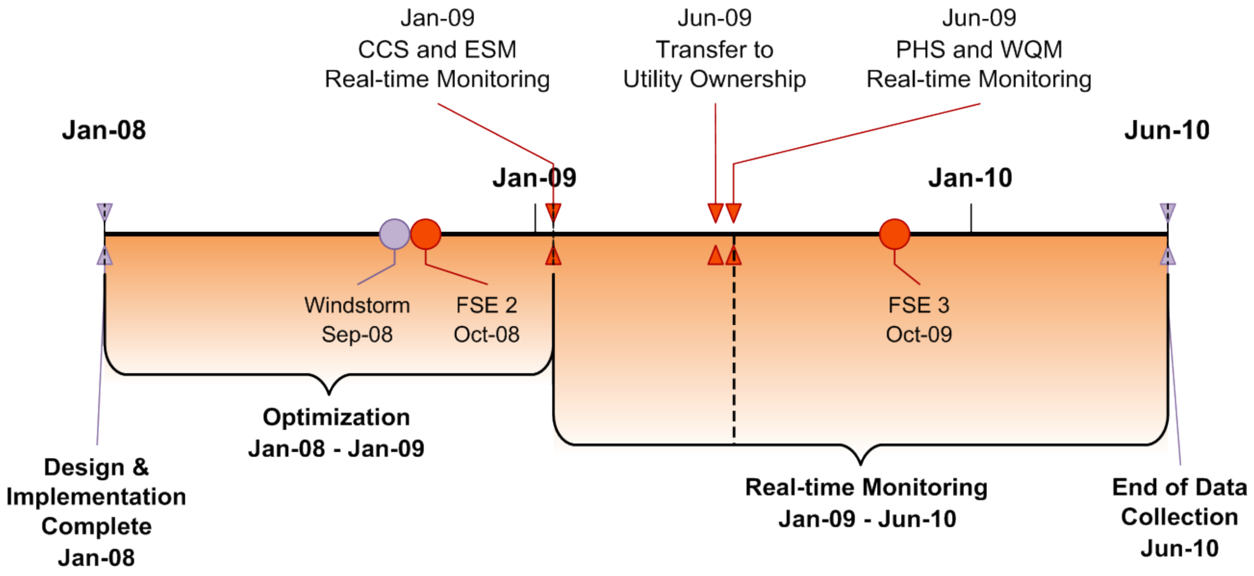

Figure 2-2. Timeline for Optimization and Real-time Monitoring of the Cincinnati CWS

The optimization phase lasted from January 2008 through January 2009, and represents a period during the pilot when the components were fully operational but not deemed ready for real-time monitoring. During the optimization phase, components generated data, which was analyzed to demonstrate performance relative to several key metrics such as availability, alert rates, data accuracy and completeness and the level of effort required to maintain the component. Findings from this ongoing evaluation were used to modify the system in an effort to improve performance. During this phase, there was one full-scale exercise (FSE) and several smaller drills and exercises, which are not shown in this figure but are described in Section 3.2. These drills and exercises were used to assess implementation of procedures by utility personnel and local partners, and the findings were used to optimize procedures. There was also a major incident during this period, a windstorm that interrupted the power supply throughout the city, which occurred in September 2008. This event had a significant impact on CWS performance, as discussed later.

January 2009 marked the start of the transition to real-time monitoring, the period during which CWS alerts were immediately investigated when they occurred. During this period, procedures were implemented to ensure that alerts were acknowledged and investigated 24/7. CCS and ESM were the first two components to begin real-time monitoring in January 2009. The transition of WQM to real-time monitoring occurred in stages from January to June 2009 when the transition was completed. PHS also completed the transition to real-time monitoring during June 2009. Coincidentally, the formal agreement between EPA and the City of Cincinnati ended in June 2009, at which time ownership of the Cincinnati CWS was completely transferred over to GCWW and its partners. Through June 2009, EPA and its contractors provided support for operation and maintenance of the CWS, but following this transfer of ownership, GCWW assumed these responsibilities. The period between June 2009 and June 2010 provided 13 months of data collection during real-time monitoring, which is indicative of expected performance for a stable, optimized CWS. The final FSE was conducted during this period in October 2009 and provided an opportunity to evaluate personnel implementation of the fully tested and optimized procedures developed during the pilot.

Section 3.0: Methodology

This evaluation includes data on the performance, operation and sustainability of the Cincinnati CWS from January 16, 2008 to June 15, 2010. The following section describes six evaluation techniques and data sources that were used to fully evaluate the performance of the Cincinnati CWS against the design objectives described in Section 1.1: empirical data from routine operations, results from drills and exercises, results from computer simulations of the Cincinnati CWS, results from a benefit-cost analysis, findings from forums such as lessons learned workshops and information from literature and research.

3.1 Analysis of Empirical Data from Routine Operations

The preferred method for evaluating the performance of the Cincinnati CWS was through the analysis of empirical data collected during the evaluation period. Empirical data was analyzed over time to illustrate the change in performance as the CWS evolved during the evaluation period. Statistical methods were also used to summarize large volumes of data collected over either the entire or various segments of the evaluation period. Data was also evaluated and summarized for each reporting period over the evaluation period. In this evaluation, the term reporting period is used to refer to one month of data that spans from the 16th of the indicated month to the 15th of the following month. Thus, the January 2008 reporting period refers to the data collected between January 16, 2008 and February 15, 2008.

One of the primary sources of empirical data used in the evaluation was the investigation checklists that were completed for CWS alerts and which documented information such as alert time, location and cause. Other sources of empirical data used in the evaluation include: O&M logs, labor reporting records and other databases used to manage data from the CWS.

3.2 Drills and Exercises

During the evaluation period, no Possible contamination incidents were detected, and thus some procedures were not utilized during routine operations. Drills and exercises, designed around mock contamination incidents were used to practice and evaluate the full range of procedures, from initial detection through response. Drills and exercises also provided an opportunity to identify procedures requiring modification to achieve the desired outcome in an effective and efficient manner. All of the drills and exercises that were designed to test and evaluate the Cincinnati pilot were compliant with Homeland Security Exercise and Evaluation Program guidelines. Findings from drills and exercises were used to evaluate several aspects of CWS performance, such as timeliness of decisions and response actions. Nineteen drills and two FSEs were conducted over the course of the evaluation period. Note that there was one FSE (FSE 1) that was conducted prior to the evaluation period, and thus is not included in this analysis. **Table 3-1** provides the date and a brief description of each drill or exercise and indicates which components were included.

Table 3-1. Drills and Exercises Performed during the Pilot Evaluation Period

Drill	Date	Description
S&A Drill 1	05/07/08	Evaluated incident response procedures, along with related CM activities.
ESM Drill 1	06/26/08	Evaluated interactions among local law enforcement and GCWW Security and Distribution Division personnel in response to an ESM alert.
WQM Drill 1	07/14/08	Evaluated response to an initial alert caused by changes in chlorine and conductivity, followed by an alert caused by a change in total organic carbon (TOC).
S&A Drill 2	07/15/08	Provided GCWW SC team members and Cincinnati Fire Department Hazardous Material (HazMat) responders with an opportunity to cross-train on SC procedures.

Drill	Date	Description
CCS Drill 1	08/19/08	Evaluated alert recognition and investigation procedures through various alert notification methods where simulated customer complaints produced both IVR and work request alerts.
PHS Drill 1	08/22/08	Evaluated the alert investigation procedures and the interactions between local public health partners and the GCWW Water Utility Emergency Response Manager (WUERM).
FSE 2	10/01/08	Provided an opportunity for the utility and local response partner agency to exercise procedures related to the detection of and response to a drinking water contamination incident. This exercise involved WQM, CCS, PHS, S&A and CM.
WQM Drill 2	02/25/09	Evaluated changes made to the component alert investigation procedures based on results from the first WQM drill and FSE 2.
ESM Drill 2	03/11/09	Evaluated interactions among local law enforcement and GCWW Security and Distribution Division personnel in response to an ESM alert.
S&A Drill 3	03/31/09	Evaluated procedures that guide interactions between GCWW and laboratories as well as the receipt and interpretation of laboratory results.
PHS Tabletop Exercise	04/22/09	Evaluated the ability of GCWW and local public health partners to determine if a simulated PHS alert was due to drinking water contamination.
S&A Drill 4	04/23/09	Evaluated the implementation of revised SC and sample collection procedures.
WQM Drill 3	04/29/09	Evaluated implementation of alert investigation procedures during non-business hours by personnel that had not previously participated in a drill.
CCS Drill 2	04/29/09	Evaluated alert recognition and investigation procedures through various alert notification methods where simulated customer complaints produced both IVR and work request alerts.
ESM Drill 3	04/30/09	Evaluated interactions among local law enforcement and GCWW Security and Distribution Division personnel in response to an ESM alert.
PHS Drill 2	07/28/09	Provided local public health partners and the GCWW WUERM the opportunity to practice PHS alert investigation procedures.
CCS / S&A Drill	09/16/09	Evaluated the alert recognition and investigative procedures associated with the CCS component and implementation of the SC procedures as they relate to field deployment and investigation following a CCS alert.
FSE 3	10/21/09	Evaluated utility and local response partner agency protocols, including implementation of the Incident Command System, external notifications, resource coordination, media relations and the execution of field investigation procedures. This exercise involved CCS, PHS, S&A and CM.
ESM Drill 4	04/13/10	Evaluated interactions among local law enforcement and GCWW Security and Distribution Division personnel in response to a witness account of an intrusion.
CCS Drill 3	04/15/10	Evaluated implementation of alert investigation procedures during non-business hours.
S&A Bioterrorism (BT) Agent Drill	05/10/10	Practiced SC and partner laboratory capabilities, including internal notification procedures to prepare to receive and analyze samples using the Laboratory Response Network BT Agent Screening Protocol.

3.3 Simulation Study

Evaluation of certain design objectives relies on the occurrence of contamination incidents with known and varied characteristics (Davis and Janke, 2011; Davis, Janke and Magnuson, 2013). Because there were no contamination incidents during the evaluation period, there is no empirical data to fully evaluate the detection capabilities of the Cincinnati CWS. To fill this gap, a computer model of the Cincinnati CWS was developed and challenged with a large ensemble of simulated contamination incidents in a simulation study. A detailed description of the Cincinnati CWS model is provided in Appendix A of this report. This section describes the design of the simulation study that generated the data used in the evaluation.

To perform a robust evaluation of system performance, the simulation study was designed to challenge the Cincinnati CWS model with a wide range of contamination scenarios. The attributes that defined a contamination scenario in this study include: contaminant, injection location, start time of the injection, and mass injection rate. Each attribute is further described below.

Contaminant

A broad range of contaminant types producing a range of symptoms was selected for the simulation study in order to characterize the detection capabilities of the monitoring and surveillance components of a CWS (http://www.epa.gov/wcit). For the purpose of the simulation study, a representative set of 17 contaminants was selected from the comprehensive contaminant list that formed the basis for CWS design. These contaminants are grouped into the following broad categories (the number in parentheses indicates the number of contaminants from that category that were simulated during the study):

- **Nuisance Chemicals (2).** These chemicals have a relatively low toxicity and thus generally do not pose an immediate threat to public health, but can make the drinking water supply unusable (e.g., dyes and malodorants).
- **Toxic Chemicals (8).** These chemicals are highly toxic and pose an acute risk to public health at relatively low concentrations (e.g., pesticides).
- **Biological Agents (7).** These materials are derived from biological sources and pose an acute risk to public health at relatively low concentrations (e.g., bacterial pathogens).

These 17 contaminants also presented a range of detection challenges. **Table 3-2** lists the 17 contaminants, indicating which of the monitoring and surveillance components have the potential to detect each. This assessment of detection potential was based largely on literature review and research, as discussed in Section 3.6, and was used to parameterize the Cincinnati CWS model. ESM is not shown in the table because the detection capabilities of this component are contaminant neutral.

Table 3-2. Theoretical Detection Capabilities of the CWS Relative to the Contaminants Modeled in the Simulation Study

Contaminant[1]	WQM	CCS[2]	PHS	S&A[3]
Nuisance Chemical 1	Yes	Yes	No[4]	Yes
Nuisance Chemical 2	Yes	No	No[4]	Yes
Toxic Chemical 1	Yes	Yes	Yes	Yes
Toxic Chemical 2	Yes	Yes	Yes	Yes
Toxic Chemical 3	Yes	Yes	Yes	Yes
Toxic Chemical 4	Yes	Yes	Yes	Yes
Toxic Chemical 5	Yes	No	Yes	Yes
Toxic Chemical 6	Yes	No	Yes	Yes

Contaminant[1]	WQM	CCS[2]	PHS	S&A[3]
Toxic Chemical 7	Yes	No	Yes	Yes
Toxic Chemical 8	Yes	No	Yes	Yes
Biological Agent 1	Yes	Yes	Yes	Yes
Biological Agent 2	Yes	No	Yes	Yes
Biological Agent 3	Yes	No	Yes	Yes
Biological Agent 4	Yes	No	Yes	Yes
Biological Agent 5	Yes	No	Yes	Yes
Biological Agent 6	Yes	No	Yes	Yes
Biological Agent 7	Yes	No	Yes	Yes

[1] The 17 contaminants modeled in the simulation study were assigned generic IDs for security purposes.

[2] Detection by CCS is possible only for contaminants that change the aesthetic character of the water in a manner that can be detected via the human senses.

[3] S&A is not considered an early detection component, but is included in this table to show the detection capabilities of this response component relative to the three monitoring and surveillance components.

[4] Based on design of simulation model, early detection via PHS does not apply to nuisance chemicals. For Nuisance Chemical 1, customers would detect odor and not consume a sufficient volume of water to produce adverse health effects. For Nuisance Chemical 2, concentrations are sufficient to produce only long-term, chronic health effects, which are not considered in this model.

Injection Location

The location where the contaminant is injected into the system has a direct and dramatic impact on consequences. It plays a role in defining the flow path of the contaminant through the system as well as to the downstream users who could be exposed to harmful concentrations of the contaminant. Given that there is no prior knowledge of the location of an intentional contamination incident, it was assumed that all distribution system model nodes are potential attack locations, with the exclusion of nodes with zero demand and nodes at terminal points in the distribution system. Applying these criteria to the GCWW distribution system model resulted in 5,799 potential injection locations. Two types of contaminant injection locations were simulated: sites at GCWW facilities and sites at distribution system nodes. Scenarios in which the injection was simulated at a distribution system node are referred to as distribution system attack scenarios, while those in which the injection was simulated at a utility facility are referred to as facility attack scenarios.

Injection Start Time

The start time of the injection will also impact the magnitude and distribution of consequences due to diurnal variations in flow patterns and water demand. In this study, two injection start times were selected based on the maximum and minimum total modeled demands across the entire distribution system. The 9:00 a.m. start time was selected to represent an injection commencing during a period of the day when the total demand across the system was large and sustained for a significant duration. The 12:00 a.m. start time was selected to represent an injection during the sustained low demand period that is characteristic of early morning.

Mass Injection Rate

The mass injection rate is directly proportional to the contaminant concentration and thus has a direct impact on consequences. The contamination concentration in the pipe also depends on the flow rate at the injection location, which varies widely throughout the system. For this reason, three mass injection rates were selected for each combination of contaminant and injection location. The duration of contaminant injection was calculated from the mass injection rate and the total mass of contaminant, which was estimated from a detailed analysis of the availability of each contaminant. However, injection duration was bounded between a minimum of 60 minutes and a maximum of 24 hours in order to represent reasonable scenario conditions. The mass injection rate remained constant over the injection duration.

A summary of the scenario variables considered in this study are summarized in **Table 3-3**, and resulted in set of 591,498 scenarios (34,794 unique scenarios per contaminant). These scenarios were screened using the Threat Ensemble Vulnerability Assessment tool, a software application that is highly efficient at executing large ensembles (http://www.epa.gov/nhsrc/toolsandapps.html).

Table 3-3. Summary of Scenario Variables Considered in the Simulation Study

Scenario Variable	Range of Values
Contaminant Type	Seventeen chemicals and biological agents representing a variety of detection challenges and a range of public health consequences or infrastructure contamination.
Injection Location	5,799 nodes, representing all feasible injection locations in the distribution system model. Injections occur at facilities (facility attack scenarios) or in the distribution system (distribution system attack scenarios).
Injection Time	Two times, representing periods of high and low water demand and different distribution system operating conditions.
Injection Rate	Three rates, with a minimum of 60 minutes and a maximum of 24 hours.

The results from the Threat Ensemble Vulnerability Assessment tool were screened to identify an ensemble of scenarios for detailed evaluation in the simulation study. The criteria for identifying scenarios for inclusion in this ensemble are:

- The scenario that produces the largest consequences for each contaminant in each of 94 pito zones in the GCWW distribution system was included in the ensemble. A pito zone is a small region of the distribution system in which water quality and pressure are fairly constant. Pito zones range in size from 0.29 to 15 square miles, with an average area of 3.1 square miles.
- One custom designed scenario for each contaminant injected at each of the 25 utility distribution system facilities was included in the ensemble.

The screening criteria yielded 2,023 scenarios or 119 scenarios per contaminant. Eight of these scenarios did not produce any significant consequences and were thus removed, resulting in an ensemble of 2,015 scenarios used in the simulation study.

This ensemble achieved the main goal of the simulation study, which was to challenge the Cincinnati CWS model with a diverse set of simulated contamination incidents, which:

- Represent a broad range of contaminants,
- Include injection locations throughout the distribution system, and
- Include scenarios that are optimized to maximize consequences.

The results from the simulation study were used to evaluate a number of performance metrics presented in this report. Several analyses were performed on two ensemble subsets: facility attack scenarios and distribution system attack scenarios. The facility attack scenarios subset consists of the 425 scenarios injected at one of the 25 facility nodes in the distribution system model. The distribution system attack scenarios subset consists of the remaining 1,590 scenarios injected at distribution nodes in the distribution system model. If a scenario subset is not specified, the results are from an analysis performed on the entire ensemble of 2,015 scenarios.

3.4 Benefit-Cost Analysis

To evaluate the sustainability of the Cincinnati CWS in a quantitative fashion, a benefit-cost analysis was conducted to compare the monetized value of costs and benefits and calculate the net present value of the CWS. Cost and benefits that cannot be monetized were evaluated qualitatively. The results of the benefit-cost analysis were used to assess the sustainability of the Cincinnati CWS.

The total cost of the Cincinnati CWS over an assumed 20-year lifecycle was determined by summing implementation costs, annual O&M costs, renewal and replacement costs, and the salvage value of major pieces of equipment at the end of the lifecycle. Implementation costs included labor and other expenditures (equipment, supplies and purchased services) for installing the system components. Implementation costs were summarized in *Water Security Initiative: Cincinnati Pilot Post-Implementation System Status* (USEPA, 2008), which was used as a primary data source for this analysis.

Annual O&M costs include labor and other expenditures (supplies and purchased services) necessary to operate and maintain the system and investigate alerts. O&M costs were obtained from procurement records, maintenance logs, investigation checklists and training records. Procurement records provided the cost of supplies, repairs and replacement parts, while maintenance logs tracked the staff time spent maintaining the system. To account for the maintenance of documents, the cost incurred to update documented procedures following drills and exercises conducted during the evaluation phase of the pilot was used to estimate the annualized cost. Investigation checklists and training records tracked the staff hours spent on investigating alerts and training, respectively. The total O&M costs were annualized by calculating the sum of labor and other expenditures incurred over the course of a year.

Renewal and replacement costs are based on the cost of replacing major pieces of equipment at the end of their useful life. In general, the useful life of each item was estimated using field experience, manufacturer-provided data, and input from subject matter experts. Equipment was assumed to be replaced at the end of its useful life over the 20-year lifecycle of the Cincinnati CWS. The salvage value is based on the estimated value of each major piece of equipment at the end of the 20-year lifecycle. Salvage value was estimated using straight line depreciation for all equipment with an initial value greater than approximately $1,000.

The benefits of a CWS were considered in two broad categories, consequence reduction and routine operations. Benefits related to consequence reduction include reductions in the following consequences of contamination: fatalities, cost of medical treatment, cost of distribution system remediation, cost of alternate water supply during remediation, lost water and wastewater utility revenues and lost wages and business revenue. Benefits related to routine operations include any value derived from operation of a CWS that are not related to detection of and response to contamination, such as the identification of unusual water quality incidents, information used to support regulatory compliance, increased public confidence in the water supply and improved coordination with external partners. Many operational benefits are difficult to monetize in a reliable manner and were thus evaluated qualitatively.

Benefits from consequence reduction were estimated using the results of the simulation study described in Section 3.3. Due to the level of effort required to estimate the consequences of a contamination incident, only 30 of the 2,015 scenarios evaluated in the simulation study were considered in the benefit-cost analysis. However, the 30 scenarios selected for this study represent a wide range of conditions and potential consequences. **Table 3-4** presents the 10 contaminants evaluated as well as their primary and secondary consequence. The selected contaminants included five toxic chemicals, four biological agents and one nuisance chemical. Three scenarios were selected for each contaminant based on the ranking of primary consequences produced by the scenario without the CWS in operation. Scenarios were selected with consequences near the 25th, 50th and 75th percentile ranking of the distribution of consequences for all scenarios in which that contaminant was used.

Table 3-4. Summary of Primary and Secondary Consequences for Contaminants Evaluated in the Benefit-Cost Analysis

Contaminant	Primary Consequence	Secondary Consequence
Toxic Chemical 1	Fatalities	Illnesses
Toxic Chemical 5	Fatalities	Illnesses
Toxic Chemical 6	Fatalities	Illnesses
Toxic Chemical 7	Fatalities	Illnesses
Toxic Chemical 8	Fatalities	Illnesses
Biological Agent 3	Fatalities	Illnesses
Biological Agent 4	Fatalities	Illnesses
Biological Agent 5	Fatalities	Illnesses
Biological Agent 6	Fatalities	Illnesses
Nuisance Chemical 1	Miles of Pipe Contaminated	Not Applicable

3.5 Forums

Qualitative information about the design and operation of the Cincinnati CWS was obtained through a variety of forums. These sessions provided an opportunity for front line personnel, supervisors, senior managers and representatives from partner organizations with an opportunity to provide feedback on the Cincinnati CWS in areas such as the value of various enhancements, potential system improvements, and long-term plans for the CWS. Three types of forums were conducted over the evaluation period: routine component review meetings, lessons learned workshops and exit interviews.

- **Routine Component Review Meetings.** Routine meetings, held at a frequency of once per month to once per quarter, were held for each component (WQM, ESM, CCS, PHS, CM and S&A). During these meetings, recent performance data was reviewed and potential component modifications were discussed. These review meetings were particularly important during the optimization phase, during which recent performance data provided feedback to the team regarding the efficacy of component modifications.

- **Lessons Learned Workshops.** Within a few months of the transition from optimization to real-time monitoring, a workshop was held for each component to capture lessons learned from the Cincinnati CWS pilot and to elicit feedback regarding how these lessons learned could be incorporated into guidance and tools. Utility personnel provided a detailed assessment of the strengths and weaknesses of the tools, equipment and procedures used in the CWS over the course of the pilot.

- **Exit Interviews.** Exit interviews were held for four of the components (WQM, ESM, CCS and PHS) at the end of the evaluation period in June 2010. The purpose of these interviews was to gather perspectives from GCWW and its partners regarding performance and operation of the Cincinnati CWS after one year of full ownership with real-time monitoring. These exit interviews also provided an opportunity to discuss GCWW's plans for the CWS into the future. Exit interviews were not conducted for CM or S&A because the last major activity for these components was FSE 3 in October 2009, and the after action report from that exercise served as the closeout for those two components.

3.6 Literature and Research

Some aspects of the evaluation required information from open source literature and the results of empirical research. One of the more important aspects of system performance that was evaluated using literature and research is the ability of the monitoring and surveillance components to detect specific contaminants or classes of contaminants. Open source literature was reviewed and assessed by subject matter experts to estimate minimum detection limits for CCS, PHS and S&A. Information gathered through literature review was also used to parameterize some modules of the Cincinnati CWS model, such as health effects (e.g., symptom thresholds, lethal doses, etc.), drinking water usage patterns, and health seeking behaviors. Additional description of information sources used to parameterize the Cincinnati CWS model can be found in Appendix A.

Empirical data derived from bench-scale studies were used to quantify the response of the water quality parameters monitored by the WQM component to specific contaminants over a range of concentrations. The bench-scale studies were performed on finished water from the two treatment plants operated by GCWW. Fresh aliquots of finished water from each treatment plant were collected and incrementally dosed with the contaminant under evaluation. The change in each water quality parameter was plotted as a function of concentration for each contaminant, and empirical relationships were developed that could be used to estimate the minimum contaminant concentration that would produce a measureable change in one of the monitored water quality parameters (Hall, et al., 2007).

Section 4.0: Operational Reliability

For a CWS to consistently detect extremely rare contamination incidents, it must achieve a high degree of operational reliability, meaning that it is available and producing data of sufficient quality and quantity for reliable event detection. To evaluate how well the CWS met this design objective, the following two metrics were evaluated: data completeness and availability. The following subsections define each metric, describe how they were evaluated, and present the results.

4.1 Data Completeness

Definition: The number of usable data hours generated by the CWS or one of its components expressed as a percentage of the total number of potential data hours. For data to be considered usable, it must have been collected and of acceptable accuracy and quality. Potential data hours are calculated as the number of hours in a defined time period multiplied by the number of data streams under consideration (e.g., a component with 3 data streams has 3 potential data hours in 1 hour).

Analysis Methodology: This metric was evaluated using empirical data collected from the pilot over the evaluation period. Periods of missing or unusable data were determined from an analysis of the data collected from each component over the evaluation period. Causes of lost data were also documented and include QC failures, data transmission errors and faulty equipment, among others. Data completeness was evaluated for the system as well as each of the four monitoring and surveillance components. Note that for the PHS component, data completeness was tracked only for the 911 and emergency medical service data streams. EpiCenter and DPIC were operational prior to implementation of the CWS, and monitoring data completeness for these systems fell outside of the scope of the pilot. For CCS, the work request data stream was included for all analyses conducted on data from the optimization period and excluded for all analyses conducted on data from the real-time monitoring period after it was discontinued in January 2009. WQM data streams include 82 sensors at 15 stations in the distribution system. ESM data streams consist of 59 pieces of physical security equipment such as motion sensors, video cameras and contact alarms installed at 12 critical facilities.

Results: The number of data streams, potential data hours per 30-day period, potential and actual data hours over the evaluation period, and percentage of data completeness for each component and the entire system is reported in **Table 4-1**. Overall, the CWS had 146 data streams providing 105,120 potential data hours in a 30-day period. Data completeness for the system was 95% over the evaluation period, while data completeness ranged from 93% to 99% for individual components. Data completeness for the system is largely influenced by ESM and WQM, which collectively have 141 data streams compared with three for CCS and two for PHS. Redundancy built into the CWS, such as multiple data streams per component, provides a sustained ability to detect potential contamination or unusual water quality conditions even when system data completeness falls below 100%.

Table 4-1. Data Completeness per Component

Component	Number of Data Streams	Potential Data Hours per 30 Days	Potential Data Hours During Evaluation Period	Actual Data Hours During Evaluation Period	Data Completeness During Evaluation Period
WQM	82	59,040	1.77 x10^6	1.65 x10^6	93%
ESM	59	42,480	1.25 x10^6	1.23 x10^6	98%
CCS	3	2,160	6.35 x10^4	6.28 x10^4	99%
PHS	2	1,440	4.23 x10^4	4.03 x10^4	95%
System	**146**	**105,120**	**3.14 x10^6**	**2.99 x10^6**	**95%**

Figure 4-1 demonstrates the percentage of system data completeness for each monthly reporting period (percentage of usable data hours relative to total potential data hours). The monthly reporting period with the lowest data completeness occurred during the September 2008 reporting period, and was due to a system-wide power outage lasting for several days caused by the Hurricane Ike windstorm. Aside from the September 2008 result, there is a gradual improvement in data completeness as the CWS was optimized leading up to the transition to real-time monitoring beginning in 2009. However, after all components transitioned to real-time monitoring by June 2009, there was a decline in data completeness due to continued challenges with some of the equipment, mostly attributable to the WQM component as discussed below.

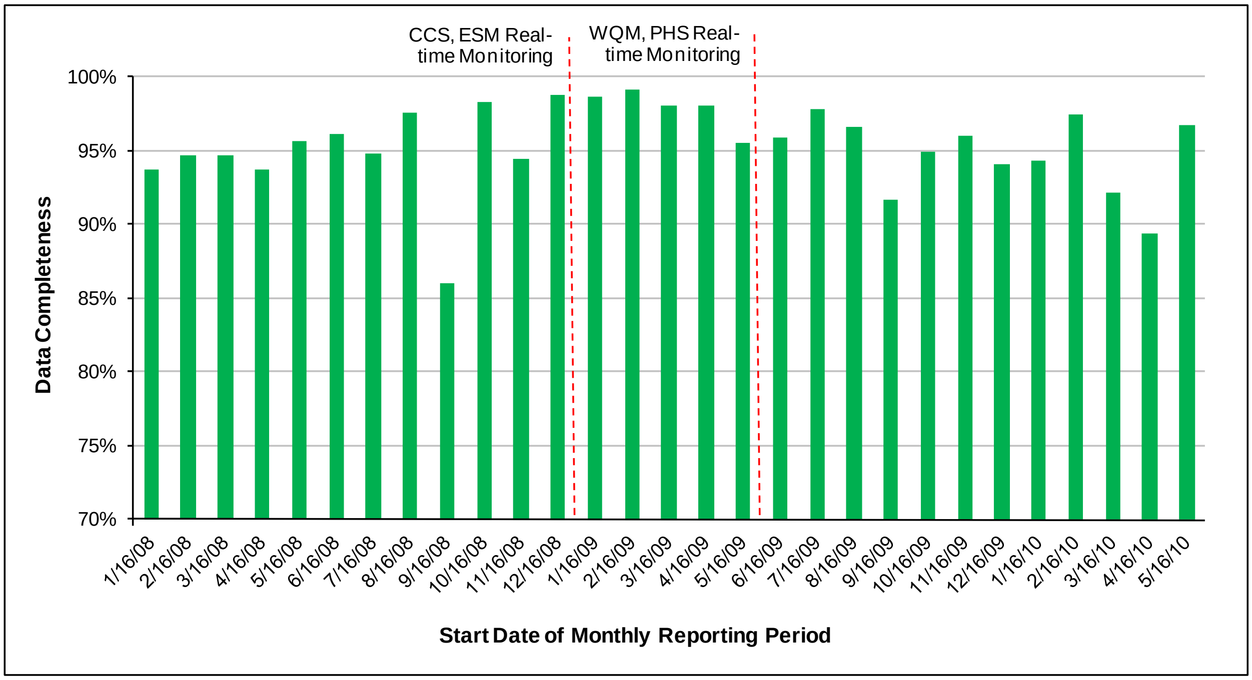

Figure 4-1. System-wide Data Completeness per Monthly Reporting Period

During the early stages of the evaluation period (between the January 2008 and February 2009 reporting periods), data completeness for the WQM component was continuously in the 80% to 95% range, but never reached 100%. The two major causes of incomplete data for the WQM component were equipment maintenance and calibration activities. Additionally, there was a significant system-wide outage due to the Hurricane Ike windstorm in September 2008, in which data was temporarily unavailable from all 15 WQM stations, resulting in a large number of lost data hours. Other system-wide outages occurred when maintenance activities required the Water Security SCADA system to be taken off-line temporarily. While there were several instances of system-wide outages that affected data completeness for all 15 of the WQM stations, localized outages affecting only one station at a time were more common.

During the latter stages of the evaluation period (between the February 2009 and May 2010 reporting periods), data completeness for the WQM component ranged between 82% and 99%, with downtime attributed to recurring equipment maintenance issues and sensors being taken off-line due to prolonged equipment malfunction. Continued fluctuation in percentage of data completeness for the WQM component (even following the transition to real-time monitoring in June 2009) demonstrates the challenge of keeping complex equipment in proper working order, even after the initial start-up issues had been resolved.

The ESM and CCS components consistently provided 100% data completeness during most monthly reporting periods, although there was some lost data for these two components. The ESM component experienced some data loss due to the windstorm in September 2008 and problems with digital cellular communication at some remote locations. The CCS component has three data streams, so when one is down, a significant reduction in percent data completeness can result. In early November 2008, no IVR data was available for nearly three weeks due to an unnoticed data communication issue. This resulted in the lowest percentage of data completeness (74%) for CCS during any monthly reporting period.

During each monthly reporting period, data completeness for the PHS component was regularly in the 86% to 100% range, achieving 100% in all but two reporting periods after PHS transitioned to real-time monitoring. Overall, the lowest value for PHS data completeness (81%) occurred during the April 2010 reporting period, due to a five day delay in data transmission.

4.2 Availability

Definition: The percentage of time that each component of the CWS is operational and maintains the ability to detect contamination incidents. Periods in which a component is not available are termed downtime events.

Analysis Methodology: This metric was evaluated using empirical data collected from the pilot over the evaluation period, which documented all downtime events lasting longer than one hour. A downtime event for the component occurs when any one of the sub-components fails to meet the availability criteria shown in **Table 4-2**. The total downtime for each component over a monthly reporting period was determined by adding the durations of the individual downtime events occurring within that period. The hours that each component was available was calculated as the difference between the total number of hours and the hours of downtime in a reporting period. Total downtime for each sub-component (i.e., data collection equipment, event detection system and alert notification) was calculated for each component and for the system to examine the underlying cause of downtime events over the evaluation period. Availability for the PHS component was tracked only for the 911 and emergency medical service data streams. EpiCenter and DPIC were operational prior to implementation of the CWS, and monitoring the availability of these systems fell outside of the scope of the pilot. However, local partners participating in the Cincinnati pilot reported that both systems have historically demonstrated a high degree of operational reliability.

Table 4-2. Availability Criteria for Each Monitoring and Surveillance Component

Component	Sub-component Availability Criteria		
	Data Collection/Equipment	Event Detection System	Alert Notification
WQM	At least 12 of the 15 monitoring stations are transmitting either chlorine or TOC data	The CANARY event detection system is operational	CANARY and SCADA systems are operational
ESM	At least 75% of intrusion detection devices are transmitting signals to SCADA	Not applicable[1]	SCADA system is operational
CCS	Either the IVR, work request, or the work order system is operational and providing data to event detection	Event detection system is operational	Email server is operational
PHS-911	Operational data is transmitted from the 911 server to event detection	Event detection system is operational	Email server is operational

Component	Sub-component Availability Criteria		
	Data Collection/Equipment	Event Detection System	Alert Notification
PHS-Emergency Medical Services	Upload of emergency medical services run data to the database server and an operational data connection from the database to event detection	Event detection system is operational	Email server is operational

[1] Enhanced security monitoring does not have event detection separate from the data provided by the intrusion detection devices.

The criteria listed in Table 4-2 define availability of individual components in terms of their sub-components. Similarly, the availability of the entire CWS is defined in terms of the primary monitoring and surveillance components: WQM, ESM, CCS and PHS. The CWS is fully available if all four monitoring and surveillance components are concurrently available, it is partially available when between one and three of the components are concurrently available, and it is unavailable when all four of the components are concurrently unavailable. Thus, an analysis of co-occurring downtime events among the components was performed to characterize overall system availability.

Results: Figure 4-2 shows the total downtime for each component (bars with color coding) and the total potential hours of operation for each monthly reporting period (gray line across the top of the figure). This figure shows that the hours of downtime varied widely by reporting period and component. However, it is apparent that WQM generally experienced the most downtime and CCS the least. The specific causes of component downtime are discussed below.

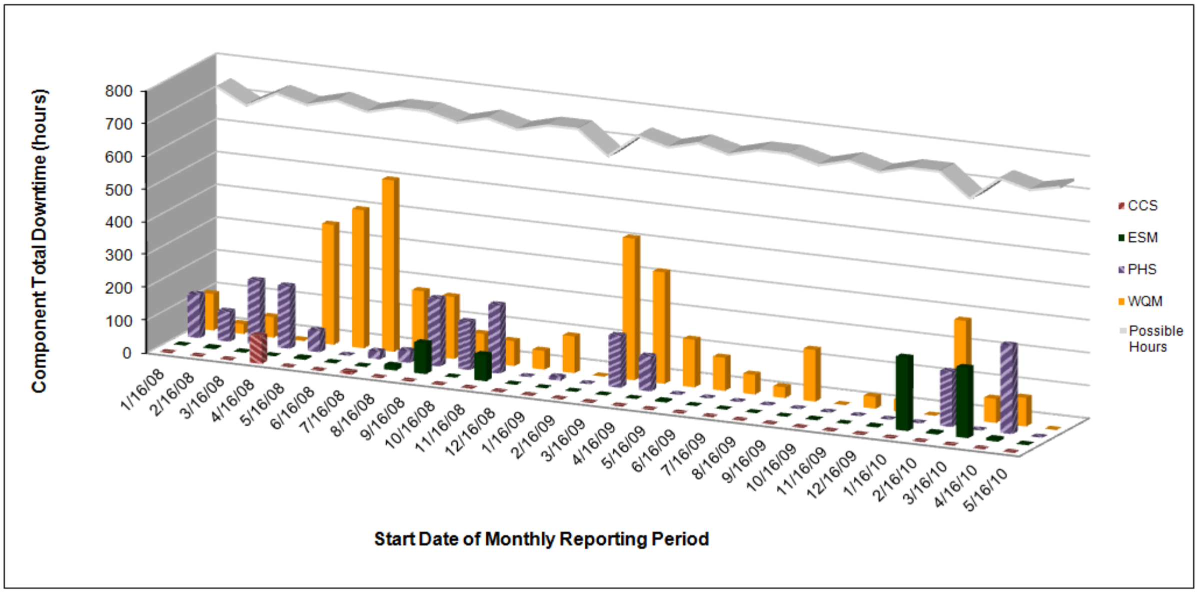

Figure 4-2. Component Downtime for Each Monitoring and Surveillance Component

Figure 4-3 demonstrates the distribution of downtime by the sub-components listed in Table 4-2 for the system and each of the four monitoring and surveillance components over the evaluation period. The large pie chart on the left includes a summation of total downtime hours, distributed among three common sub-components. There was a total of 6,786 hours of system downtime, of which event detection system downtime was the largest contributor (60% of overall downtime hours). This was predominately the result of downtime of the CANARY event detection system used by the WQM component, as discussed in more detail below. Data collection and alert notification downtime occurred less frequently at 29% and 11%, respectively.

The four smaller pie charts in Figure 4-3 depict the underlying causes of component downtime over the evaluation period. The pie chart representing downtime hours for the WQM component demonstrates that the vast majority of downtime hours, 3,710 hours (92%), were due to event detection system downtime. The CANARY event detection system was still under development during the evaluation period and frequent, planned updates and maintenance required it to be taken off-line. Furthermore, once CANARY was taken off-line for even a short period, it remained non-functional for one to three days as it collected the data to create a baseline, which was necessary to perform event detection. This resulted in additional downtime hours until it returned to full operational status. The remaining 8% of downtime was the result of outages of equipment at water monitoring stations, most often sensors or communication systems.

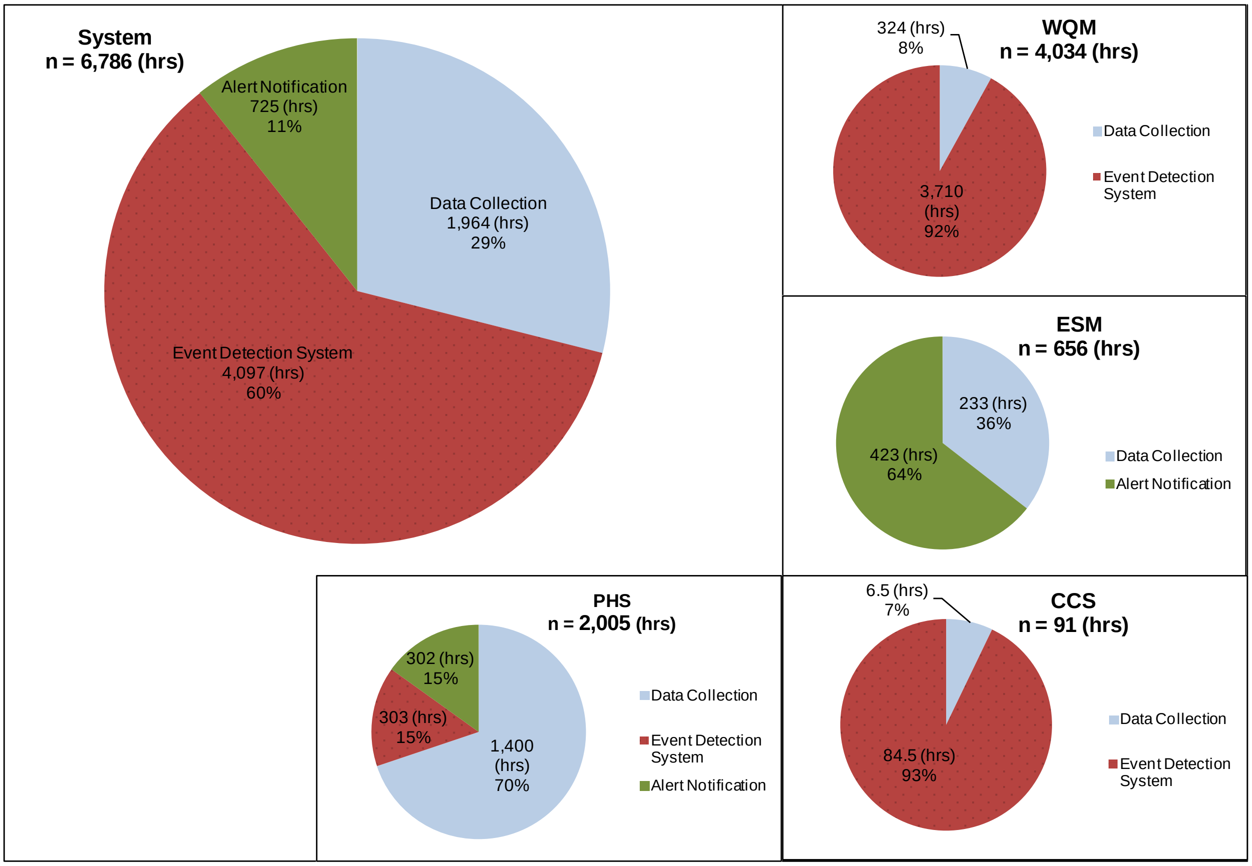

Figure 4-3. Downtime Attributed to Sub-components for Each Monitoring and Surveillance Component

The pie chart in Figure 4-3 representing the PHS component shows a total of 2,005 downtime hours over the evaluation period, which is the second highest number of downtime hours after the WQM component. In contrast to the WQM component, the event detection systems implemented for the PHS component were fully developed software products at the time of implementation. Thus, there were not nearly as many downtime hours involving the event detection system sub-component. The majority of downtime hours (1,400 hours or 70%), were due to problems with the data collection sub-component, specifically network instability concurrent with database unavailability and one instance of an extended period of data communication failure.

As described in Table 4-2, only two sub-components are applicable to ESM, data collection and alert notification. The corresponding pie chart in Figure 4-3 shows that ESM experienced 656 downtime hours attributable to alert notification (423 hours or 64%) and data collection (233 hours or 36%). The predominant cause of alert notification downtime was the result of planned maintenance and updates to the SCADA system. Data collection downtime occurred due to intermittent issues with the digital cellular communications at remote ESM stations.

CCS proved to be the most reliable component with only 91 downtime hours over the evaluation period. This downtime was attributable to issues with either the event detection system (84.5 hours or 93%) data collection (6.5 hours or 7%). This was the result of two events, one required the event detection system to be shut down for a weekend and another that resulted from a power outage that interrupted all CCS data streams.

Table 4-3 summarizes the availability of each component over the evaluation period, which was calculated as a percentage of the total hours in which the components were operational according to the availability criteria described in Table 4-2. During the evaluation period CCS had the highest availability (>99%), as the only major event, which resulted in downtime was an unexpected problem with the event detection system, which required the system to be taken off-line for a weekend. ESM also experienced minimal downtime events, which resulted in 97% availability. PHS experienced more issues, particularly with the data collection sub-component, resulting in an availability of 90% over the evaluation period. WQM had the lowest availability (73%), which was largely attributable to issues with the CANARY event detection system, as discussed previously.

Following the conclusion of the evaluation period, the CANARY event detection system was updated to allow the buffer to be filled with recent water quality data captured by the monitoring stations and stored in a database. As a result of this enhancement, the event detection system could immediately recover from a downtime event as long as the data collection sub-component remains operational. To estimate the potential availability of the WQM component if the new version of CANARY had been in operation during the entire evaluation period, WQM availability was recalculated excluding CANARY downtime events. In Table 4-3, the value in parenthesis (89%) represents WQM component availability when downtime caused by the CANARY event detection system was excluded, which is comparable to the availability of PHS.

Table 4-3. CWS Component Availability

Component	Percent Availability
WQM	73% (89%)[1]
ESM	97%
CCS	>99%
PHS	90%

[1] The value in parenthesis (89%) represents WQM component availability when downtime caused by the CANARY event detection system was excluded.

The inherent redundancy built into a multi-component CWS allows it to maintain protection when individual components of the system are temporarily unavailable. However, the loss of any component can impact other design objectives such as contaminant coverage, spatial coverage and timeliness of detection. Availability of the entire CWS was evaluated in terms of the availability of its four monitoring and surveillance components.

The percentage of time when one, two, three or four components were concurrently available is represented in **Table 4-4**. The CWS was fully available 78% of the time (i.e., all four monitoring and surveillance components were concurrently available). The concurrence of multi-component downtime events was infrequent, and at least three of the four components were available more than 99% of the time (i.e., system was partially available for 99% of the evaluation period). The CWS was never completely unavailable during the evaluation period.

The high degree of system availability is largely due to the resilient design of the CWS and its components. The CCS and PHS components utilize stable computer algorithms and analyze highly reliable data streams. ESM uses rugged equipment with a demonstrated capability to operate continuously for extended periods. WQM is more prone to downtime events due to the complexity of the monitoring equipment; however, this is compensated by the fact that the component monitors many independent data streams that provide resiliency. Finally, the system as a whole is equipped with back-up power supply, servers, and other equipment to provide an additional level of reliability.

Table 4-4. Concurrent CWS Component Availability

Number of Components Available	Percent Availability[1]
1	100%
2	99.9%
3	99.3%
4	78.0%

[1] Percentages are calculated relative to 21,160 hours in the evaluation period.

The only event during the evaluation period that had the ability to create a significant period of multi-component downtime was the Hurricane Ike windstorm, a rare event that left 90% of GCWW's service area without electricity for several days and exhausted uninterruptible power supply built into the system. Even with the temporary loss of some electronic equipment due to the power failure, the CWS provided monitoring and response capabilities that were used to mitigate the impacts of the windstorm on utility operations.

The longest period that two and three components were simultaneously unavailable was 26 and 8 hours, respectively. To evaluate whether these period represent significant gaps in detection capabilities, these values were compared with simulation results. The distribution system model was used to estimate the amount of time that contaminated water remains in the distribution system for the 30 simulated contamination scenarios used in the benefit-cost analysis described in Section 3.4. The average time that contaminated water remains in the distribution system for these scenarios was determined to be 5.3 days, which is substantially longer than the 26 hours that two components were concurrently unavailable. Thus, while these periods of multi-component downtime may impact the timeliness of detection, it is unlikely that the overall ability of the CWS to detect contamination would be impacted.

4.3 Summary

As a result of the layers of redundancy designed into the multi-component CWS, the system demonstrated sustained, continuous detection capabilities, even when components or sub-components were temporarily unavailable. Overall, the optimized CWS demonstrated a high degree of operational reliability and a sustained ability to detect contamination incidents.

Data completeness was 95% for the CWS over the entire evaluation period. Issues with WQM equipment during the early stages of deployment contributed significantly to lost data, while ESM, CCS and PHS had intermittent periods of data loss. However, after the systems were optimized by June 2009, data completeness for the system regularly exceeded 95%.

On average, the individual CWS components were available between 73% and >99% of the time. The single greatest contributor to downtime was the WQM event detection system (CANARY), especially during the early portion of the evaluation period. After issues with CANARY were resolved, the availability of the WQM component and the entire CWS increased. Had CANARY been fully operational during the entire evaluation period, the WQM component would have been available for 89% of the time, rather than the 73% availability observed during the evaluation period. The CCS component had the highest availability at >99%, followed closely by ESM at 97%. The PHS tools deployed specifically for this project, 911 and emergency medical service surveillance, were available 90% of the time, whereas the PHS tools that were in place prior to the pilot were mature systems that were available >99% of the time.

Overall, downtime of multiple components was rare. Three of the four components were available >99% of the time. The longest periods of multi-component downtime was 26 hours for two components and 8 hours for three components, which was well below estimates of the time that contaminated water would remain in the system, and thus potentially be detected. This indicates that even with multiple components unavailable for a period, it is still likely that a significant contamination incident will be detected by the CWS.

Section 5.0: Spatial Coverage

Given the large number of access points in a drinking water distribution system and the uncertainty regarding where a contaminant might be injected, the Cincinnati CWS was designed to cover the entire distribution system. Specifically, monitoring and surveillance components were selected and designed to provide redundant coverage throughout the distribution system. To evaluate how well the CWS met this design objective, the following metric was evaluated: area and population coverage. The following subsections define this metric, describe how it was evaluated, and present the results.

5.1 Area and Population Coverage

Definition: Area coverage is defined as the percentage of the distribution system area that is monitored and protected by the integrated CWS. A portion of the distribution system is monitored by the CWS if a contaminant injected in that area would flow past a point where it could be detected by any of the monitoring and surveillance components. An area is protected by the CWS if it is downstream of a point of potential detection. Population coverage is defined as the number of people that reside within the area covered by the CWS, expressed as a percentage of the total population in the study area.

Analysis Methodology: Area coverage was determined for each of the four monitoring and surveillance components using a variety of techniques as described below:

- The area covered by the ESM component was evaluated using the CWS simulation model to estimate the area and population that would be impacted by an uninterrupted contaminant injection at ESM locations.
- The area covered by the WQM component was evaluated using GCWW's distribution system model to simulate contaminant injections throughout the distribution system and determine which WQM locations observed a potentially detectable concentration.
- The area covered by the CCS component was determined from the design of the component and an analysis of availability of telephone service in the GCWW service area.
- The area covered by the PHS component was determined from the design of the component (e.g., regions of the distribution system monitored by the various surveillance tools) and was further evaluated using the location data from PHS alerts that occurred during the evaluation period.
- The area covered by the S&A component was determined from the design of the component.

The results from these component assessments of spatial coverage were used to characterize the area covered by the integrated CWS, including an analysis of portions of the distribution system covered by multiple components.

In addition, the results of the simulation study were used to evaluate detection of simulated contamination scenarios originating from locations throughout the distribution system. This analysis provides another perspective on area coverage by demonstrating the ability of the system to detect contamination from geographically distributed sources.

The results from the analysis of area coverage were converted to population estimates using 2000 census block data. Specifically, the population that lives in the area covered by the CWS is considered to be covered by the system. Interpolation was used in cases where a census block was only partially in the area covered by the CWS. Note that while data from the 2010 census was available at the time this report was developed, data from the 2000 census was used because the distribution system model used for these analyses better represents that time period.

These analyses are limited to the portion of GCWW's retail area in the City of Cincinnati and surrounding communities in Hamilton County, a region that covers 294 square miles and serves approximately 760,000 people. GCWW sells treated water to large wholesale customers outside of Cincinnati, but these areas were not considered in this analysis. While this analysis was constrained to the study region, it is worth noting that some components of the CWS provide coverage for customers outside of the study region. For example, CCS and the DPIC and EpiCenter PHS data streams extend through most of GCWW's retail and wholesale areas.

Results: Table 5-1 shows the area and population coverage for each component as well as the entire system. WQM covered 72% (244 square miles) of the study area and 84% of the population with only 15 monitoring locations. ESM is designed to monitor for intrusions that may lead to contamination at a limited number of sites in the distribution system. But even with this limited number of sites, the results from simulated contamination incidents show that the ESM sites supplied water to 96% of the study area and 99% of the population within the study area. Thus, while the area monitored by ESM is small, the area protected by ESM encompasses most of the study area. CCS is potentially capable of monitoring the entire study area if a customer is able to contact the utility. Empirical data suggests that 96% of GCWW customers have access to a telephone, and this result was used as an estimate of the population coverage for CCS. The 911 and emergency medical service data streams cover the portion of the study area in the boundaries of the City of Cincinnati, while DPIC and EpiCenter cover the entire study area and associated population. Theoretical coverage for S&A was also 100%, because samples can be collected at any location within the distribution system in response to an alert. The results of this analysis demonstrate that all components of the CWS provide robust spatial coverage throughout the distribution system.

Table 5-1. Area and Population Coverage

Component	Population Coverage	Area Coverage
WQM	84%	244 square miles
ESM	99%	24 sites
CCS	96%	294 square miles
PHS	100%	294 square miles
S&A	100%	294 square miles
System	**100%**	**294 square miles**

In addition to the analysis of theoretical spatial coverage presented above, the results from the simulation study were analyzed to estimate the ability of the Cincinnati CWS to detect simulated contamination incidents originating from locations throughout the distribution system. This analysis was based on 94 pito zones, which are areas of relatively constant water quality and pressure within the distribution system. During the study, contaminant injection was simulated for the 17 contaminants listed in Table 3-2 in each of the 94 pito zones, resulting in 1,590 scenarios (eight scenarios in which no consequences were generated were eliminated during the study design).

Table 5-2 summarizes the detection percentages by the pito zone in which contaminant injection occurred. The first column shows the detection percentage and the second column displays the number of pito zones, which had the corresponding detection percentage. For example, 100% of all injections occurring in 51 pito zones were detected by the CWS. The remaining three columns show the total, median, and range of populations in the group of pito zones with the corresponding detection percentage. Considering the population range, it is apparent that the two groups of pito zones with the highest detection percentages (89 of 94 pito zones) include some of the most populous areas in the distribution system. This group of 89 pito zones with detection percentages greater than 94% contains 91.6% of the population.

Table 5-2. Number of Pito Zones with Corresponding Detection Percentages

Detection Percentage	No. of Pito Zones	Population in Pito Zones		
		Total	Median	Range
100%	51	429,955 (56.6%)	7,701	1,561 to 24,362
94.1%	38	265,314 (35%)	5,841	504 to 31,055
93.8%	3	34,674 (4.6%)	13,412	6,725 to 14,537
93.3%	1	1,085 (0.1%)	1,085	1,085 to 1,085
88.2%	1	16,440 (2.2%)	16,440	16,440 to 16,440

The CWS successfully detected 1,546 out of the 1,590 scenarios, for an overall detection percentage of 97%. The 44 scenarios that went undetected by the CWS involved injections spread over 43 pito zones indicating that there was no specific area of the distribution system that was poorly covered by the CWS. Thirty-eight of the undetected scenarios involved Nuisance Chemical 2, which can be detected only by one water quality parameter monitored by the WQM component. Six of the undetected scenarios involved Biological Agent 6 and Biological Agent 7. While these two contaminants can be detected by both WQM and PHS, contaminated water did not flow through any of the WQM stations for the six undetected scenarios. Furthermore, the scenarios produced relatively few health consequences, making them difficult to detect through PHS. Thus, all 44 of the scenarios that were not detected produced relatively few consequences.

5.2 Summary

Through a multi-component design, the Cincinnati CWS achieved broad spatial coverage of the study area, which includes the most populous region of GCWW's service area and covers 294 square miles. Area coverage ranged from 82% for WQM to 100% for CCS, PHS and S&A. Population coverage was greater than area coverage, ranging from 84% for WQM to 100% for PHS and S&A.

Results from the simulation study were evaluated to determine the number of contamination scenarios originating from each of the 94 pito zone that were detected by the CWS. This analysis showed that 100% of the scenarios originating from 51 pito zones and 94.1% of scenarios originating from another 38 pito zones were detected by the CWS. The 44 scenarios (3% of the total number of scenarios) that were not detected by the CWS were spread across 43 pito zones, indicating that there is no specific area of the distribution system that is not effectively covered by the CWS. The undetected scenarios produced few consequences relative to the rest of the ensemble, which is the primary reason they were difficult to detect.

Section 6.0: Contaminant Coverage

Given the large number of potentially harmful drinking water contaminants and the uncertainty regarding which contaminant might be involved during a specific incident, the Cincinnati CWS was designed to provide redundant coverage for a broad range of contaminants. To evaluate how well the Cincinnati CWS met this design objective, the following two metrics were evaluated: contaminant detection threshold and contaminant scenario coverage. The following subsections define each metric, describe how it was evaluated and present the results.

6.1 Contaminant Detection Threshold

Definition: The lowest concentration of a specific contaminant that can be reliably detected by the CWS.

Analysis Methodology: Contaminant detection threshold was assessed for each of the 17 contaminants evaluated under the simulation study. This metric could not be directly assessed from the Cincinnati CWS pilot due to the lack of contamination incidents. Instead, contaminant detection thresholds were estimated based on the design of the components in conjunction with results from research and studies available in the open literature. The following methods were used to estimate the detection thresholds for individual components:

- ESM was designed to detect intrusions that could provide access to distributed drinking water rather than indicators of contamination, thus detection thresholds do not apply to this component.
- For WQM, the detection threshold was estimated from bench-scale laboratory studies that measured the change in water quality parameter values at known contaminant concentrations. For some of the biological agents, the detection threshold was estimated for the co-contaminant that would be necessary to maintain viability of the biological agent in chlorinated water.
- For CCS, the detection threshold was estimated from taste and odor threshold reported in the literature. These odor and taste thresholds represent a sample of the population, and the actual detection thresholds for an individual can vary widely from these estimates. Furthermore, some individuals may not be able to detect the contaminant at any concentration through the senses.
- For PHS, the detection threshold was estimated as the minimum contaminant concentration that could produce a dose that would result in acute symptoms in the exposed population. Similar to taste and odor thresholds, the dose resulting in onset of acute symptoms varies widely for individuals.
- For S&A, the detection threshold was estimated as the minimum reporting limit for the analytical method used in the Cincinnati CWS pilot.

Detection thresholds were assessed relative to contaminant-specific critical concentrations that are based on adverse consequences to the exposed population or utility infrastructure. The critical concentration provides a useful benchmark against which to assess whether the detection threshold is low enough to detect contamination that could result in substantial public health or infrastructure consequences. Each contaminant was grouped into the categories described in Section 3.3, which determined how the critical concentration was determined:

- **Nuisance Chemical**. The critical concentration for nuisance chemicals was selected at levels that would make the water unacceptable to customers (e.g., concentrations that result in objectionable aesthetic characteristics).

- **Toxic Chemical**. For chemical contaminants that are lethal to individuals exposed to a high dose, the critical concentration was based on the mass of contaminant that a 70 kg adult would need to consume in one liter of water to have a 10% probability of dying (LD_{10}).
- **Biological Agent**. For biological agents that are infectious or lethal to individuals exposed to a high dose, the critical concentration was based on the mass of contaminant that a 70 kg adult would need to consume in one liter of water to have a 10% probability of dying (LD_{10}).

To determine whether the detection threshold was sufficient to detect water contaminated at concentrations equal to or greater than the critical concentration, the ratio of the critical concentration to detection threshold was calculated.

Results: Table 6-1 presents the ratio of critical concentration to detection threshold for each contaminant across the components. A ratio of 1.0 or greater indicates that the component can detect the contaminant at or below the critical concentration. Large ratios demonstrate the contaminants that can be detected at concentrations significantly lower than the critical concentration. Conversely, ratios less than 1.0 indicate that the component would not detect the contaminant until the concentration has exceeded the critical concentration that would result in adverse public health or infrastructure consequences.

Table 6-1. Ratio of Critical Concentration to Detection Threshold

Contaminant	WQM	CCS	PHS	S&A
Nuisance Chemical 1	4.76	20.0	–	2.00×10^4
Nuisance Chemical 2	33.3	–	–	2.00×10^4
Toxic Chemical 1	225	5.86	458	1,470
Toxic Chemical 2	463	50.5	3,640	3.39×10^4
Toxic Chemical 3	185	22.8	1,640	3.69×10^6
Toxic Chemical 4	104	4.03	290	5.80×10^4
Toxic Chemical 5	57.6	–	668	6,680
Toxic Chemical 6	352	–	850	4.08×10^4
Toxic Chemical 7	1.97	–	950	57.0
Toxic Chemical 8	0.0333	–	300	6.60×10^7
Biological Agent 1	265	88.2	4,500	2.25×10^4
Biological Agent 2	1,310	–	3,940	4.93×10^5
Biological Agent 3	2.40	–	2.40×10^4	24.0
Biological Agent 4	3.57	–	4.54	90.7
Biological Agent 5	7.87	–	10.0	20.0
Biological Agent 6	9.70	–	1.74	5.79×10^4
Biological Agent 7	0.582	–	1.64	3.30×10^5

This table shows that WQM can theoretically detect all 17 contaminants, and 15 of them at concentrations below the critical concentration. The ratio of critical concentration to detection threshold is below 1.0 for Toxic Chemical 8 and Biological Agent 7, which indicates that adverse health consequences might occur prior to detection. Note that for some of the biological agents, a co-contaminant is needed to maintain the viability of the agent. These co-contaminants produce a significant change in water quality, and thus are responsible for the detection capabilities of WQM for these biological agents. If a co-contaminant were not at concentrations high enough to be detected by WQM, then the biological agent would be inactivated, and thus of no concern to public health. CCS can theoretically detect six of the 17 contaminants at ratios greater than 1.0. PHS can theoretically detect 15 of the 17 at ratios greater than 1.0, but it would not be expected to pick up the nuisance chemicals as they are not toxic.

Comparing across the three monitoring and surveillance components (WQM, CCS and PHS), the ratios are generally larger for PHS in comparison to WQM and CCS, which indicates that PHS can detect concentrations of most contaminants well below the critical concentration. This is because most contaminants produce symptoms in exposed individuals at concentrations much lower than the LD_{10}, which in turn would generate a PHS alert.

All of the contaminants are theoretically detectable by S&A with very high ratios for most of the contaminants, indicating the ability of this component to detect contaminant concentrations several orders of magnitude lower than the critical concentrations. This result indicates that as long as sampling is initiated soon after the initial detection occurs at a location hydraulically connected to the location of an alert, it is likely that the contaminant will be present in the sample at detectable concentrations.

As indicated in Table 6-1, five of the 17 contaminants (Toxic Chemicals 1 through 4 and Biological Agent 1) are detectable by all three of the monitoring and surveillance components (WQM, CCS, and PHS), providing redundant detection capabilities. Furthermore, the ratio of critical concentration to detection threshold is above 1.0 for these five contaminants across all three components, demonstrating reliable detection capabilities.

Eleven contaminants are detectible by two of the monitoring and surveillance components (either WQM and CCS or WQM and PHS), with detection ratios above 1.0 for all except Toxic Chemical 8 and Biological Agent 7 for WQM. Only one contaminant (Nuisance Chemical 2) is theoretically detectable by just one monitoring and surveillance component, WQM. However, the detection threshold for this contaminant is 33 times lower than the critical concentration. Thus, if Nuisance Chemical 2 is in the area covered by WQM at concentrations above the critical concentration, it will likely be detected.

6.2 Contamination Scenario Coverage

Definition: The number or percentage of simulated contamination scenarios that generate an alert from at least one component.

Analysis Methodology: This metric could not be directly assessed from the Cincinnati CWS pilot due to the lack of contamination incidents during the evaluation period. Instead, the results from the simulation study were used to characterize contamination scenario coverage. As discussed in the previous section, each of the 17 contaminants simulated in this study is detectable by at least one component; thus, all 2,015 scenarios evaluated in the study are potentially detectable by the CWS. Results were aggregated by contaminant type and by detection status to determine the relative detection rates for different contaminants.

Results: The results of the simulation study demonstrate that the CWS successfully detected 1,971 out of the 2,015 scenarios, a 98% detection rate. **Figure 6-1** shows the counts and percentages of scenarios detected by the CWS for each of the 17 contaminants in the simulation study.

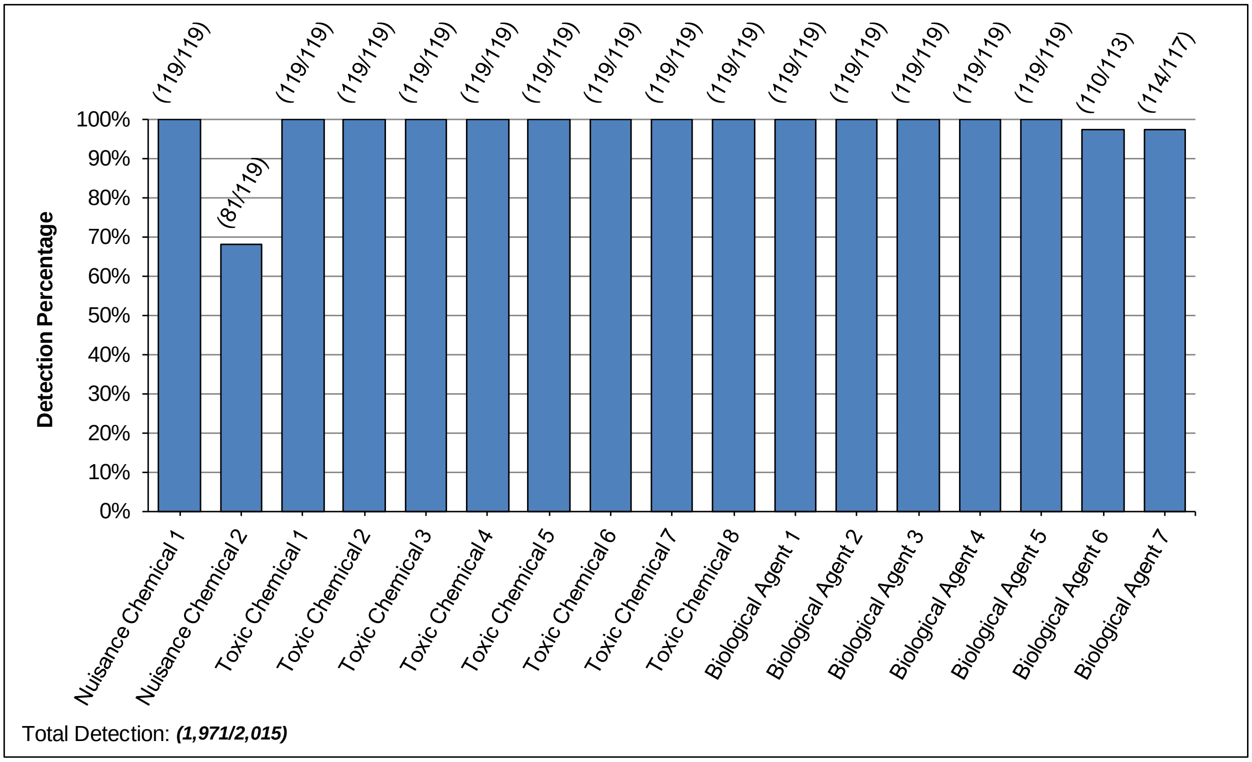

Figure 6-1. Scenarios Detected by Contaminant

The 44 scenarios that went undetected by the CWS involved injections spread over 43 pito zones, indicating that they were not spatially clustered. Of the undetected scenarios, 86% (38) involved Nuisance Chemical 2, which can be initially detected only by WQM, a component with spatial coverage limited to 244 square miles of the 294 square miles in the study area. Given the near perfect detection of the other 16 contaminants, the underperformance of the CWS for Nuisance Chemical 2 demonstrates the value of multiple surveillance components. The remaining 14% (6) of the undetected scenarios involved Biological Agents 6 and 7, which are theoretically detectable by both WQM and PHS. Overall, WQM did not detect many of the scenarios involving these two biological agents (less than 11%); however, PHS was able to detect most scenarios that were not detected by WQM. Therefore, the six scenarios involving Biological Agents 6 and 7 that were not detected by either WQM or PHS can be explained by three factors: no appreciable change in water quality conditions, which prevented detection by WQM (applicable to all six undetected scenarios), the absence of any significant health consequences (applicable to five of the undetected scenarios), and one instance where significant symptomatic cases and deaths would have occurred, but were spread out in time making detection by PHS difficult.

6.3 Summary

The design of the Cincinnati CWS ensures the system has robust detection capabilities for a variety of contaminants, including nuisance chemicals, toxic chemicals, and biological agents. All 17 contaminants evaluated in the simulation study were theoretically detectable by at least one monitoring and surveillance component (WQM, CCS or PHS) at a concentration equal to or less than the critical concentrations necessary to cause significant public health consequences (lethal to 10% of the exposed population) or infrastructure consequences (would require distribution system remediation). Eleven contaminants were detectable by two components, and five were detectable by all three components. ESM was not considered in this analysis because its detection capabilities are independent of contaminant type. With respect to response capabilities, S&A can detect all 17 contaminants at detection limits well below the critical concentration.

The Cincinnati CWS detected 98% of simulated contamination incidents from an ensemble of 2,015 scenarios involving 17 contaminants and injected at locations throughout the entire distribution system, including locations at utility facilities. The majority of the 44 scenarios that went undetected involved a contaminant that does not cause acute health effects and is detectable by only a single component. This result emphasizes the value of a multi-component CWS, in which the detection capabilities of the monitoring and surveillance components are complementary and provide broad contaminant coverage. As expected, it was observed that small, isolated contamination incidents that produced limited consequences were more difficult to detect than incidents producing widespread consequences.

Section 7.0: Alert Occurrence

Ideally a CWS would generate an alert only when a contamination incident, public health incident, or other significant water quality anomaly is occurring. However, invalid alerts do occur. The goal of this design objective is to minimize the number of invalid alerts without compromising the ability of the system to detect real water quality anomalies or public health incidents. In the Cincinnati CWS, alert occurrence was optimized by improving the quality of the underlying data analyzed by each component and optimizing the event detection system configuration used by the components. To evaluate how well the CWS met this design objective, the following three metrics were evaluated: invalid alert occurrence, valid alert occurrence and alert co-occurrence. The following subsections define each metric, describe how it was evaluated and present the results.

7.1 Invalid Alert Occurrence

Definition: The occurrence of alerts with a cause other than a verified water quality anomaly, contamination incident or public health incident.

Analysis Methodology: During the evaluation period of the Cincinnati CWS pilot, alerts were generated in real time for each of the four monitoring and surveillance components (WQM, ESM, CCS and PHS), and recorded in a data management system. Personnel from GCWW or one of the public health partners reviewed the alerts to determine a probable cause and designate the alert as valid or invalid. In most cases, the results of the alert investigations were recorded on a checklist and ultimately uploaded to a database for further analysis. These data were used to characterize the rate and cause of invalid alerts generated by each component over the evaluation period.

In the case of WQM, alert occurrence was evaluated using the “reprocessed alerts,” which were generated by running the water quality data generated by the sensors during the evaluation period through an updated (bug-free) version of CANARY.

The total number of invalid alerts is equal to the number of total alerts minus the number of valid alerts observed during the evaluation period. Invalid alerts were categorized by one of the four general causes described below:

- **Equipment faults**. Alerts caused by equipment that is not functioning properly. Equipment faults can directly generate invalid alerts (e.g., an improperly configured motion sensor), or can produce inaccurate data that subsequently generates invalid alerts (e.g., malfunctioning water quality sensors).
- **Procedural errors**. Alerts caused by deviations from standard operating procedures, such as miscoding data or propping open alarmed doors at secure utility locations. Invalid alerts resulting from procedural errors can be reduced with additional staff training.
- **Background variability**. Alerts caused by typical variations in a data stream monitored by a component of the CWS. Invalid alerts due to background variability can be minimized but not eliminated entirely.
- **Other**. Alerts due to a cause other than equipment faults, procedural errors, or background variability. The actual cause of an alert categorized as “other” may be known or unknown.

Results: Each of the components experienced periods of downtime during the evaluation period. In particular, the WQM and PHS components experienced significant downtime early in the evaluation period. This results in an artificially low alert rate because no alerts occurred during periods of downtime. To correct for downtime and allow for an equivalent, cross-component comparison, alert rates for all components were normalized for downtime. Normalization was achieved by dividing the number of alerts for that period by the percent availability of the component during the reporting period (i.e., if a component availability was 100%, no adjustment is made to the alert rate). These normalized alert rates are shown in **Figure 7-1**.

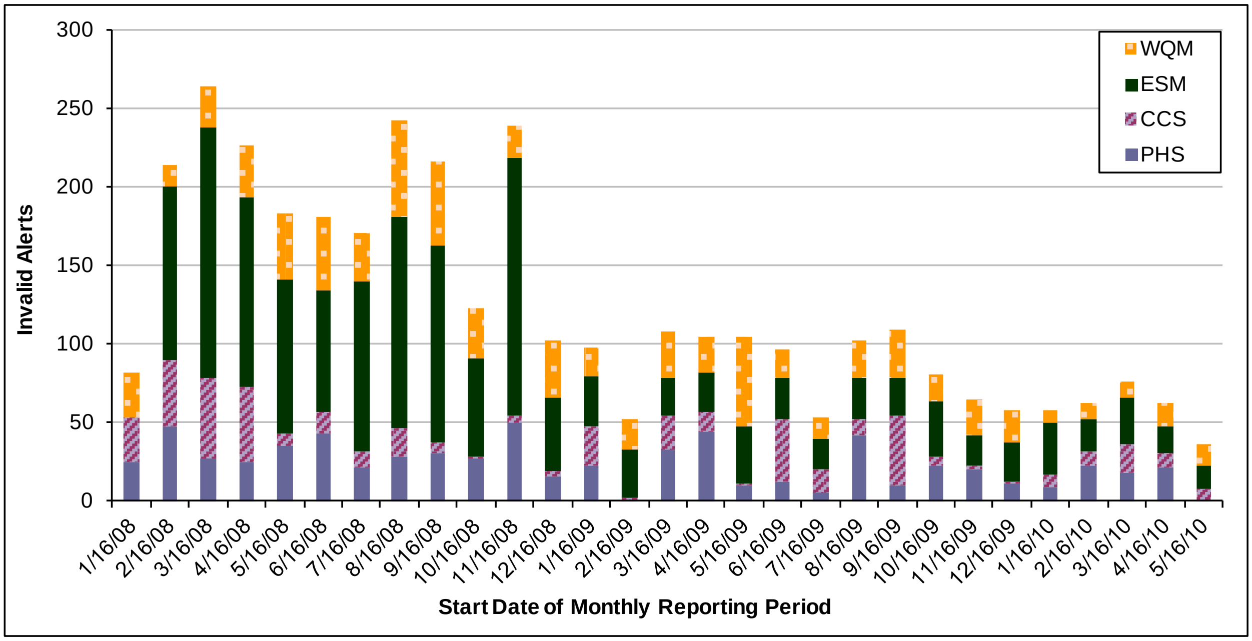

Figure 7-1. Invalid Alerts by Component per Reporting Period (Normalized for Downtime)

During the first year of the evaluation period, alert occurrence was typically above 150 per reporting period. While the vast majority of alerts were determined to be invalid, there were 12 valid WQM alerts and 7 valid CCS alerts during the first year, although none were due to water contamination. The number of CWS alerts gradually decreased as the evaluation period progressed, largely due to successful efforts to optimize performance.

The majority of invalid alerts were due to equipment problems. The first step in reducing the number of invalid alerts was to improve the performance of equipment and improve the quality (i.e., accuracy and precision) of the underlying data. Next, procedural errors that generated invalid alerts were reduced through staff training and practice with the alert investigation procedures. After equipment and procedural issues had been largely resolved, the next step in the optimization process was to adjust the configuration of automated event detection systems (e.g., alerting thresholds, precision settings, etc.). These adjustments could be made only after sufficient baseline data had been collected, which provided information about the variability that could be expected under normal conditions. The event detection systems were configured to maintain detection capabilities without producing an excess number of invalid alerts. This optimization process was largely completed by the December 2008 reporting period, and the resulting reduction in invalid alert occurrence is evident in Figure 7-1.

The number of sources monitored by a component can impact the number of alerts, and in general, the more sources that are monitored, the greater the number of alerts that are generated. **Table 7-1** shows the number of sources monitored by each component along with the total number of invalid alerts that occurred during the evaluation period. To account for the effect of the number of sources on alert occurrence, the number of alerts was divided by the number of sources to normalize the alert rate. For CCS, the number of sources is equivalent to the number of data streams monitored by the component.

For WQM and ESM, the number of sources is defined by the number of monitoring locations, 15 and 12, respectively. While ESM and WQM had the highest number of total alerts over the evaluation period, they had the lowest normalized alert rates.

Table 7-1. Number of Total Alerts and Normalized Alerts for the CWS and each Component

Component	Number of Sources Monitored by the Component	Total Number of Invalid Alerts During the Evaluation Period	Number of Invalid Alerts Normalized by Number of Sources
WQM	15	770	51
ESM	12	1,579	132
CCS	3	466	155
PHS	3	602	201
System	**33**	**3,417**	**104**

Throughout the evaluation period, the causes of invalid alerts were tracked for each component. All but 1% of invalid alerts were caused by procedural issues, equipment problems, or background variability as represented in **Figure 7-2**.

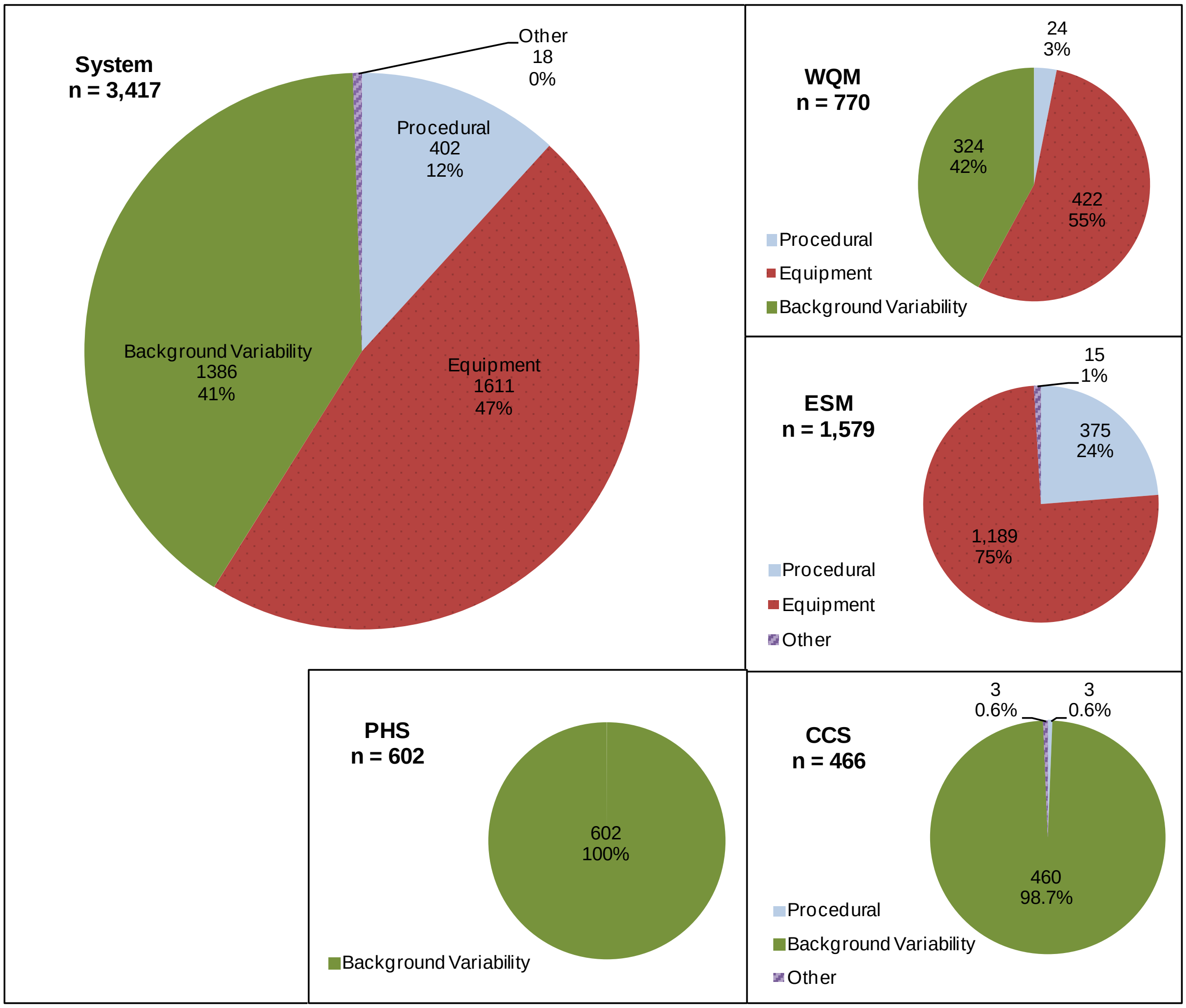

Figure 7-2. Causes of Invalid Alerts for the CWS and each Component

The reprocessed WQM data produced fewer alerts than the real-time alerts, because many alerts in the real-time dataset were caused by problems with CANARY (USEPA, 2014b). In the reprocessed dataset, equipment issues caused by system-wide and station outages were the most common causes of invalid alerts. Additionally, some water quality sensors suffered from chronic performance issues, which contributed to invalid alerts until the sensors were taken off-line. Background variability was the second highest cause of invalid alerts. Procedural issues were not a significant contributor to invalid alerts for WQM.

Equipment issues, most commonly associated with communications equipment, were the most significant cause of invalid ESM alerts. Interference with the radio transmissions used to communicate ESM alerts to the GCWW SCADA system caused ESM alerts and was the greatest contributor to this category of invalid alerts. After the issue was resolved, the number of equipment/communication-related alerts was reduced. Another change to the component during the same period was the switch from ladder motion sensors to physical hatch barriers at all indoor elevated storage tank locations. There were also a few invalid alerts caused by motion sensors exposed to the elements (such as wind causing outdoor motion sensors to trigger), even though no intruders were attempting to enter these sites. Many procedural invalid alerts were caused by employees not informing security when entering an ESM site and by doors being propped open when contractors were working on-site.

Most invalid CCS alerts are attributed to background variability caused by normal variation in call volume. During the April 2008 reporting period, alert thresholds were increased to reduce the number of alerts caused by normal fluctuations. Following these changes, the average number of CCS alerts per reporting period was reduced to a level deemed acceptable by utility personnel responsible for performing CCS alert investigations.

For the PHS component, all invalid alerts for the 911, EMS, and DPIC data streams were attributed to background variability in call volume. Equipment associated with the component proved reliable, and as a result no equipment-related alerts occurred during the evaluation period.

The invalid alert rates for all four monitoring and surveillance components decreased from the optimization phase to the real-time monitoring phase. **Table 7-2** demonstrates this trend through the average number of invalid alerts per reporting period during each of these phases.

Table 7-2. Invalid Alerts per Reporting Period During Optimization and Real-time Monitoring

	Average Number of Invalid Alerts per Reporting Period	
Component	**Optimization**	**Real-time Monitoring**
WQM	33	17
ESM	82	23
CCS	17	14
PHS	25	15
System	**152**	**69**

The ESM component produced the most alerts during each of these phases, but also showed the greatest percentage reduction in invalid alert rates during the transition from the optimization to the real-time monitoring phase. This resulted in comparable alert rates among the four components during real-time monitoring. This reduction in alerts was achieved through an intensive effort to correct problems with equipment, IT systems, and O&M procedures during the first year of operation. Following system optimization, the time and resources required to maintain this level of alert occurrence was substantially lower compared with that required to optimize the system.

7.2 Valid Alert Occurrence

Definition: The occurrence of alerts caused by verified water quality anomalies, contamination incidents, or public health incidents.

Analysis Methodology: Occurrence of valid alerts was evaluated using two different data sources: simulation study results and empirical data.

As described in Section 3.3, the simulation study challenged a computer model of the Cincinnati CWS with simulated contamination incidents. Furthermore, the baseline data used for each component in the simulation study was screened to ensure that it would not generate invalid alerts, which would have confounded interpretation of the study results. Thus, when a component generated an alert during the simulation study, it was by design a valid alert. The results from this study were evaluated to determine the frequency at which each of the CWS components generated a valid alert during a contamination scenario, and the frequency that each component generated the first alert during a scenario. Many of the results presented in this section are based on analyses that were limited to either distribution system attack scenarios or facility attack scenarios. If a specific scenario type or subset is not specified, the results are from an analysis performed on the entire ensemble of scenarios. This distinction is important because ESM can detect only facility attack scenarios, but will typically be the first to detect this type of scenario.

The empirical data was collected from the Cincinnati CWS pilot during the evaluation period, as described in Section 7.1. While valid alerts were rarer than invalid alerts, three of the four monitoring and surveillance components did generate a few valid alerts, which were evaluated under this metric.

Results: A summary of the number of scenarios theoretically detectable and the number of scenarios actually detected during the simulation study is presented in **Table 7-3**. Whether a scenario is theoretically detectable or not depends on the contaminant used in the scenario. The assumptions regarding which contaminants are detectable by each component is summarized in Table 3-2. Table 7-3 shows the number of scenarios that were detected and those that were first detected by each component for the full ensemble and for the distribution system attack scenarios only. The detection results for each component are discussed below.

Table 7-3. Simulated Contamination Scenarios Detected by each Component

Component	ESM	WQM	CCS	PHS	SC	LA
Scenarios Theoretically Detectable	425	2,015	714	1,777	2,015	2,015
Scenarios Actually Detected (full ensemble)	425	649	693	1,706	1,666	1,729
First Detected (full ensemble)	425	257	547	742	–	–
Scenarios Detected (distribution system attack scenarios only)	–	458	564	1,396	1271	1,307
First Detected (distribution system attack scenarios only)	–	257	547	742	–	–

Detection of Simulated Contamination Scenarios by Component

Figure 7-3 shows the detection percentage for each component, evaluated relative to the number of scenarios each component could theoretically detect, as shown in Table 7-3, but also relative to the total number of scenarios in the ensemble (2,015). The former analysis provides an indication of how well the component performed relative to its intrinsic detection capabilities. Ideally, a component would detect

100% of the scenarios that are theoretically detectable. The detection percentage calculated relative to the full ensemble provides an indication of component performance relative to a broad spectrum of contamination threats; however, this metric is heavily influenced by the design of the scenarios included in the ensemble. For example, if the ensemble included more scenarios using contaminants that have aesthetic characteristics, then CCS would have had a higher detection rate relative to the full ensemble.

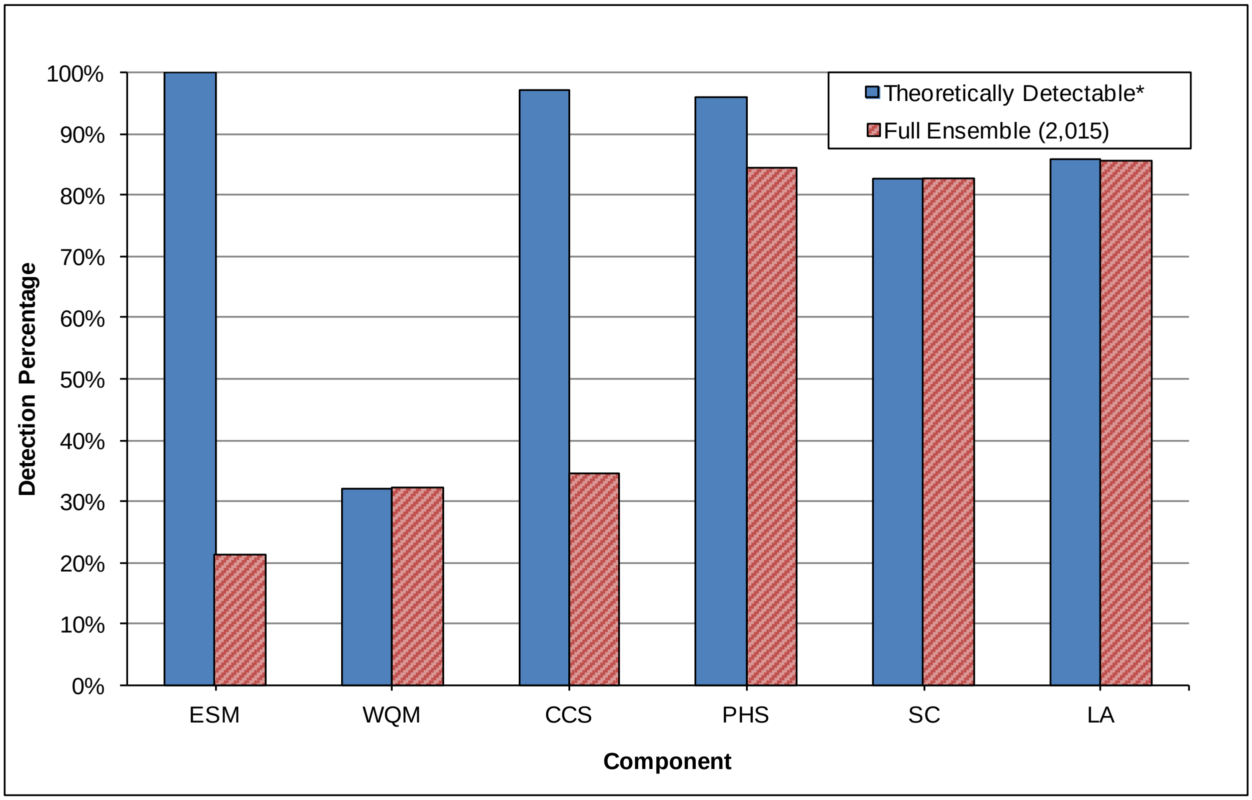

Figure 7-3. Detection Percentage of Simulation Scenarios by Component
* Total count varies by component; see Table 7-3 for details.

All facility attack scenarios (425) were detected by ESM yielding a detection rate of 100%. At the ensemble level, ESM had a detection rate of 21%, reflecting its ability to detect injections only at facilities with security monitoring. CCS can detect only the six contaminants in the ensemble that change the aesthetic character of the water, but detected 97% (693) of the 714 scenarios that were theoretically detectable by CCS. All of the scenarios that were theoretically detectable but not actually detected by CCS were facility attack scenarios in which early detection by ESM, followed by isolation of the contaminated facility, resulted in few exposed customers and thus few calls to the utility. At the ensemble level, CCS detected 34% (693) of the 2,015 scenarios. PHS detected 96% (1,706) of the 1,777 scenarios that could have been theoretically detected (all scenarios involving 15 of the 17 contaminants that produce health consequences). At the ensemble level, PHS detected 85% (1,706) of the 2,015 scenarios. The theoretically detectable scenarios that PHS failed to detect involved contaminants that pose a risk to public health primarily through inhalation. For these contaminants, only a single exposure event in the morning was modeled (7:00 a.m. showering event). The limited opportunity for exposures resulted in fewer symptomatic individuals and a larger temporal spread in clusters of related cases, which presented a challenge for detection by PHS.

All scenarios were theoretically detectable by WQM; however, the contaminant concentration must be sufficiently high at one of the 15 monitoring location to change water quality in a manner that causes the event detection system to generate an alert. WQM detected 649 of the 2,015 scenarios, yielding a detection rate of 32%, the lowest among the four components. While the 15 monitoring stations are strategically located throughout the distribution system to maximize spatial coverage, several scenarios used injection locations that produced a contaminant spread that did not reach a monitoring station at a detectable concentration. In the simulation study, it was observed that all scenarios with injections in 28 of the 94 pito zones (30%) were not detected by WQM, indicating that contaminated water did not reach any of the monitoring stations at detectable concentrations. Injections at these 28 pito zones include 592 scenarios over all 17 contaminants, indicating that failure to detect by WQM can be attributed to system hydraulics and location of the monitoring stations rather than contaminant properties. While the detection rate is low for WQM, it did successfully detect almost all of the scenarios that would have produced significant consequences. Many scenarios that were missed by WQM would have produced only a few illnesses and no fatalities.

SC can theoretically detect all contamination scenarios at concentrations high enough to produce a positive result from either a rapid field test or a water quality parameter test. SC detected 1,666 of the 2,015 scenarios, a detection rate of 83% relative to the entire ensemble. The LA component can also theoretically detect all contamination scenarios; however, the sample must be sent to the proper laboratory and have a sufficiently high concentration to produce a positive result using LA methods. LA detected 86% (1,729) of the 2,015 scenarios. For the majority of contaminants, samples were collected in sufficient time to capture a detectable concentration. However, the conditions of some scenarios resulted in delayed sample collection, and by the time samples were collected, the contaminated water had passed through the distribution system and samples collected did not have a contaminant concentration above the detection threshold.

First Detection of Simulated Contamination Scenarios by Component

A majority of contamination scenarios are theoretically detectable by multiple components. The component that generates the first alert in a scenario is referred to as “the first component to detect.” The first component to detect a scenario has a significant influence on how the scenario unfolds including progression and timeliness of threat level determination, timeliness of response actions and ultimately the reduction in potential consequences. Hence, the data were analyzed to determine the number and percentage of scenarios that were first detected by each component relative to the total number of scenarios detected by that component. This analysis was performed on both the full ensemble and just the distribution system attack scenarios. The results are displayed in **Figure 7-4**.

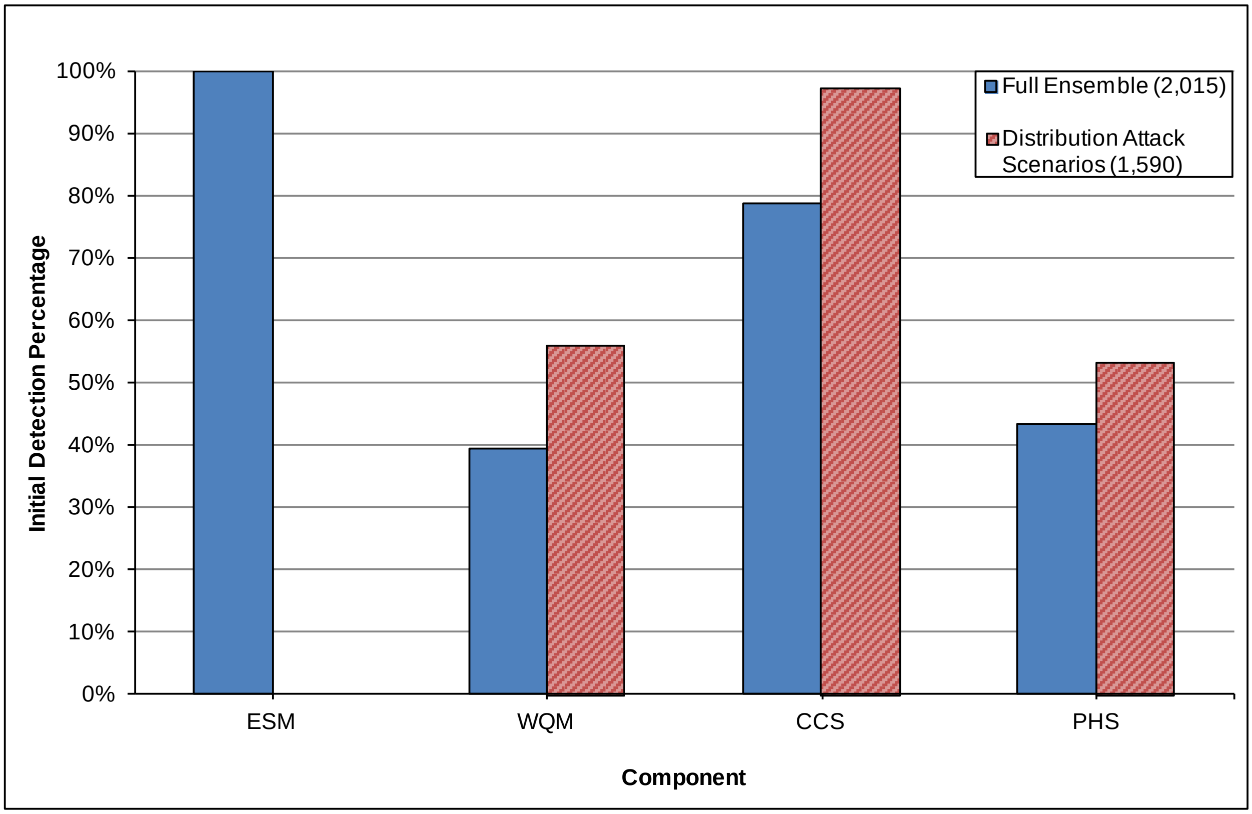

Figure 7-4. Simulation Scenarios First Detected by Each Component

The analysis of the distribution system attack scenarios, excluding the facility attack scenarios, was conducted because ESM is always the first to detect an attack at a utility facility with security monitoring, as evident in Figure 7-4. The analysis of distribution system attack scenarios provided a useful comparison of initial detection by the three remaining components, WQM, CCS and PHS. In all distribution system attack scenarios that were detected by CCS, it was the first component to detect 97% of the time (547 out of 564 scenarios). WQM and PHS were the first component to detect in a little more than half of the distribution system attack scenarios that they detected. However, with significantly higher number of detections by PHS (1,396) compared to WQM (458), more scenarios were detected first by PHS (742) than by WQM (257).

Valid Alerts Observed in the Empirical Data

Analysis of empirical data generated during the evaluation period demonstrates that valid alerts were rarer than invalid alerts. However, WQM, CCS and PHS did generate a total of 84 valid alerts over the course of the evaluation period. **Figure 7-5** shows the causes of valid alerts for the entire system as well as for each of these three monitoring and surveillance components. Seven categories of valid alerts were identified:

- **Main Break.** A confirmed break in a water distribution system pipe.
- **Distribution System Work.** A planned activity in the distribution system such as flushing and pipe repair or replacement.
- **Treatment Plant Change.** An adjustment in chemical feed or a unit process at a drinking water treatment facility.
- **Verified, Non-Standard System Operation.** Atypical system operations, such as an unusual change in system pumping or valving, resulting in unusual water quality patterns.

- **Public Health Incident.** An occurrence of disease, illness or injury within a population that is a deviation from the disease baseline in the population.
- **Confirmed Water Contamination.** A confirmed change in water quality that is the result of the introduction of a contaminant into the distribution system. There were no confirmed water contamination alerts during the evaluation period.
- **Other.** A verified alert that could not be definitively attributed to one of the above causes. For CCS, an example of a valid alert categorized as "other" was an alert generated by a backlog of complaints due to customers calling the utility after a long holiday weekend during which the call center was closed. For WQM, an example of a valid alert categorized as "other" was an alert caused by a real TOC spike for which a cause could not be identified.

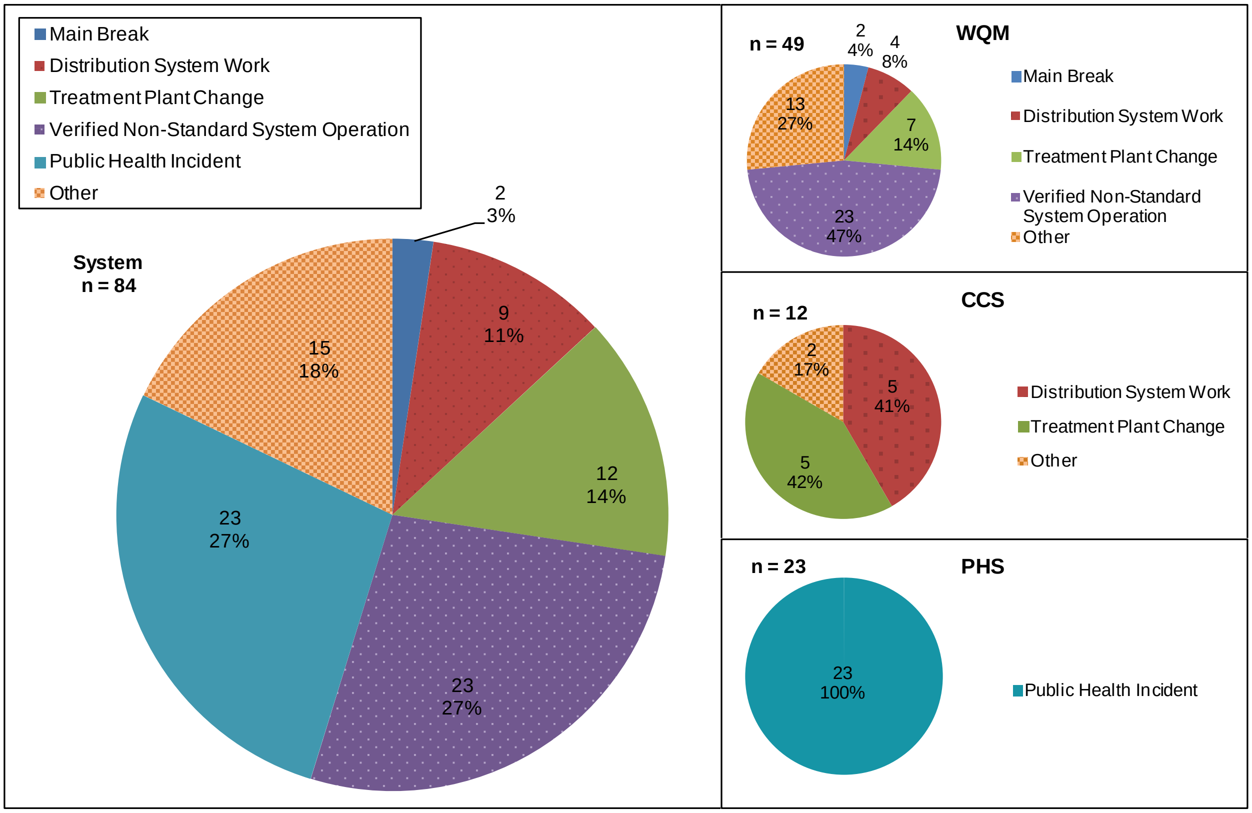

Figure 7-5. Causes of Valid Alerts for the System and each Component

WQM generated 49 valid alerts during the evaluation period. The most common cause of valid WQM alerts was verified non-standard system operations (47%), such as changes in pumping or valving that produced a detectable change in water quality. The next common causes were distribution work (27%) and treatment plant changes (14%). An example of a treatment plant change occurred on February 9, 2010 at 10:40 p.m., when unusual finished water quality was observed leaving GCWW's primary treatment plant. Most notably, chlorine residual levels increased from 0.77 to 1.95 mg/L with a corresponding decrease in pH from 8.42 to 8.17. The duration of this unusual water quality incident was approximately 1.5 hours, and the abrupt change in finished water quality can be seen in **Figure 7-6**.

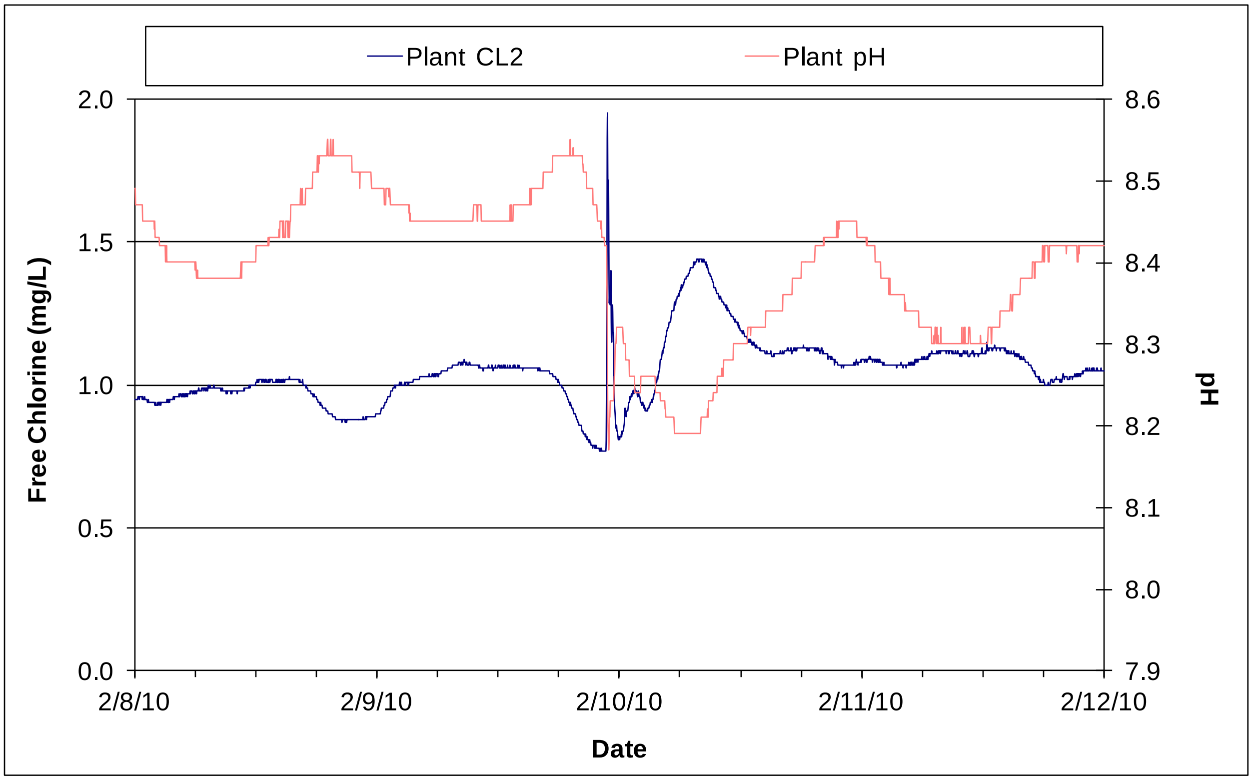

Figure 7-6. Change in Finished Water Quality Resulting from a Treatment Plant Change

This slug of water propagated out into the distribution system, and although the slug was attenuated, it was observed at six of the WQM stations deployed throughout the distribution system. **Figure 7-7** shows the attenuated signal at one of these monitoring stations, which generated an alert on February 10, 2010 at 6:20 a.m., or 7.7 hours after the slug of water left the treatment plant. The investigator was able to quickly identify the source of this unusual water quality by reviewing recent data for finished water quality leaving the treatment plant.

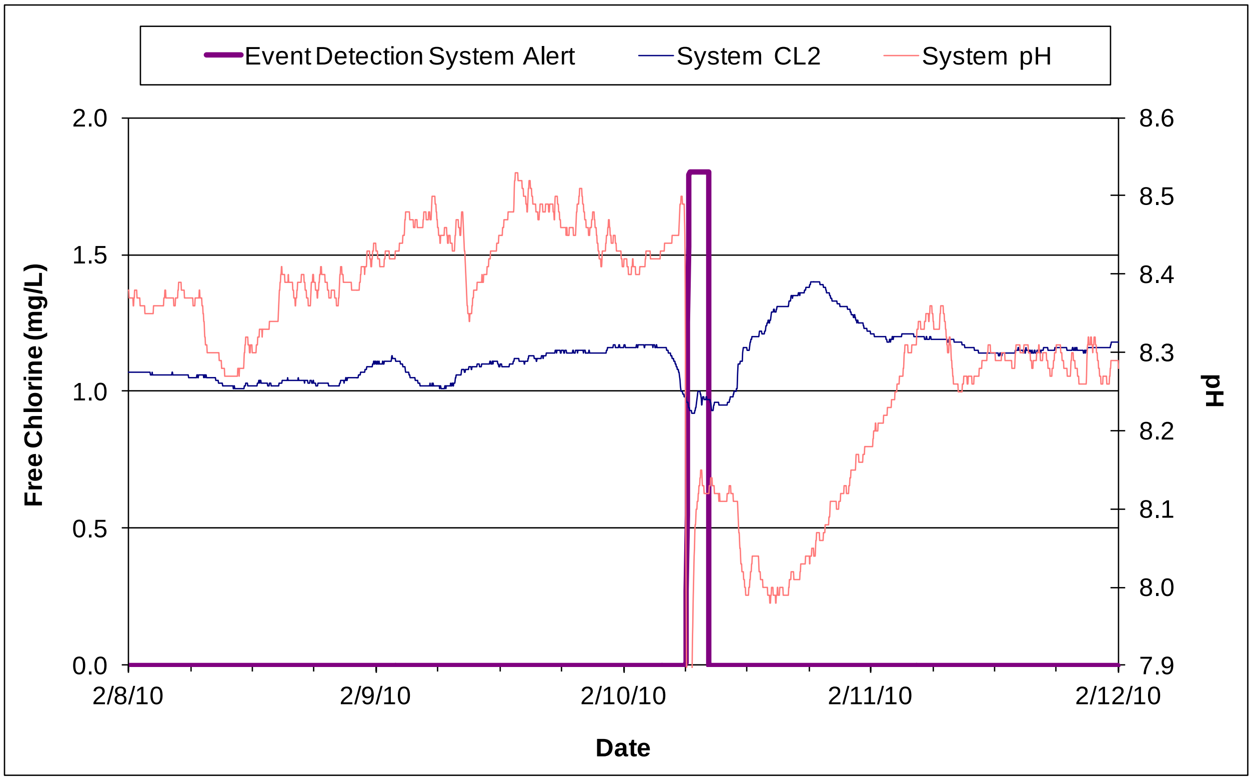

Figure 7-7. WQM Alert Caused by the Treatment Plant Change Shown in Figure 7-6

There were 12 valid CCS alerts that were primarily the result of two events. In January 2009, there were five CCS alerts that were ultimately determined to be related to distribution system work being performed in the area where calls originated. In August 2008, the CCS component generated five valid alerts due to elevated chlorine levels in the distribution system, which could be correlated to data produced by the WQM component to provide further corroboration of the change in water quality.

PHS generated 23 valid alerts, all attributable to public health events that were unrelated to water quality. These were typical seasonal health events, such as an increase in respiratory distress at the onset of the allergy season. In another example, a series of alerts were received in October 2009, which public health officials determined were related to an increase in H1N1 influenza cases in Cincinnati.

While the number of valid alerts was only a small percentage of the total number of alerts generated over the evaluation period, these examples demonstrate the ability of the monitoring and surveillance components of the Cincinnati CWS to detect unusual conditions in the system that are related either to water quality or to public health. These detection capabilities support the contaminant detection function of the CWS as well as routine monitoring of distribution system and public health conditions.

7.3 Alert Co-occurrence

Definition: Alerts from multiple components that occur within a specified period. Alerts that meet this criterion define a cluster. If the alerts are valid and share a common cause, the cluster is considered valid.

Analysis Methodology: Co-occurrence of alerts was evaluated using two different data sources: simulation study results and empirical data.

As described in Section 7.2, all alerts generated during the simulation study are valid by design. Furthermore, all alerts generated during a specific contamination scenario are caused by the same contamination scenario, and thus constitute a valid cluster. This large dataset of valid alert clusters was divided into groups of similar contaminants, which were evaluated to determine the combinations of components that detected simulated contamination incidents. The time delays between consecutive alerts in a cluster were also evaluated.

Alerts were tracked throughout the Cincinnati CWS pilot evaluation period, as described in Section 7.1. The dataset of WQM, CCS and PHS alerts was used to identify alert clusters from multiple components, and each cluster was categorized as valid or invalid based on observations from the alert investigations. Comparison between these observed alert clusters and the simulation study results demonstrate the frequency with which the predicted alert patterns derived from the simulation study results occur in the empirical data from the pilot.

Results: This analysis is intended to provide insight regarding the combinations of alerting components that are indicative of an actual contamination incident. For this analysis, the number of scenarios in the ensemble of distribution system attack scenarios that were detected by all relevant combinations of two or more components was determined. The components considered in the permutations include: CCS, PHS, WQM, SC and LA. This analysis was performed for the following four groups of contaminants:

- **Nuisance chemicals: Nuisance chemicals 1 and 2.** These two contaminants do not produce acute health consequences at concentrations modeled in the study and are thus undetectable by PHS.
- **Contaminants with taste or odor: Toxic Chemicals 1 through 4; Biological Agent 1**. These five contaminants change the aesthetic character of the water (taste, odor, color, or dermal irritation) and are detectable by CCS. Note that Nuisance Chemical 1 also has a taste and odor but was placed exclusively in the “nuisance chemicals” group for this analysis.
- **Contaminants with rapid symptom onset: Toxic Chemicals 5 through 7; Biological Agents 2 and 3.** These five contaminants produce symptoms in exposed individuals between 10 minutes and 4 hours after the time of exposure. Note that Toxic Chemicals 1 through 4 and Biological Agent 1 also lead to a rapid onset of symptoms but were placed exclusively in the “contaminants with taste and odor” group for this analysis.
- **Contaminants with delayed symptom onset: Toxic Chemical 8; Biological Agents 4 through 7.** These five contaminants produce symptoms in exposed individuals between 1 day and 2 weeks after the time of exposure. None of the contaminants in this group are detectable by CCS.

Additionally, note that all contaminants are detectable by WQM and S&A. **Figures 7-8(a)** through **7-8(d)** show the combinations of alerting components that are indicative of a simulated contamination incident for each of the four categories listed above.

Figure 7-8(a) indicates that none of the scenarios involving nuisance chemicals were detected by PHS, which was expected given that these contaminants do not produce illness. CCS successfully detected all scenarios involving Nuisance Chemical 1, but none involving Nuisance Chemical 2, which was expected given that it does not alter the aesthetic character of the water. CCS and WQM both generated alerts in 67% of scenarios for Nuisance Chemical 1, with CCS being the first to generate alerts in 77% of those scenarios. WQM was involved in the detection of 79% of scenarios involving nuisance chemicals that were detected by multiple components and one scenario in which it was the only component to detect contamination. S&A successfully detected all but one of the scenarios that involved nuisance chemicals, providing important corroborating information to establish the credibility of the incident.

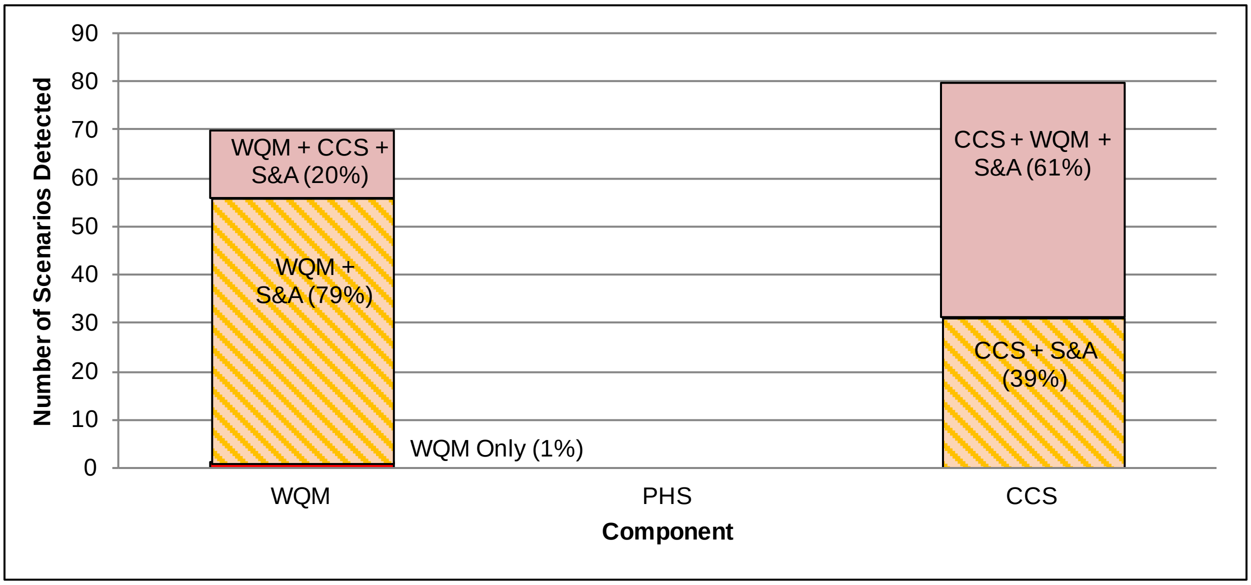

Figure 7-8(a). Multiple Component Detections of Nuisance Chemicals

Figure 7-8(b) shows that CCS detected all contaminants that impart a taste or odor to the water, as expected. In all but three scenarios, CCS was the first to detect, indicating its importance as an early warning system for contaminants with aesthetic characteristics. These contaminants were also detected by PHS and S&A and in that order, with one exception in which PHS alerted before CCS. In 15% of the scenarios, WQM provided a fourth method of detection, and always alerted before PHS for this contaminant group. In general, this group of contaminants that impart a taste or odor to the water can be reliably detected by multiple components.

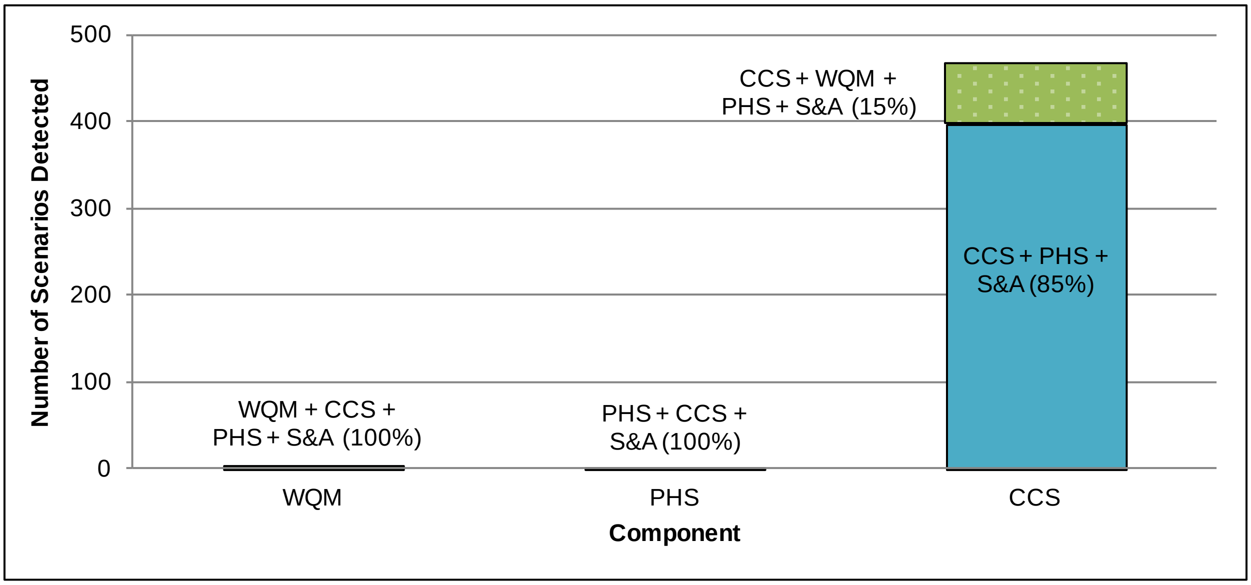

Figure 7-8(b). Multiple Component Detections of Contaminants with Taste or Odor

Figure 7-8(c) shows that initial detection by PHS followed by S&A was the most common detection pattern for contaminants that produce rapid onset of symptoms. In 60% of scenarios in which the PHS and WQM both detected contamination, PHS detected contamination before WQM. Because of the rapid onset of symptoms, enough cases are generated to quickly trigger a PHS alert. This demonstrates that PHS is valuable as an early warning component of the CWS for contaminants with rapid symptom onset.

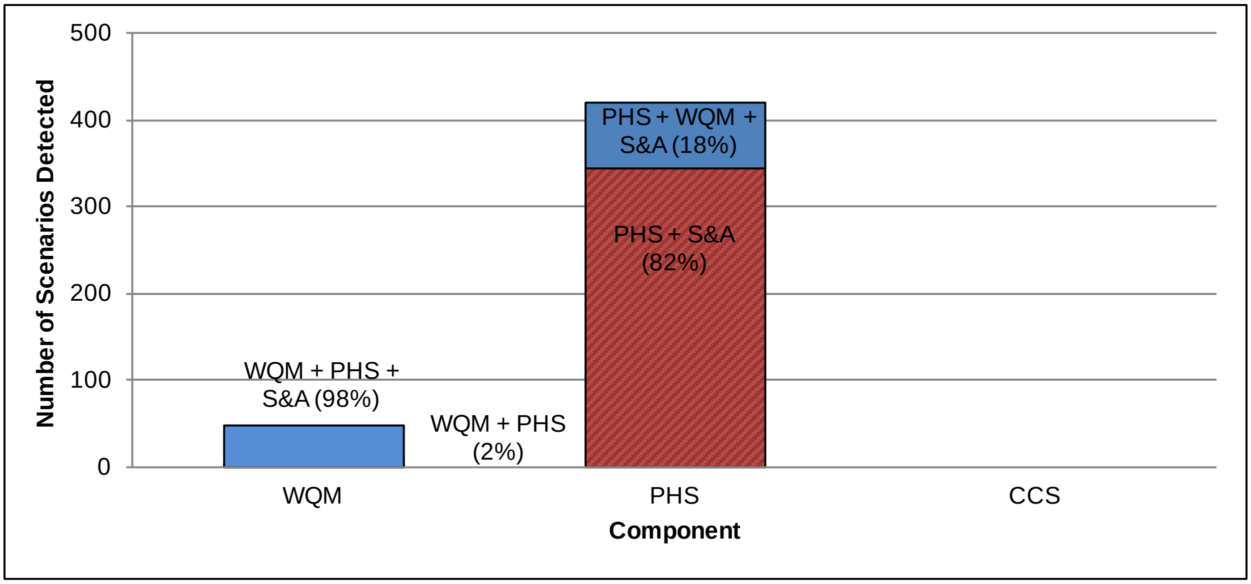

Figure 7-8(c). Multiple Component Detections of Contaminants with Rapid Symptom Onset

Figure 7-8(d) shows that all scenarios involving contaminants with delayed symptom onset were detected by PHS. Initial detection occurred via either PHS or WQM, and WQM was the first to detect 94% of the scenarios involving both components. S&A detected 48% of scenarios involving contaminants with delayed symptom onset. It was more common for S&A to successfully detect the contaminant when the scenario was also detected by WQM because the WQM alert also triggers automated sample collection at the site and time of the alert, thus preserving an aliquot of water that likely has a contaminant concentration above the detection threshold for S&A (i.e., laboratory analysis or field testing). On the other hand, PHS alerts occur only when enough symptomatic individuals seek healthcare. In the case of contaminants with delayed symptom onset, the PHS alert is often delayed until after the contaminated water has largely left the distribution system, making it challenging to collect a sample with a concentration above the detection threshold for S&A. While WQM detected only 32% of the scenarios with delayed symptom onset, timely response to these alerts is critical because WQM may be the only component to provide early detection of contaminants with delayed symptom onset.

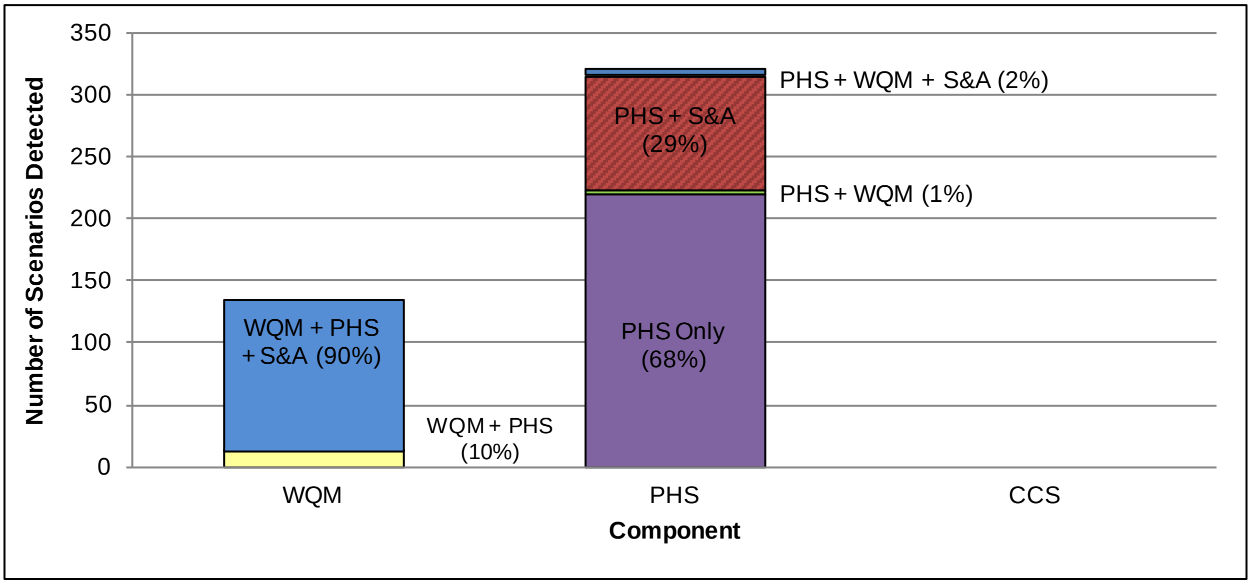

Figure 7-8(d). Multiple Component Detections of Contaminants with Delayed Symptom Onset

The simulation study results were also used to evaluate the time between sequential component alerts. For example, the time difference between the start of the first and second alerts is calculated for each scenario and referred to as the second alert delay. This analysis considered the first alert from WQM, each CCS subcomponent (with two subcomponents) and each PHS subcomponent (with five subcomponents). For example, if a CCS IVR alert occurred at 30 minutes, a PHS-911 alert at 45 minutes, and a PHS-ED alert at 120 minutes, the second alert delay is 15 minutes (45 minutes – 30 minutes) and the third alert delay is 75 minutes (120 minutes – 45 minutes). **Figure 7-9** presents the median alert delays, as calculated over all distribution system attack scenarios.

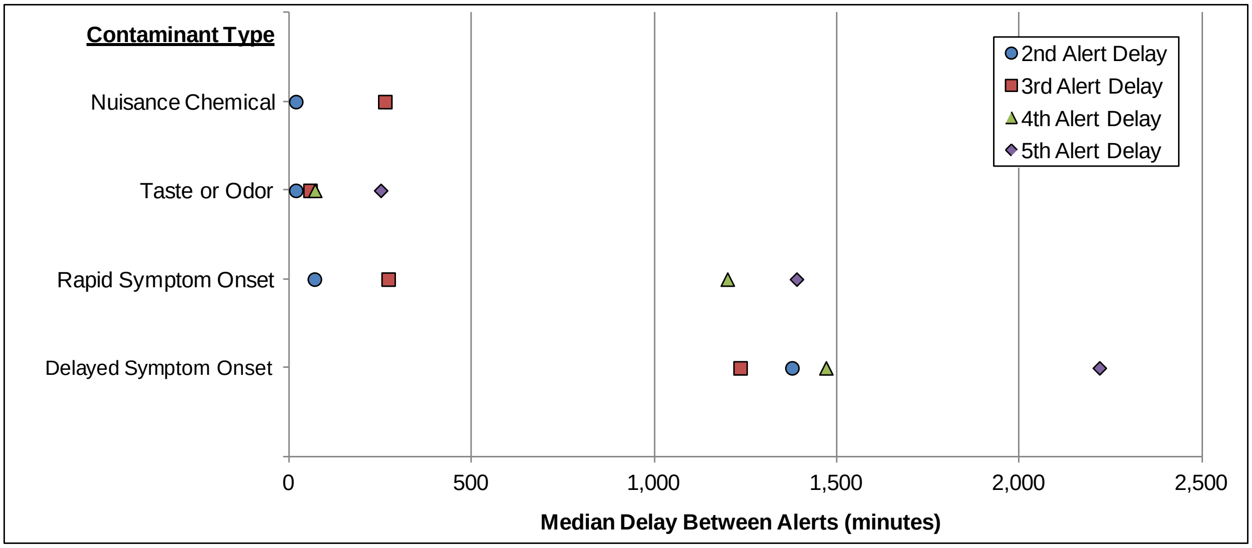

Figure 7-9. Distribution of Time Delays between Consecutive Alerts from the Simulation Study

In general, the median delay time for successive alerts showed an increasing trend, where the second alert delay < third alert delay < fourth alert delay < fifth alert delay. The median time delay of the distribution system attack scenario ensemble for the fifth alert onwards was greater than 18 hours. Alerts occurring this late, after four other alerts have already occurred, are unlikely to expedite threat level determinations or responses.

Table 7-4 shows the occurrence of alert clusters for the different sequences of components listed in the first column. The Alert Cluster Order reflects the sequence and combination of alerts (e.g., CCS/PHS indicates a CCS alert followed by a PHS alert, while PHS/CCS indicates that the PHS alert occurred before the CCS alert). The analysis of alert clusters in simulated contamination scenarios was performed independently on toxic chemicals and biological agents, as defined in Section 3.3, due to the significantly different detection patterns for these two broad contaminant groups. For each of these two groups, the number of scenarios in which the indicated alert cluster order occurred is shown in the column titled "# Alert Clusters." The average delay columns show the average number of minutes between the alert start times for the components listed in the first column. For example, in the CCS/PHS row, the average delay is calculated as the difference between the start of the first CCS alert and the first PHS alert. For rows with three components in the alert cluster order, Delay 1 is the difference between the alert start times for the two components listed first, and Delay 2 is the difference between the alert start times for the second and third components. For example, in the row with alert cluster order CCS/PHS/WQM, Delay 1 represents the average time between a CCS and PHS alert and Delay 2 represents the average time between a PHS and WQM alert. The most frequently occurring alert pattern for toxic chemicals was CCS/PHS, with a count of 317 alert clusters and an average delay of 97 minutes. The most frequently occurring alert pattern for biological agents was WQM/PHS, with a count of 169 alert clusters and an average delay of 2,933 minutes.

Table 7-4. Co-occurrence of WQM, CCS and PHS Alerts for Simulated Contamination Scenarios

Alert Cluster Order[1]	Toxic Chemicals		Biological Agents	
	# Alert Clusters	Average Delay (minutes)	# Alert Clusters	Average Delay (minutes)
CCS/PHS	317	Delay 1 = 97	81	Delay 1 = 74
PHS/CCS	1	Delay 1 = 181	0	–
PHS/WQM	49	Delay 1 = 458	34	Delay 1 = 472

Alert Cluster Order[1]	Toxic Chemicals		Biological Agents	
	# Alert Clusters	Average Delay (minutes)	# Alert Clusters	Average Delay (minutes)
WQM/PHS	16	Delay 1 = 99	169	Delay 1 = 2,933
CCS/PHS/WQM	48	Delay 1 = 77 Delay 2 = 342	9	Delay 1 = 75 Delay 2 = 412
CCS/WQM/PHS	8	Delay 1 = 59 Delay 2 = 28	4	Delay 1 = 27 Delay 2 = 46
WQM/CCS/PHS	2	Delay 1 = 49 Delay 2 = 51	0	–

The alert cluster patterns observed in the simulation study results (shown in Table 7-4) were used to characterize alert clusters observed in the empirical data from the Cincinnati CWS pilot in order to identify how often the patterns seen in the simulation study results were observed in the empirical data. **Table 7-5** shows these results using a table structure similar to that used in Table 7-4. To perform this analysis, the delay window listed in Table 7-5 was created based on one standard deviation above and below the average delay reported in Table 7-4 for each alert cluster order, and for both toxic chemicals and biological agents. The real-time monitoring alerts were then searched to identify clusters that match those observed in the simulation study results and have alert start times that fall within the delay window. For example, for toxic chemicals, all CCS alerts were searched to identify if a PHS alert started within 50 to 134 minutes of the start of a CCS alert, matching the pattern observed in the simulation data. Alert clusters that met these criteria were included in the counts reported in Table 7-5.

Table 7-5. Co-occurrence of WQM, CCS and PHS Alerts Observed in the Emperical Data

Alert Cluster Order	Toxic Chemicals		Biological Agents	
	# Alert Clusters	Delay Window (minutes)	# Alert Clusters	Delay Window (minutes)
CCS/PHS	5	Delay 1 = 50 to 134	3	Delay 1 = 61 to 85
PHS/CCS	6	Delay 1 = 135 to 227	–	–
PHS/WQM	51	Delay 1 = 75 to 841	52	Delay 1 = 67 to 877
WQM/PHS	10	Delay 1 = 30 to 168	412	Delay 1 = 508 to 5,358
CCS/PHS/WQM	1	Delay 1 = 36 to 108 Delay 2 = 48 to 636	1	Delay 1 = 67.5 to 83 Delay 2 = 198 to 626
CCS/WQM/PHS	0	Delay 1 = 26 to 91 Delay 2 = 2 to 53	0	Delay 1 = 8 to 47 Delay 2 = 27 to 63
WQM/CCS/PHS	0	Delay 1 = 10 to 88 Delay 2 = 47 to 55	–	–

Table 7-5 shows the frequency of the alert clusters occurring in the real-time alerts. The most frequently occurring alert pattern for toxic chemicals was PHS/WQM, with a count of 51 alert clusters and a delay window of 75 to 841 minutes. The most frequently occurring alert pattern for biological agents was WQM/PHS, with a count of 412 alert clusters and a delay window of 508 to 5,358 minutes. In both cases, the component alerting order with the maximum occurrence also had the largest delay window. Thus, the number of alert clusters associated with the indicated order appears to be a function of the size of the alert window more than an intrinsic characteristic of the system.

The combination of PHS/WQM for both toxic chemicals and biological agents appears with similar frequency in both simulated and empirical data sets. The alert cluster order observed most frequently in the empirical data, WQM/PHS with a long delay window, was also observed frequently in the simulation study results. As discussed above, the frequency of occurrence of this pattern is due, at least in part, to the large delay window. However, this large delay window has a basis in reality because in the case of a biological agent with delayed symptom onset, it is possible to have a WQM alert occur within a few hours of the start of a contamination incident, while the PHS alert can be delayed for several days or weeks. Thus, even though these alert patterns can appear randomly in an operational CWS, it is important to investigate potential causal relationships between WQM and PHS alerts that occur within a temporally and spatially meaningful cluster. In the Cincinnati CWS, this concept was incorporated into PHS alert investigation procedures that require investigators to review data and alerts from other components within a 2-week period preceding the PHS alert.

Other alert cluster patterns that were observed in the simulation study results were not observed in the empirical data. For example, the most frequent combination for the simulated results (CCS/PHS) did not occur with nearly the same frequency in the empirical data. While only one instance of three components alerting occurred in the empirical data for each contaminant group (CCS/PHS/WQM), this alert cluster order was the third most frequent for toxic chemicals in the simulation study.

Overall, the co-occurrence of temporally related alerts from all three monitoring and surveillance components (WQM, CCS and PHS) was extremely rare in the empirical data. Additionally, during real-time monitoring, there was never an occurrence of an alert cluster consisting of multiple, valid alerts from different monitoring and surveillance components. These results indicate that a temporally and spatially significant alert cluster consisting of valid alerts from multiple components is likely related to a real water quality issue, and thus should be thoroughly investigated.

7.4 Summary

The occurrence of valid and invalid alerts has a significant impact on the benefits and sustainability of the CWS. Benefits of a CWS are realized through detection of unusual water quality conditions that are of interest to the utility. On the other hand, too many invalid alerts can divert personnel from other duties and may ultimately be perceived as an indication that the CWS is unsustainable. Although invalid alerts initially occurred frequently, with more than 150 invalid alerts during most reporting periods in the first year of operation, once the system was optimized by improving the quality of the underlying data and updating event detection system configurations to reflect normal variability, the number of invalid alerts was reduced to about 69 per reporting period. While most alerts were determined to be invalid, the CWS did detect 84 valid alerts, with more than half of the valid alerts caused by non-standard system operations and public health events that were unrelated to drinking water.

The Cincinnati CWS was designed to include a variety of surveillance tools to increase contaminant coverage as well as the reliability of the system for utility managers that need to decide whether or not contamination may be Possible. Through this multi-component design, weaknesses in the detection capabilities of one component are offset by the strengths of another. In particular, co-occurring alerts from multiple components can increase the utility manager’s confidence that the alerts are valid and indicative of a potential water quality issue. Different contaminant types such as nuisance chemicals or those with rapid or delayed symptom onset trigger different combinations of component alerts and the timing of those alerts occur in predictable patterns. The co-occurrence of two alerting components, especially the combination of PHS and WQM, was frequent in both simulated and empirical data. While any combination of three components alerting was observed only once in the empirical data, alert clusters involving three or more components was common in the simulation study results. This would suggest that valid alert clusters involving alerts from multiple components are probably the result of a real water quality issue in the distribution system.

Section 8.0: Timeliness of Detection and Response

For a CWS to have the maximum potential to reduce consequences of a contamination incident, it must detect the incident early enough to allow sufficient time to implement effective response actions. The timeliness of detection is heavily dependent upon the design of the individual monitoring and surveillance components. The timeliness of response is primarily governed by consequence management. However, the overall timeline of a contamination incident is largely influenced by the details of the scenario, most notably the injection location, contaminant mass, and contaminant injection rate, which will determine the hydraulic travel time and spread of the contaminant through the distribution system. The specific contaminant used in the incident will determine which monitoring and surveillance components have the potential to generate alerts as well as the manner in which consequences unfold.

This design objective was evaluated through analysis of detection and response times measured during routine operations, drills and exercises, and simulations. However, to evaluate whether the timing of detection and response actions was sufficient, the reduction in consequences for simulated contamination scenarios, attributable to deployment and operation of the CWS, was assessed. Thus, this section will present results for the reduction in consequences in addition to an analysis of detection and response times.

To evaluate how well the CWS met this design objective, the following three metrics were evaluated: detection time, response time, and consequence reduction. The following subsections define each metric, describe how it was evaluated and present the results.

8.1 Detection Time

Definition: The time between the initial presence of abnormal water quality in the distribution system (e.g., injection of a contaminant) and the start of a component alert. The delays that occur between these two events vary by component, but generally result from the following:

- Hydraulic travel time between the injection location and a customer or a sensor,
- Time to generate data (e.g., a security alert, a reading from a water quality sensor, a call from customer with a water quality complaint, a health seeking behavior from a symptomatic individual), and
- Time to analyze the data and generate an alert, which in the case of WQM, CCS and PHS relies on an automated event detection system.

Analysis Methodology: Results from the simulation study were used to calculate the detection time for each contamination scenario as the difference between the start of a component alert and the start of contaminant injection. The resulting detection times were analyzed by component and contaminant. The latter is an important stratification of the results because the contaminant properties can impact which component detects the contamination incident as well as the relative timing of alerts. Many of the results presented in this section are based on analyses that were limited to either distribution system attack scenarios or facility attack scenarios. If a specific scenario type or subset is not specified, the results are from an analysis performed on the entire ensemble.

Results: Five sets of results are presented for the analysis of detection times. First, timelines for five representative simulated contamination scenarios are presented to illustrate how typical contamination scenarios unfold. Next, the results of a statistical analysis of initial alert times by component are presented. The remaining three subsections present the results of further analysis of the differences in the times of initial alerts for each of the following components: CCS, PHS and WQM.

Illustrative Contamination Scenario Timelines

The five scenarios presented in this section were selected to demonstrate the variability in the sequence and timing of alerts and response actions, which is largely driven by differences in the scenario variables such as contaminant type, injection location and injection start time (12:00 a.m. or 9:00 a.m.).

The timeline for a typical contamination scenario with Nuisance Chemical 1 is shown in **Figure 8-1**. The injection occurred at a distribution system node during the morning, a period of high water demand. The first CCS alert occurred 2.5 hours after injection and led to a Possible determination within the next half hour. CCS was the first component to detect in 85% of the distribution system attack scenarios involving this contaminant, and the scenario represented in Figure 8-1 reflects this tendency. WQM was the first to detect this contaminant in 15% of the distribution system attack scenarios. In scenarios where WQM was the first to detect, the injection was at midnight and detection by CCS was delayed until the first exposure event in the morning, approximately seven hours later.

Possible determination was followed by an operational (Op) response to limit the spread of the contaminant 15 minutes later. Water quality (WQ) field testing occurred approximately 2.5 hours after the Possible determination and the results from rapid field testing (RFT) elevated the threat level to Credible less than six hours after injection, and public health (PH) response occurred at the same time. The first WQM alert occurred approximately eight hours after the start of the injection and provided information sufficient to elevate the threat level to Confirmed. Public notification was issued approximately nine hours after the start of the injection. While preparation of the public notice began at the time contamination was determined to be Possible, issuance of the notice was delayed until contamination was Confirmed because there were no adverse health impacts during this scenario. An assumption of the model is that public notification will be issued before contamination is Confirmed only if there is clear a risk to public health, which is based on observations from drills and exercises.

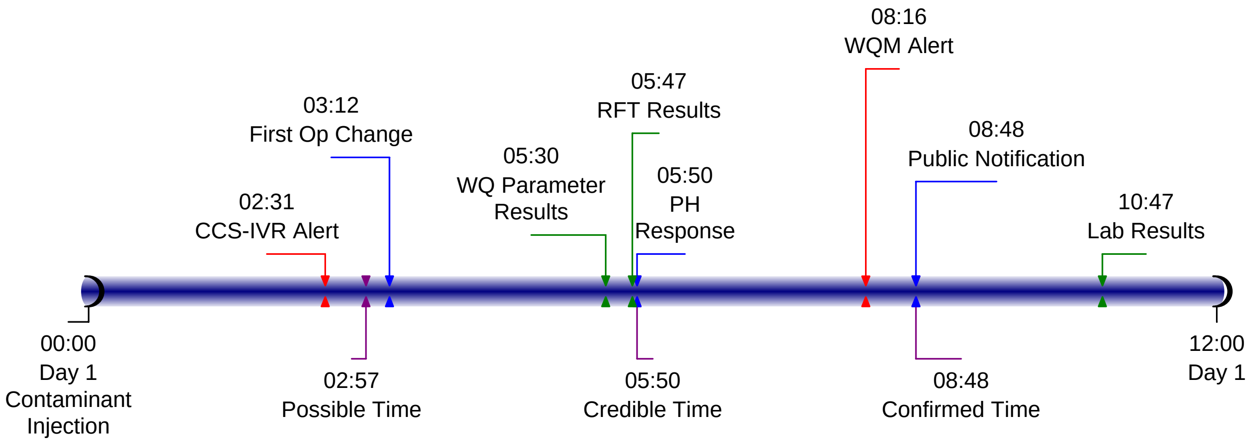

Figure 8-1. Timeline for a Typical Contamination Scenario with Nuisance Chemical 1

The timeline for a typical contamination scenario with Toxic Chemical 1 is shown in **Figure 8-2**. The injection occurred at a distribution system node at midnight. The first CCS alert occurred 6 hours and 40 minutes after injection, which corresponds to the first opportunity for exposure in the model design. CCS was the first component to detect all distribution system attack scenarios that involve Toxic Chemical 1. This is true even for scenarios with injections at midnight where detection by CCS is delayed until the first exposure event occurs approximately 7 hours after the start of the injection. Thus, the example scenario shown in Figure 8-2 is considered representative of most scenarios involving Toxic Chemical 1.

The first CCS alert led to a Possible determination 27 minutes after the alert, and operational response actions were implemented 7 minutes later. The public health response occurred within half an hour of the Possible determination. A PHS-DPIC alert occurred next, 7 hours and 40 minutes after the start of the injection, and provided sufficient information to elevate the threat level to Credible. The first WQM alert occurred 8 hours and 17 minutes after injection and provided sufficient information to Confirm contamination. Public notification was issued approximately 9 hours after the start of the injection, and exactly 2 hours after the Possible determination, which is the assumed time needed to prepare the notice. The field testing and laboratory analysis results were available approximately 10 and 17 hours after the injection, respectively. While these results were not available in time to inform the response actions simulated in the model, definitive identification of the contaminant through laboratory analysis would certainly inform later stages of the response to an actual contamination incident.

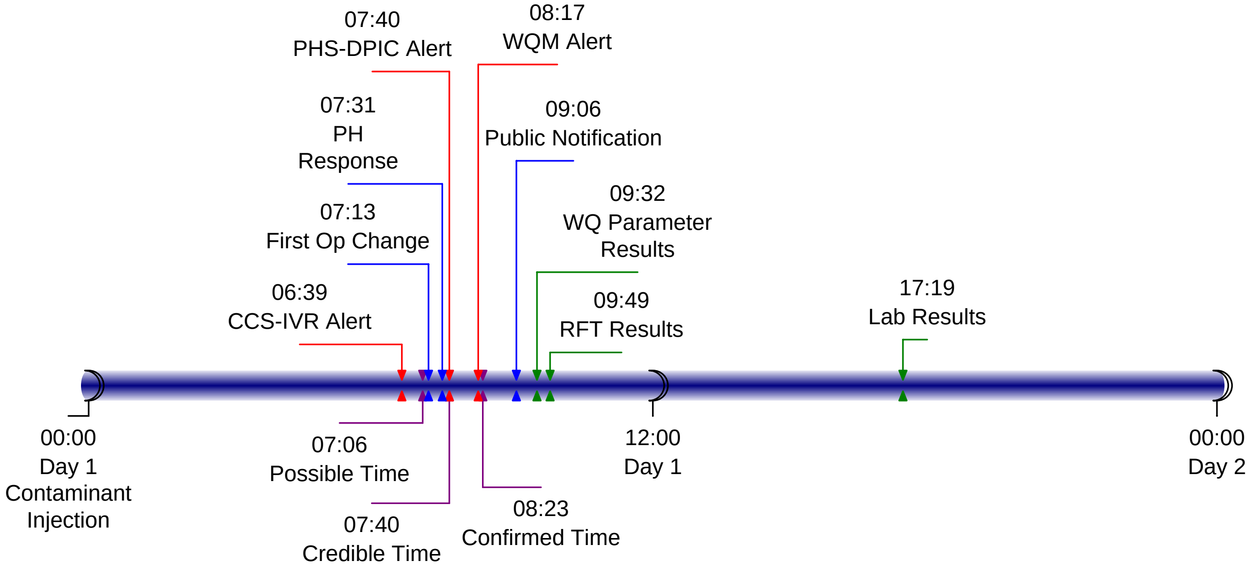

Figure 8-2. Timeline for a Typical Contamination Scenario with Toxic Chemical 1

The timeline for a typical contamination scenario with Toxic Chemical 5, which lacks a taste or odor, is shown in **Figure 8-3**. The injection occurred at a distribution system node in the morning. The public health response occurred 1.5 hours after injection, but before the first alert. The rapidity of the public health response was due to an unusually high number of cases seen in the emergency department and clear indications of the causative agent based on observed symptoms, which prompted officials to mobilize public health resources to care for the injured even though the source of exposure had not yet been determined. The first alert occurred just 4 minutes after the public health response and was from the PHS-DPIC component. This alert triggered a teleconference among public health partners, including the drinking water utility, where it was determined that contaminated water was a possible source of the exposures. This prompted the utility to implement operational response actions 20 minutes later. While another PHS alert (from the Astute Clinician (AC) data stream) occurred about 1 hour after the Possible determination, there was still no direct evidence linking the exposures to contaminated drinking water. However, utility SC teams were sent to locations of suspected exposure, where the results of water quality parameter testing indicated a potential problem with the water, which was sufficient evidence to consider water contamination to be Credible about 2.5 hours after the Possible determination was made. The determination that water contamination was Credible, combined with the number of reported illnesses, was sufficient for the utility to issue public notification at this point. The first WQM alert occurred 5 hours after the start of the injection. The preponderance of evidence from all of these signals was sufficient to Confirm contamination 5.5 hours after the start of the injection, even though confirmatory laboratory results would not be available until 5 hours later.

Comparing this scenario with the one shown in Figure 8-2 shows the impact of the injection start time on the scenario timeline. In Figure 8-2, the injection begins at midnight, and the first exposures and subsequent alerts are delayed for several hours. Figure 8-3 shows that exposures and alerts occur soon after the start of an injection in the morning. However, contamination was determined to be Possible with half an hour of the first alert in both cases. This reflects the efficient, streamlined alert investigation procedures developed for the Cincinnati CWS.

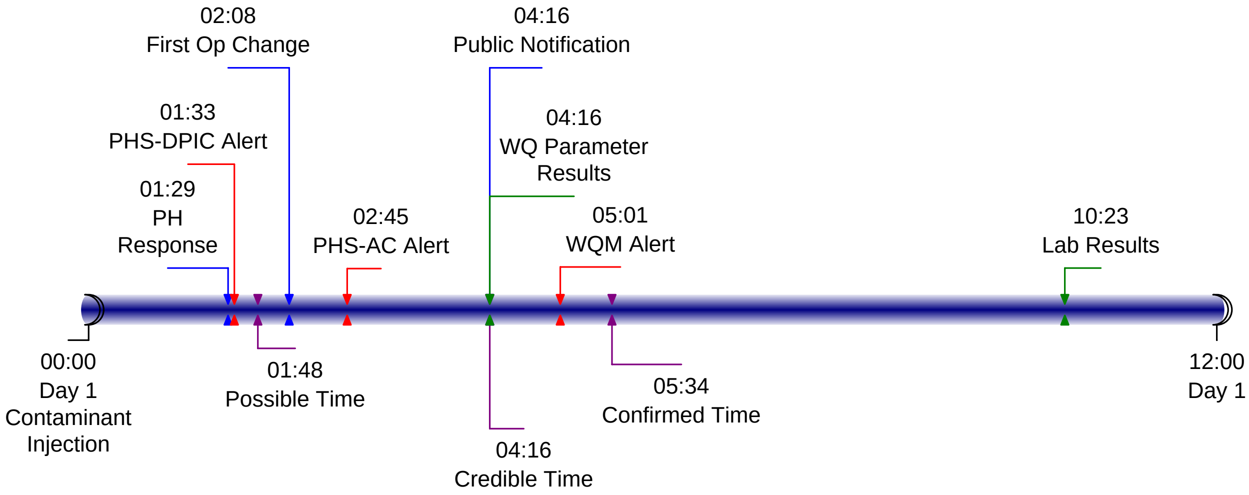

Figure 8-3. Timeline for a Typical Contamination Scenario with Toxic Chemical 5

The timeline for a typical contamination scenario with Biological Agent 3, which lacks a taste or odor, is shown in **Figure 8-4**. The injection occurred at a distribution system node at midnight. The first alert was generated by the Astute Clinician data stream of the PHS component, which occurred 9 hours and 45 minutes after the start of the injection. This alert triggered a teleconference between the utility and public health partners, which resulted in a Possible determination 45 minutes later, and implementation of an operational response 20 minutes after that. The first WQM alert occurred approximately 12 hours after the start of the injection, and once the initial investigation of this alert was completed 45 minutes later, contamination was deemed Credible. Similar to the example for Toxic Chemical 1, the combination of Credible contamination and a large number of illnesses was sufficient for the utility to issue a public notification. The results of the laboratory analysis were available 25 hours after the start of the injection, and were sufficient to confirm contamination when they were reported to the WUERM one hour later. Additional PHS alerts occurred after contamination had been Confirmed and thus were inconsequential to the investigation and response.

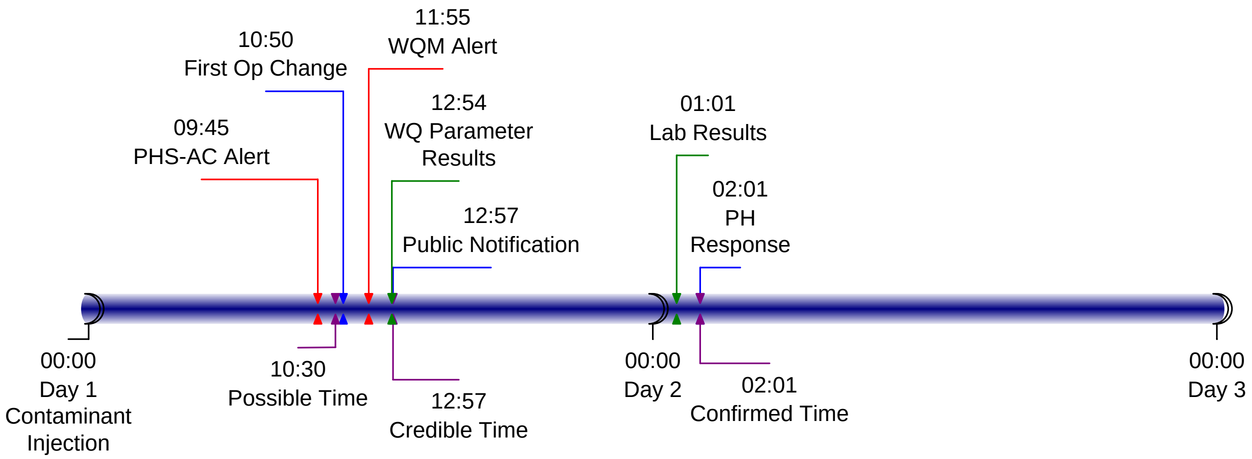

Figure 8-4. Timeline for a Typical Contamination Scenario with Biological Agent 3

The timeline for a typical contamination scenario with Biological Agent 4, which lacks a taste or odor and has a delayed symptom onset, is shown in **Figure 8-5**. The injection occurred at a distribution system node in the morning. The first WQM alert occurred eight hours after injection, and once the initial investigation of this alert was completed 42 minutes later, contamination was determined to be Possible. Results of WQ parameter testing were available approximately three hours after the Possible determination, but were insufficient to establish that contamination was Credible. It was not until a PHS alert from the Astute Clinician data stream occurred 20 hours after the injection that there was sufficient evidence to establish that contamination was Credible and issue public notification. Further investigation of the PHS alert and discussions between the utility and public health partners provided enough evidence to Confirm contamination a little more than one hour later, even though the identity of the contaminant was still unknown at that time. Public health response was delayed until there was sufficient information about the probable identity of the contaminant approximately seven hours after contamination was Confirmed. Results of laboratory analysis were not available until late on the second day of the scenario.

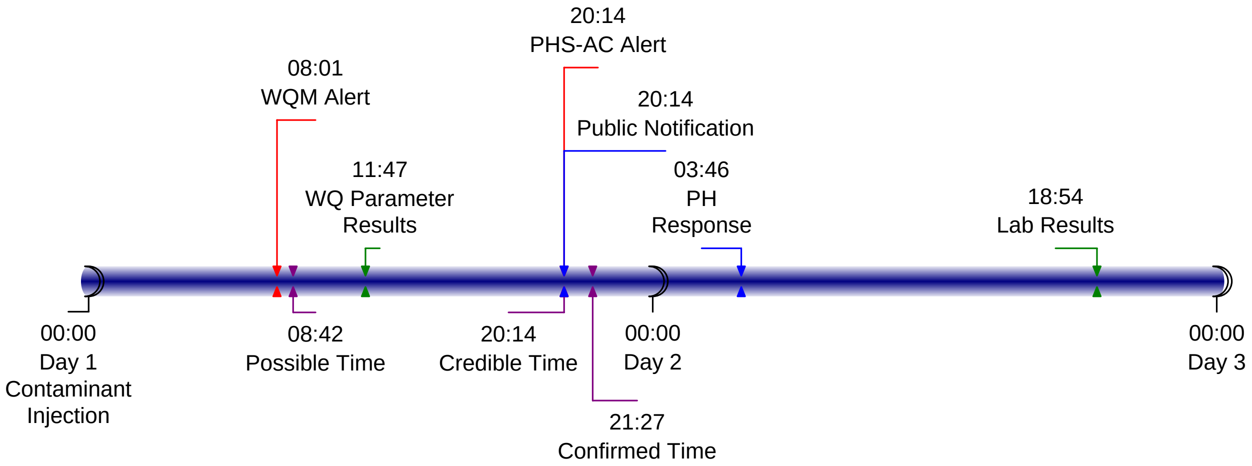

Figure 8-5. Timeline for a Typical Contamination Scenario with Biological Agent 4

The timelines for biological agents with delayed symptom onset are significantly longer than those for nuisance and toxic chemicals. These biological agents cannot be detected by CCS, which leaves only WQM and PHS to provide initial detection of distribution system attack scenarios. WQM can detect these agents within hours of the injection, but if WQM fails to detect the contamination scenario, the first PHS alert can be delayed by several days.

Timeliness of Initial Alerts by Component

Figure 8-6 shows a box-and-whisker plot of the timeliness of alerts from the monitoring and surveillance components and analytical results from the investigative components plotted for distribution system attack scenarios. This figure shows the statistical distribution of alert times for each component for the subset of scenarios that was detected by that component (the number of scenarios detected is shown to the right of the plot). The median CCS alert occurs much earlier than PHS or WQM alerts, which is consistent with CCS being the first component to detect in 97% of the scenarios that are detectable by CCS, as shown in Figure 7-3. This is anticipated as contaminants that have a perceptible taste, smell or color are detected quickly by customers at fairly low concentrations. This prompts a percentage of them to call the utility, consequently triggering CCS alerts. The call threshold to trigger a CCS alert in the Cincinnati CWS is relatively low, and thus the component could detect a contamination incident after just a few calls.

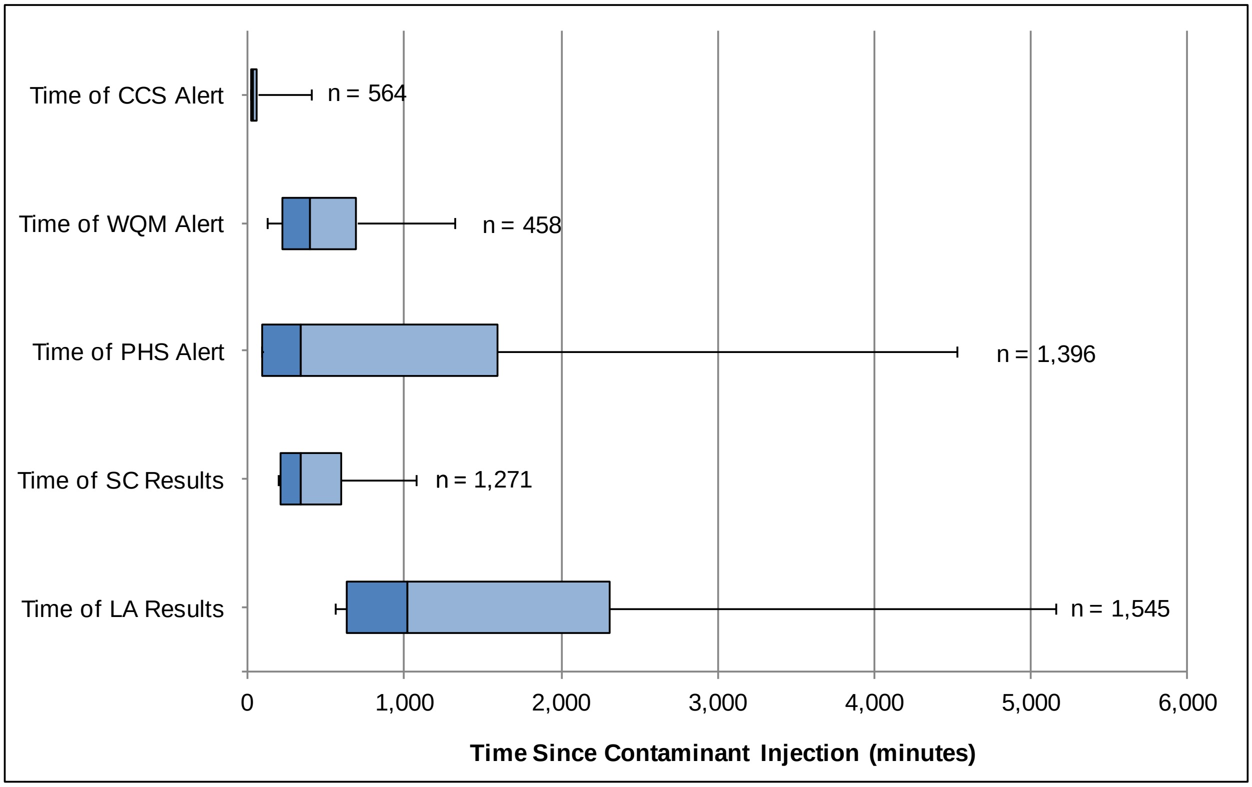

Figure 8-6. Timeliness of Monitoring and Surveillance Component Alerts and Sampling and Analysis Results for Distribution System Attack Scenarios

The PHS alert times show high variability over the entire ensemble. However, when the PHS alert times are analyzed by contaminant, much less variability in initial alert times is observed, indicating that the contaminant-specific delays in onset of symptoms contribute significantly to the variability in PHS alert time. On the other hand, the variability in the time of the initial WQM alert is primarily driven by the hydraulic travel time between the injection location and the WQM station. The timing of results from the investigative components, SC and LA, is largely driven by the time to reach a Possible determination, which is a precursor to initiating these activities. The distribution in the time of LA results is further expanded by contaminant-specific properties, such as the time to deliver the sample to a lab that can analyze for the specific contaminant and the method analysis time.

To illustrate the impact of contaminant-specific properties on detection times, the time of initial alerts for CCS, PHS and WQM is analyzed by contaminant for the distribution system attack scenarios in the following subsections.

Timeliness of Alerts by Contaminant for CCS

Figure 8-7 shows the timeliness of CCS alerts by contaminant for distribution system attack scenarios involving contaminants with a taste or odor. CCS alerts for Nuisance Chemical 1, Toxic Chemical 1 and Toxic Chemical 4 showed significant variability while those for Toxic Chemical 2, Toxic Chemical 3 and Biological Agent 1 had a much smaller distribution. This result can be attributed to the different percentage of injection times during high and low demand periods for each contaminant rather than to contaminant properties.

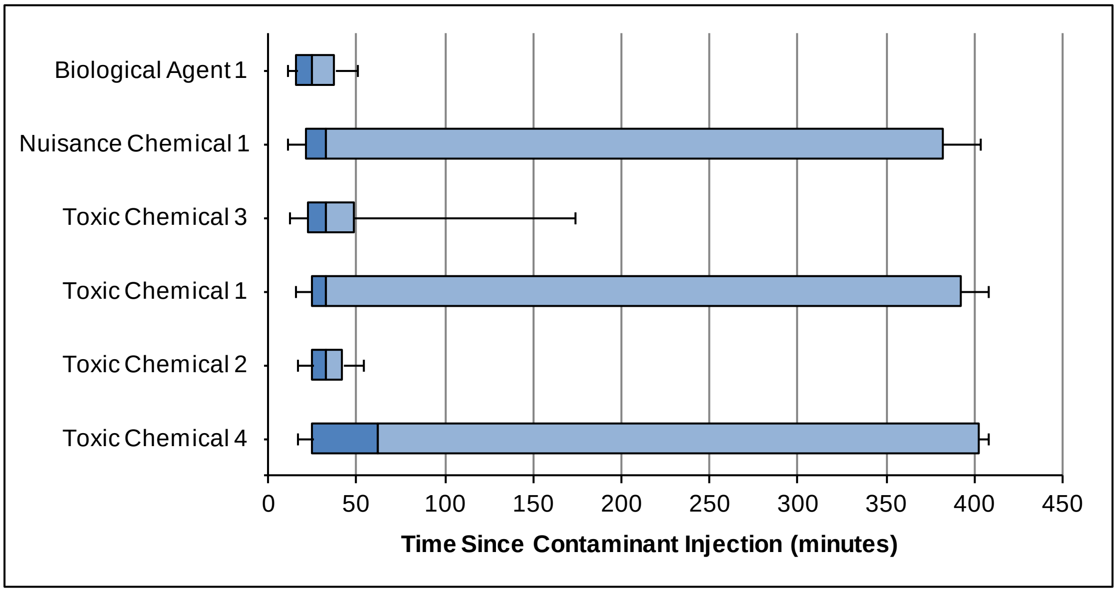

Figure 8-7. Timeliness of CCS Alerts by Contaminant

As seen in **Table 8-1**, for Nuisance Chemical 1, Toxic Chemical 1, and Toxic Chemical 4, one half to one third of the injections occurred at low demand (12:00 a.m.) whereas more than 91% scenarios for Toxic Chemical 2, Toxic Chemical 3, and Biological Agent 1 had injections at high demand (9:00 a.m.). Injections at 12:00 a.m. result in a delay of several hours between the start of the scenario and the first exposure, which yields a delay in the first CCS alert. Thus, a subset of scenarios that are predominately morning injections (i.e., Toxic Chemical 2, Toxic Chemical 3, and Biological Agent 1) will have a much narrower distribution of alert times compared with those that have a more equivalent mix of injections at high and low demand (9:00 a.m. and 12:00 a.m., respectively). The significant delay in CCS alert times in scenarios with injections at low demand (12:00 a.m.) is an artifact of the model design in which no customer is exposed until the morning, several hours after the start of the injection. While this modeling assumption was considered reasonable because water demand in the GCWW distribution system is substantially lower at midnight than it is in the morning, it is possible that there would be enough calls shortly following an injection at midnight to trigger a CCS alert.

Table 8-1. Number of Scenarios with Injections at High and Low Demand Periods

Contaminant ID	High Demand (9:00 a.m.) Injection	Low Demand (12:00 a.m.) Injection	Total	% High Demand Injections

Contaminant ID	High Demand (9:00 a.m.) Injection	Low Demand (12:00 a.m.) Injection	Total	% High Demand Injections
Toxic Chemical 2	93	1	94	98.9%
Biological Agent 1	90	4	94	95.7%
Toxic Chemical 3	86	8	94	91.5%
Nuisance Chemical 1	63	31	94	67.0%
Toxic Chemical 1	61	33	94	64.9%
Toxic Chemical 4	48	46	94	51.1%

Timeliness of Alerts by Contaminant for PHS

Figure 8-8 shows the timeliness of PHS alerts plotted for distribution system attack scenarios involving injection of contaminants with rapid onset of symptoms, including those that have a taste or odor. The time between an exposure and onset of low-level symptoms is also shown in Figure 8-8 by the “x” symbol. Those contaminants with longer symptom delays generally have later PHS alert times. A strong correlation (r = 0.84) was observed between the contaminant-specific symptom onset delays and the median PHS alert times for these contaminants. Toxic Chemical 6 was an exception to this correlation where the median PHS alert was later than projected based its symptom onset delay. This was the result of a large number of low demand (12:00 a.m.) injection scenarios in the ensemble for Toxic Chemical 6, which resulted in a seven hour delay before the first consumption event and subsequent symptoms and health seeking behaviors necessary to trigger a PHS alert.

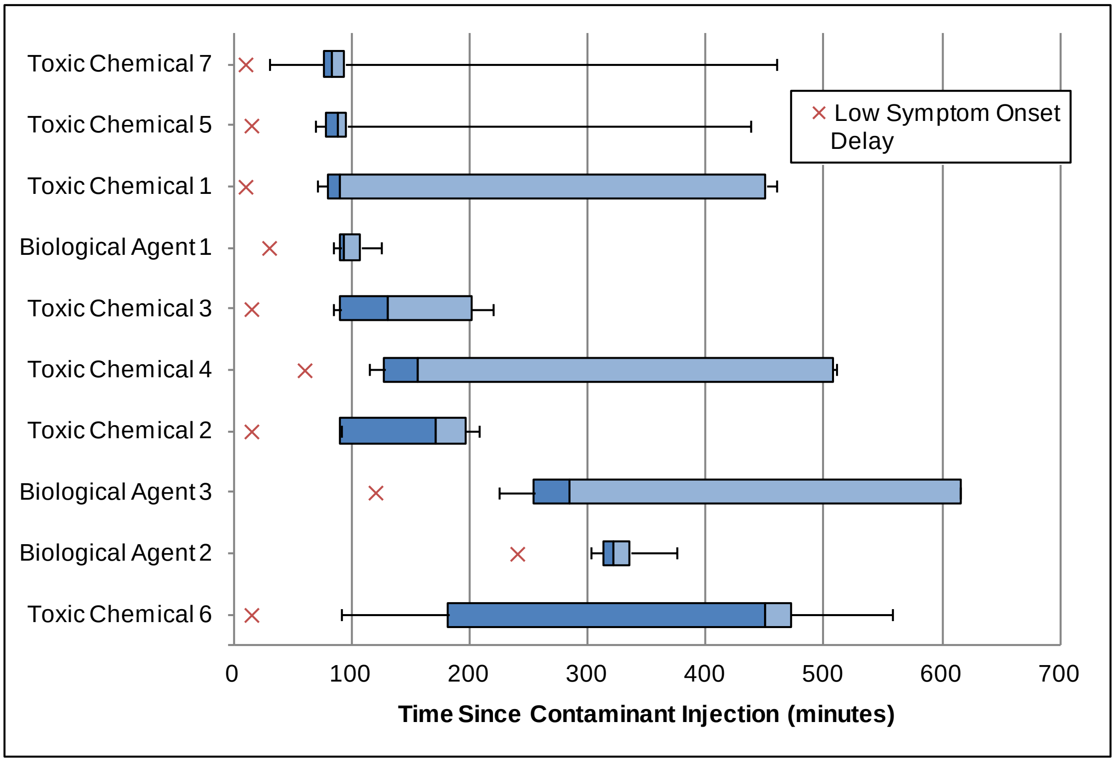

Figure 8-8. Timeliness of PHS Alerts for Contaminants with Rapid Symptom Onset (including those with a taste or odor)

PHS alerts for Biological Agent 1, Toxic Chemical 2 and Biological Agent 2 exhibited the least variability. This can be attributed to the distribution of injection times in ensembles for each contaminant, where these three contaminants had more than 95% of the injections during high demand (9:00 a.m.).

The remaining seven contaminants had simulations with a more diverse blend of injections at both low and high demands. These contaminants with a mix of injection times show more variability because there is a significant difference between the times of injection and first consumption (and consequently health seeking behavior and PHS alerts) for injections at low and high demand.

Figure 8-9 shows the timeliness of PHS alerts plotted for distribution system attack scenarios involving injection of contaminants with delayed symptom onset. The time between an exposure and onset of low-level symptoms is also shown on this figure (X). Similar to the results for contaminants with delayed symptom onset, those contaminants with longer symptom delays generally have later PHS alert time. A strong correlation (r = 0.95) was observed between the symptom onset delay and the median PHS alerts times. This is particularly evident when the results in Figures 8-8 and 8-9 are compared, noting the different scales on the x-axis. Biological Agents 6 and 7 have longer median alert times and a larger distribution of alert times compared with Toxic Chemical 8, even though all three have identical symptom onset delays. The reason for this is that exposure to Biological Agents 6 and 7 occurs by inhalation, and there is only one inhalation exposure event per day (during showering at 7:00 a.m.). This artifact of the model will result in both later alerts and a broader distribution of alert times.

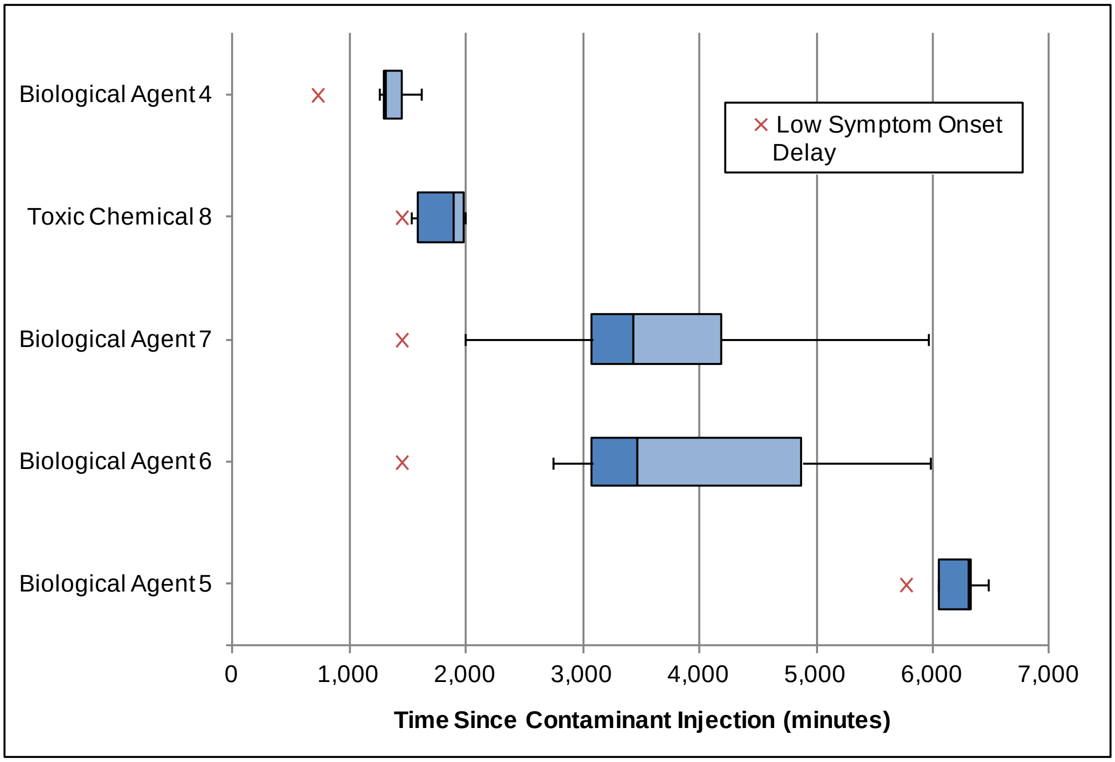

Figure 8-9. Timeliness of PHS Alerts for Contaminants with Delayed Symptom Onset

Timeliness of Alerts by Contaminant for WQM

The WQM alerts showed no discernible trend when plotted by contaminant. This can be attributed to the fact that all contaminants evaluated in this study are theoretically detectable by WQM and most produce a detectable change in water quality at concentrations significantly lower than those that would cause acute health effects (Allgeier, et al, 2010), as shown in Table 6-1. Modeling results indicate that the timing of WQM alerts is driven by the hydraulic travel time between the injection location and the WQM stations.

Figure 8-10 shows the number of WQM alerts and distribution of WQM alert times generated during the distribution system attack scenarios for each of the 15 WQM stations. As can be seen from the counts in this figure, six WQM stations were responsible for 79% of the alerts: F, L, K, B, M and C. However, the six monitoring stations (O, E, H, I, N and G) consistently generated the earliest alert times. These six monitoring stations are located closely downstream of major pump stations and in fairly populous areas.

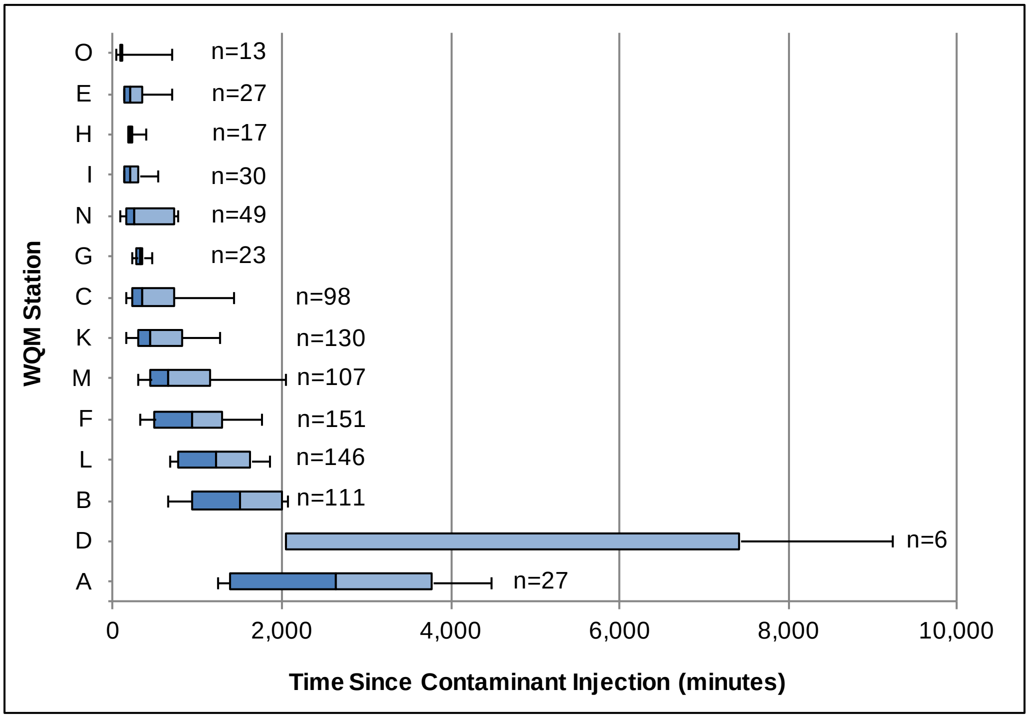

Figure 8-10. Timeliness of WQM Alerts by Station

The median total time to alert ranged from 1.6 hours (Station O) to 43.8 hours (Station A). The three stations with the longest alert delays (Stations A, B and D) were also the stations with the lowest percentage of alerts produced with respect to the number of potential alerts (the number of scenarios in which the WQM station witnessed a detectable contaminant concentration). These stations experience high water quality variability that can mask water quality anomalies. Thus, CANARY was configured to require a longer period of unusual water quality before an alert is generated. This is intended to reduce the number of invalid alerts received, though it also increases the time to detect when a true water quality anomaly is present.

Each component has different factors that drive the timeliness of the alerts. CCS alerts occur quickly after the first opportunity for consumption due to the low thresholds of the event detection system. The timing of PHS alerts is impacted by the symptom onset delay, and thus the characteristics of the contaminants. The timing of WQM alerts are driven by hydraulic travel time to the WQM station from the injection site. Taken independently, these factors show that each component has the ability to detect some types of scenarios more quickly than others. However, when all of these components are integrated into a CWS, the resulting system has the potential to detect a wide variety of scenarios early enough to provide time for effective response and consequence mitigation.

8.2 Response Time

Definition: The time between detection of a contamination incident and implementation of various investigative and response actions, including: threat level determination, operational response, public notification, and public health response.

Analysis Methodology: Response time was evaluated using two different data sources: results from drills and exercises and simulation study results.

The results from 21 drills and exercises conducted during the evaluation period, described in Section 3.2, were used to estimate various metrics on the response timeline. These drills and exercises provided evaluators with the opportunity to observe and characterize the time required to implement various response actions in real time under conditions of a simulated contamination incident. The timeliness metrics evaluated during drills and exercises can be broadly grouped into two categories:

1. Threat level determination process, which includes the time to Possible, Credible and Confirmed determinations, as well as the time for results from SC and LA
2. Response actions, which include operational response, public health response and public notification

Some artificialities are introduced during drills and exercises because participants are aware of the activity, which can result in more aggressive response actions than might be observed in the early stages of a real-world alert investigation. Additionally, the results from drills and exercises are limited by the conditions of the specific contamination incident developed for the drill or exercise. However, these results provide a useful benchmark for the response time metrics. Furthermore, the results from the simulation study, described in Section 3.3, provide an expanded set of contamination scenarios from which to evaluate response timeliness metrics.

Results: The results from drills and exercises were one of the data sources used to parameterize the CWS model used in the simulation study. Thus, the results from these simulations should provide a reasonable estimate of response times for a variety of contamination scenarios. For illustrative purposes, the timelines generated during two full-scale exercises are described below.

FSE 2 was conducted on October 1 and 2, 2008, with the objective of exercising protocols for investigating and responding to a Possible drinking water contamination incident. The FSE was based on a scenario involving the intentional injection of a large quantity of a biological agent into the distribution system. The exercise was initiated with a WQM alert.

Figure 8-11 shows significant events along the timeline for FSE 2. Following the initial WQM alert, additional WQM alerts were initiated two hours later, followed by the first CCS alert 30 minutes after that. The combination of WQM and CCS alerts prompted the utility to conclude that contamination was Possible, and to subsequently deploy the SC team. Additional customer calls were sufficient to establish that contamination was Credible 3 hours and 45 minutes after the start of the exercise. Field sampling results from site characterization were available 2 hours and 40 minutes after the site characterization team deployed. A PHS alert was initiated 6.5 hours after the start of the exercise, and was instrumental in the decision to issue a public notification two hours later.

FSE 2 occurred early in the evaluation period, before the investigation and response procedures for the Cincinnati CWS had been streamlined. Observations from this exercise led to many revisions and refinements to the CWS procedures, including updates to roles and responsibilities for responders and streamlining of communication protocols, such as the development of the PHS communicator protocol. This led to improved response times in later drills and exercises.

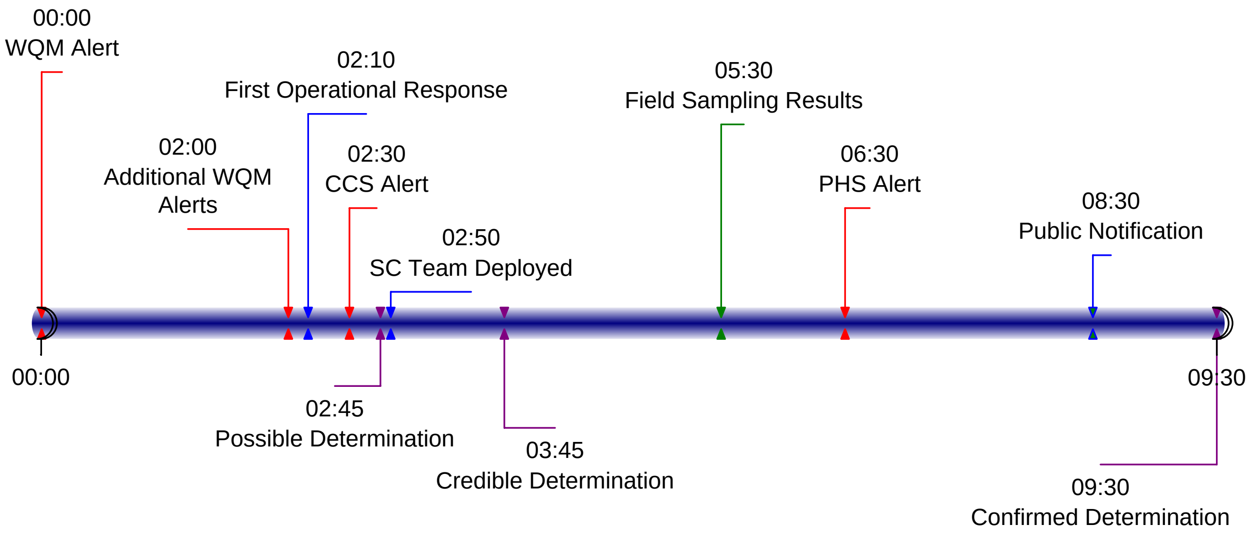

Figure 8-11. Timeline for Full Scale Exercise 2

FSE 3 was conducted on October 21 and 22, 2009, to provide GCWW's Incident Command System second-in-command personnel and local response partner agencies with the opportunity to exercise response procedures. The FSE was based on a scenario involving the intentional injection of a large quantity of a toxic chemical into the distribution system. The exercise was initiated with a CCS alert.

Figure 8-12 shows significant events along the timeline for FSE 3. The initial CCS alert was generated by the IVR data stream, and a second CCS alert, generated by the work orderdata stream, occurred 30 minutes later. A review of the underlying calls associated with these alerts showed that they were all from the same neighborhood, which led to the conclusion that contamination was Possible 44 minutes after the start of the exercise. The first operational response was implemented 16 minutes after the Possible determination and the SC team was deployed 40 minutes later. Rapid field test results from SC were available three hours after the SC team was deployed, and were sufficient to establish that contamination was Credible 15 minutes later. Contamination was Confirmed based on the preponderance of evidence just 15 minutes after the Credible determination, and before the PHS alert was initiated. This prompted the utility to issue a public notification 5 hours and 15 minutes after the start of the exercise.

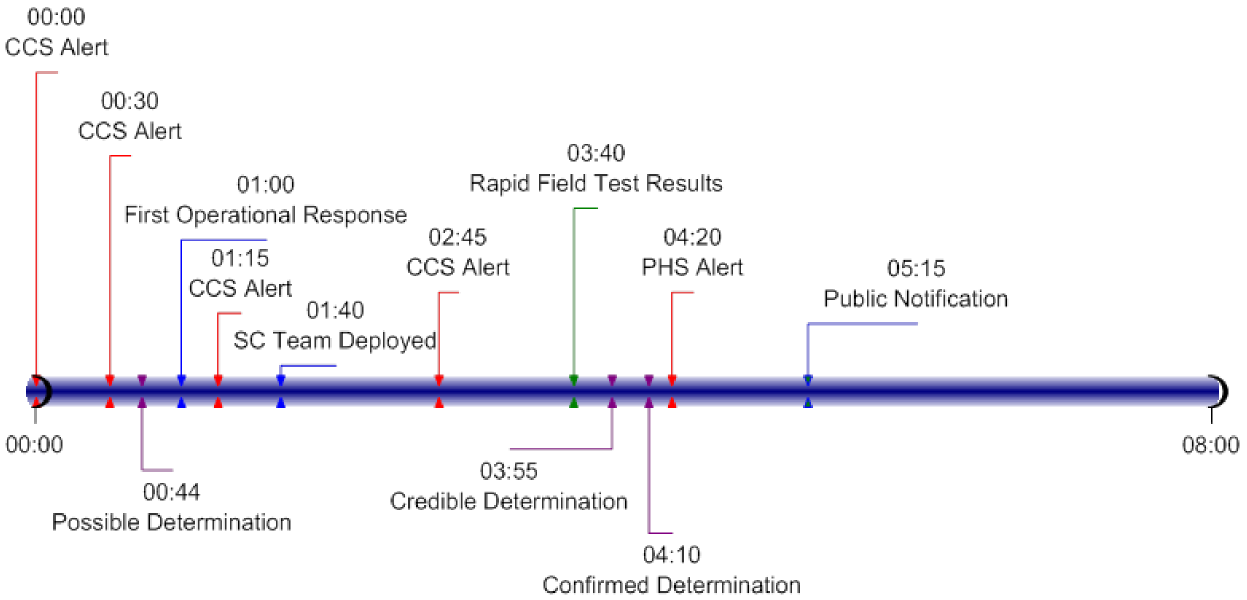

Figure 8-12. Timeline for Full Scale Exercise 3

Comparison of the timelines for FSE 2 and FSE 3 shows a marked improvement in response times in FSE 3. During FSE 3, the cluster of calls that triggered the CCS alert was sufficient to conclude that contamination was Possible, while in FSE 2 that determination was delayed for several hours. Additionally, operational responses were implemented sooner during FSE 3 than they were during FSE 2. The critical decision to issue a public notification was made three hours and fifteen minutes sooner during FSE 3, which would have a dramatic impact on limiting further exposures. The improved performance observed during FSE 3 was a result of acting on the lessons learned from FSE 2 and an increased confidence in implementing procedures and decision-making that resulted from drills held during the year between the two FSEs.

As noted previously, these two examples, as well as the other 19 drills and exercises conducted over the evaluation period, represent a limited number of contamination scenarios. Furthermore, the performance of the personnel involved in implementation of investigative and response procedures improved over the course of the pilot. Thus, the dataset of timeline metrics derived from these drills and exercises is limited. To address this limitation, the timeline metrics from the simulation study were analyzed for response times. **Figure 8-13** shows the timeliness of threat level determination and response actions for all simulated distribution system attack scenarios. The median time that each of the three threat levels was reached occurred sequentially, as expected: Possible determination at 330 minutes, followed by Credible at 385 minutes, followed by Confirmed at 562 minutes. Overall, the time at which operational response was implemented (a median of 320 minutes) corresponded closely to the time of Possible determination. This outcome is related to the model assumption that once a CWS alert is validated, the utility would begin implementing operational response actions that do not impact customers in an effort to limit the spread of potentially contaminated water. This simplifying assumption is consistent with utility decisions and actions that were demonstrated during drills and exercises held later in the evaluation period, such as FSE 3.

The median time of public notification (458 minutes) is between the median times of Credible and Confirmed determinations. This is consistent with utility response actions during FSEs, in which public notification was issued only after contamination was deemed Credible, but often before contamination was Confirmed. The median public health response was 477 minutes, and this response action is driven primarily by public health information derived from cases at hospital emergency departments.

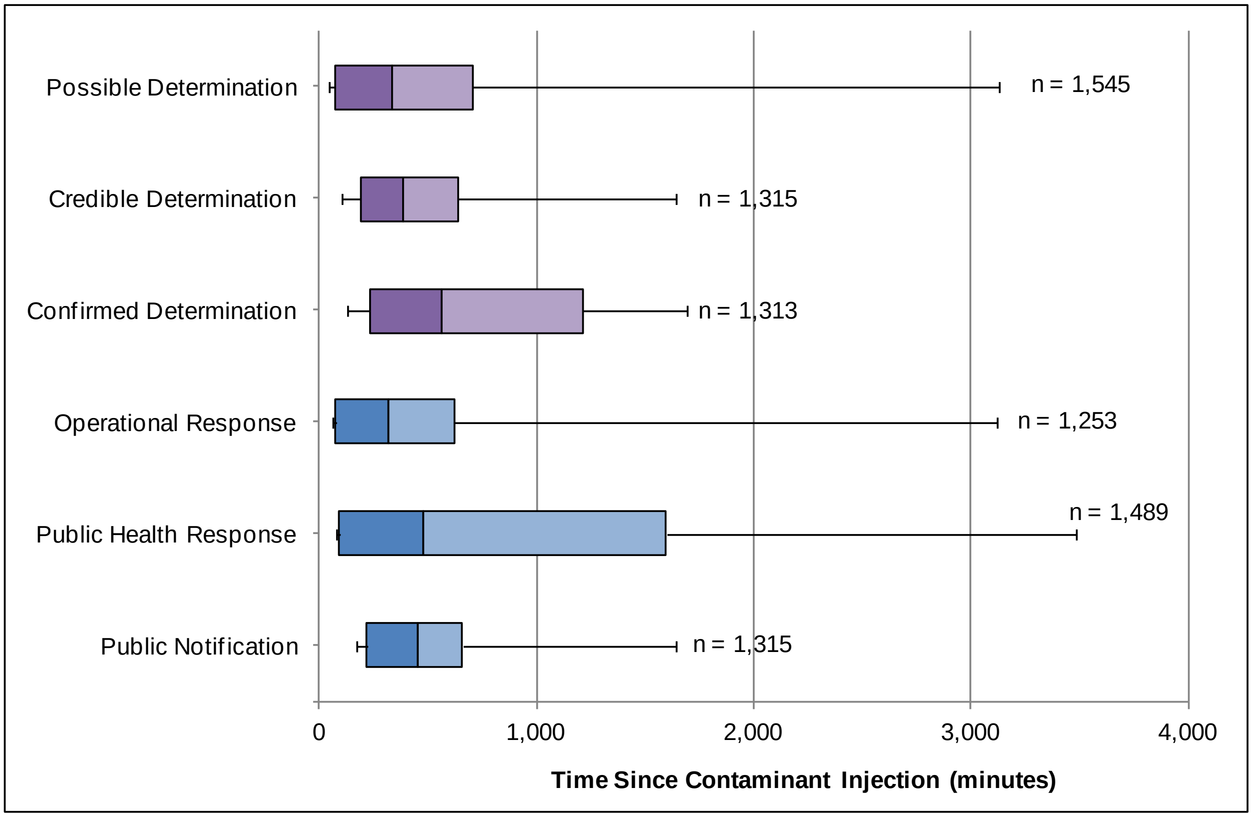

Figure 8-13. Timeliness of Threat Level Determination and Responses

The ensemble was broken down by the contaminant groups described in Section 7.3 (nuisance chemicals, contaminants with taste or odor, contaminants with rapid symptom onset and contaminants with delayed symptom onset) and the corresponding timeliness plots are shown in **Figures 8-14** through **8-17**. Grouping contaminants in that manner led to a reduction in variability of the timeliness metrics indicating that these metrics were a function of contaminant properties.

Figure 8-14 shows the threat level determination and response timeline metrics for the subset of distribution system attack scenarios that involve injection of nuisance chemicals. The median times for the three threat levels occurred sequentially, as expected: Possible determination at 341 minutes, followed by Credible at 417 minutes, followed by Confirmed at 611 minutes. These threat level determination times were similar to those observed for the complete set of distribution system attack scenarios. However, the median time for operational response (91 minutes) occurred earlier than the median Possible determination for nuisance chemicals. This is a result of the large number of nuisance chemical scenarios that were detected by WQM, and the fact that operational responses can be implemented in response to a verified WQM alert before a Possible determination is made. For nuisance chemicals, the median times for Confirmed determination and public notification were identical (611 minutes). This is due to the fact that no health consequences are involved in scenarios involving the nuisance chemicals, which eliminates the triggers that could prompt public notification before contamination is Confirmed.

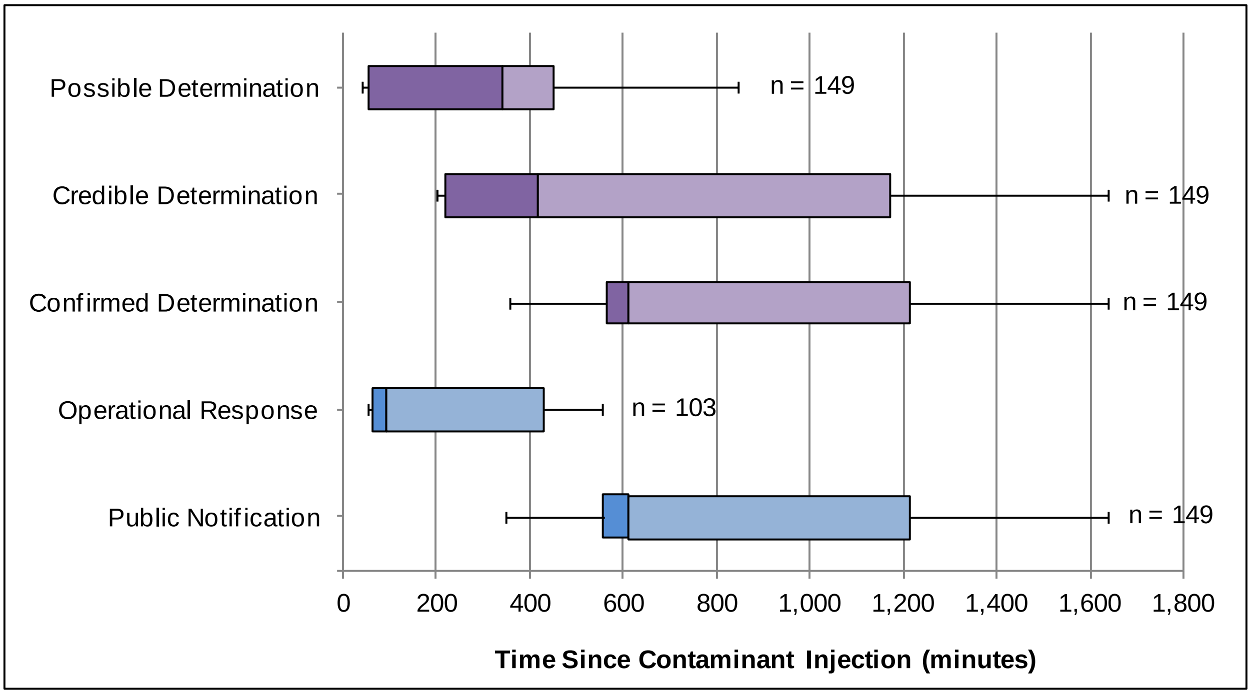

Figure 8-14. Timeliness of Threat Level Determination and Responses for Nuisance Chemicals

Figure 8-15 shows the threat level determination and response timeline metrics for the subset of distribution system attack scenarios that involve injection of contaminants with taste or odor. Of the four groups of contaminants, those with taste and odor have the shortest times for threat level progression and response actions. This is primarily due to rapid detection of these contaminants through CCS, or PHS in the case of chemicals that are also toxic. The median times for the threat level determination are 59 minutes for Possible, 117 minutes for Credible, and 182 minutes for Confirmed. The median time for operational response was 71 minutes, similar to the median time for Possible determination. In general, CCS alerts will not result in an operational response until a Possible determination is made. The median time for public notification was 184 minutes, which is very close to the median time for Confirming contamination. However, the time of public notification in scenarios that are rapidly detected is driven primarily by the two hour period required to prepare the notice rather than by the time to determine that contamination is Credible. The median time for public health response was 96 minutes.

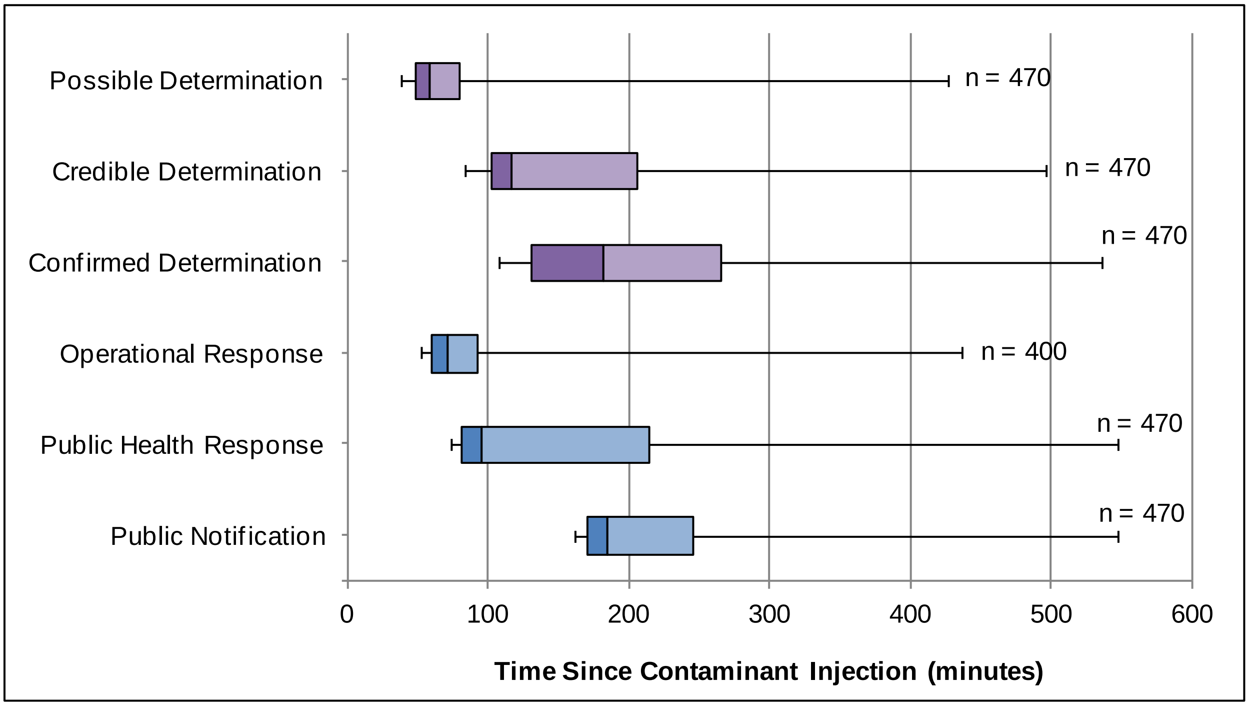

Figure 8-15. Timeliness of Threat Level Determination and Responses for Contaminants with Taste or Odor

Figure 8-16 shows the threat level determination and response timeline metrics for the subset of distribution system attack scenarios that involve injection of contaminants with rapid symptom onset. The median times for the threat level determination are 300 minutes for Possible, 448 minutes for Credible and 679 minutes for Confirmed, which are slightly longer than those for the full set of distribution system attack scenarios. The distribution of times for operational response is comparable to that for Possible determination. The time distribution of public notification corresponds closely with Credible determination, and the median times were exactly the same at 448 minutes. The reason public notification is issued around the same time as contamination is deemed Credible for this class of contaminants is that the rapid symptom onset quickly generates a large number of cases, which increases the urgency to issue the notification. The median public health response time was 447 minutes, similar to the time of Credible determination but with more variability that is driven by differences in the difficulty of quickly identifying a causative agent for this group of contaminants. Specifically, for contaminants with unique and uncommon symptoms, a small number of cases can be sufficient to draw a tentative conclusion about the causative agent. However, contaminants that produce symptoms that are similar to those caused by common illnesses require more cases to make a tentative identification.

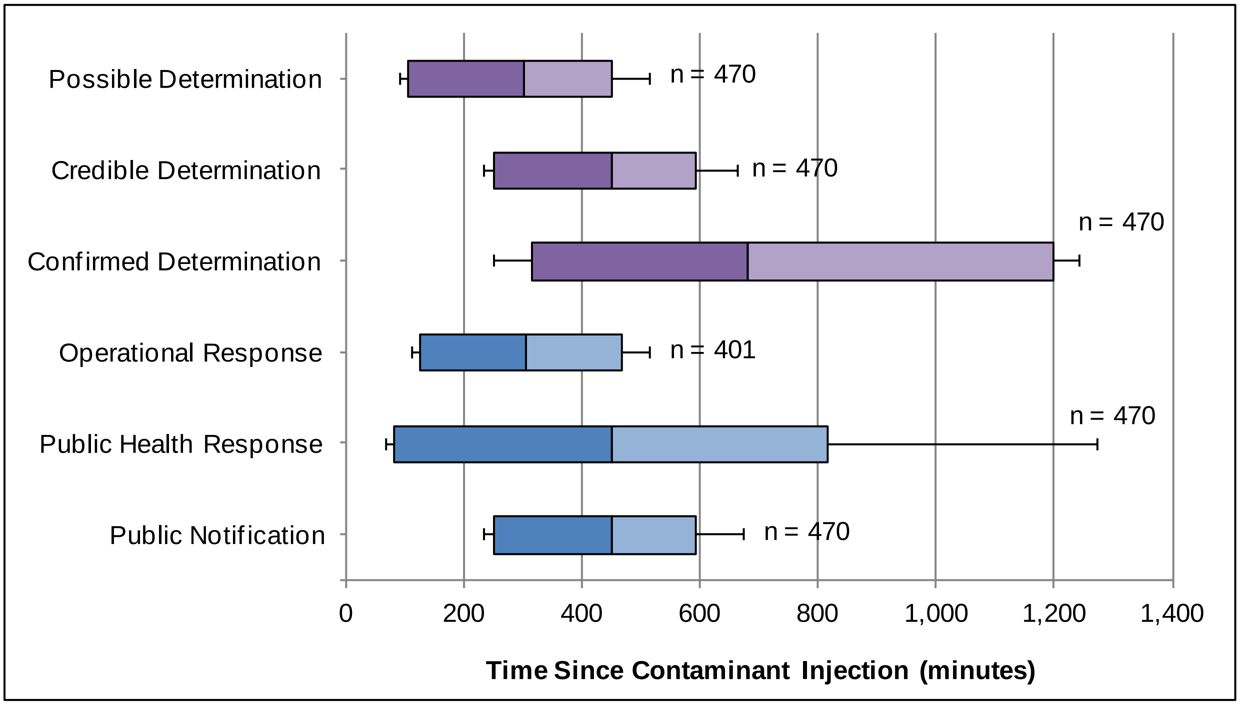

Figure 8-16. Timeliness of Threat Level Determination and Responses for Contaminants with Rapid Symptom Onset

Figure 8-17 shows the threat level determination and response timeline metrics for the subset of distribution system attack scenarios that involve injection of contaminants with delayed symptom onset. The median times for the threat level determination are 2,013 minutes for Possible, 1,644 minutes for Credible and 1,704 minutes for Confirmed. These times are 2.5 to 6.7 times longer than the times for contaminants with rapid symptom onset, which is driven by the long delay between exposure and symptom onset and the fact that none of these contaminants can be detected by CCS. Furthermore, the median time for Possible determination is longer than that for Credible or Confirmed determination due to the fact that less than half of the scenarios that reached Possible went on to reach Credible or Confirmed.

The time distribution of operational response corresponds closely to the time of Possible determination with a median time for operational response of 1,922 minutes. In this group of contaminants, the necessary condition to implement an operational response is reached close to the time of Possible determination, which requires notification of the WUERM in addition to sufficient confidence that contamination is possible. The time distribution of public notification corresponded closely with Credible determination where the median time for public notification was 1,900 minutes, which was driven by either cases of illness in the public or widespread absence of a chlorine residual in the distribution system (as determined by WQM alerts or the results of chlorine residual testing in the distribution system as part of SC).

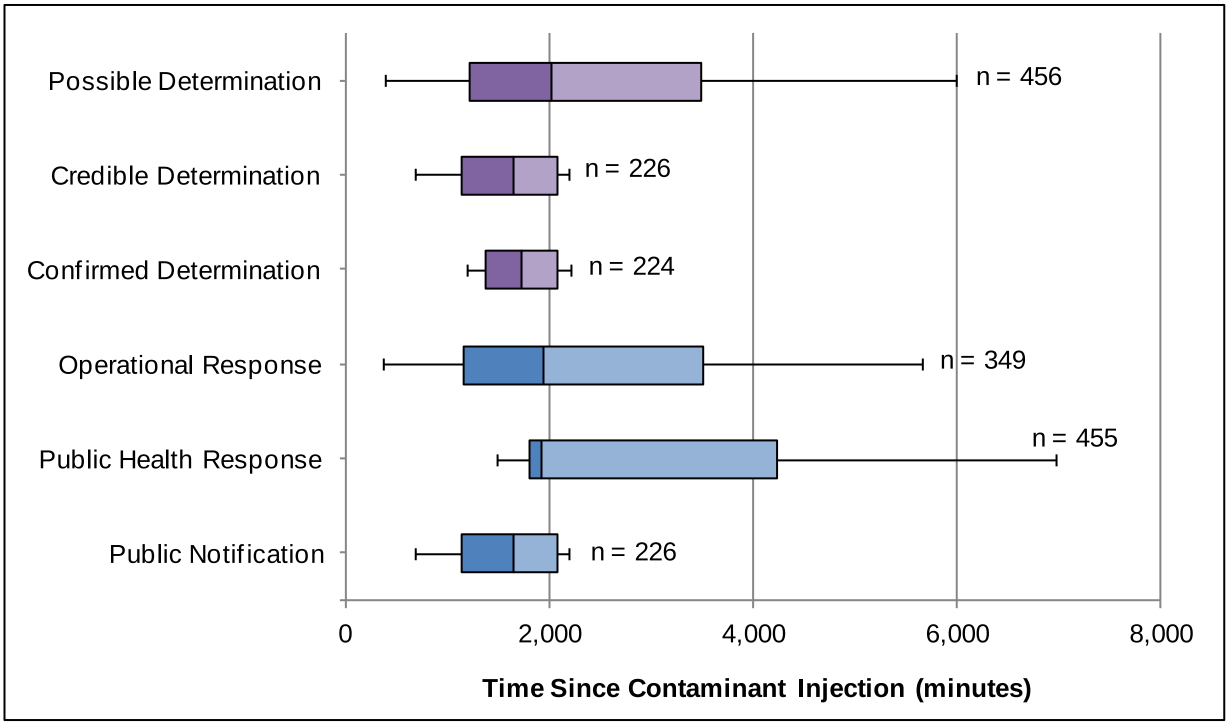

Figure 8-17. Timeliness of Threat Level Determination and Responses for Contaminants with Delayed Symptom Onset

Figure 8-18 shows the median value of each timeline metric for all distribution system attack scenarios that were detectable by one, two or three monitoring and surveillance components (CCS, PHS and WQM). The figure shows a modest improvement in threat level determination and response times for scenarios that can be detected by two components compared with those detectable by only one component. A significantly larger incremental improvement in threat level determination and response times was observed for scenarios that were detectable by three components. The largest improvement in the threat level determination timeline occurred for the Credible and Confirmed determinations. This is consistent with results from drills and exercises that indicate that information from multiple components is necessary to conclude that contamination is Credible or Confirmed. The timing of operational response is closely coupled with the time of Possible determination, and both of these timeline metrics improved by approximately nine hours for scenarios detectable by three components compared with those detectable by only one component. The median time for public notification was reduced from 21 hours for scenarios detectable by only one component to around three hours for scenarios detectable by three components. Public health response did not occur for scenarios that were detectable by only one component but had a median time of approximately one and a half hours for scenarios detectable by three components.

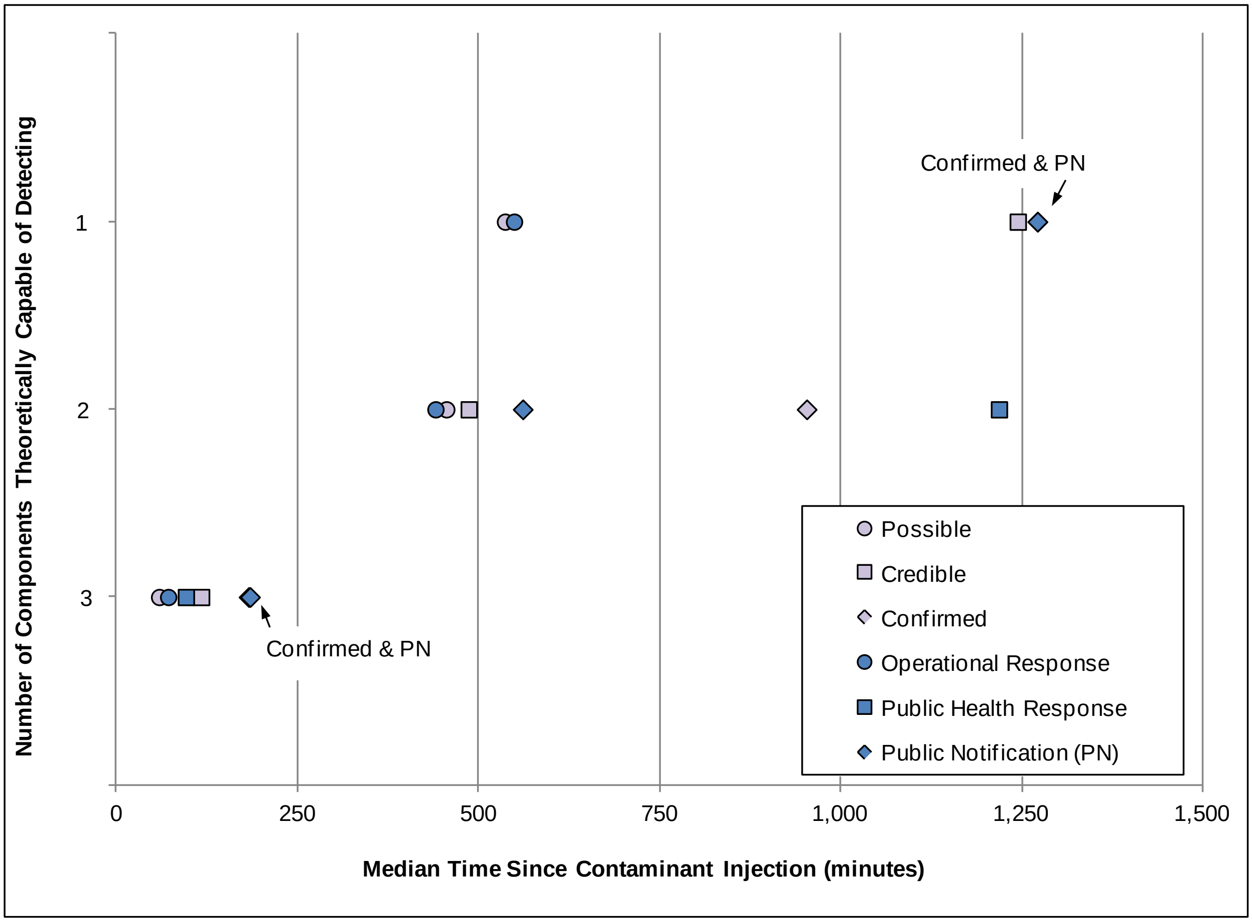

Figure 8-18. Timeliness of Threat Level Determination and Responses for Contaminants Detectable by 1, 2 or 3 Components

As demonstrated in previous sections, integration of data from multiple monitoring and surveillance components greatly improves spatial and contaminant coverage. The analysis presented in Figure 8-18 shows that a multi-component CWS can also significantly improve timeliness of the threat level determination process and response actions. This is largely due to the increased confidence in a system that provides indicators of contamination through multiple independent data sources. This increased confidence yields a more efficient and timely threat level determination process, which drives implementation of response actions that can dramatically reduce consequences. The reduction in consequences achieved through timely response actions is discussed in the next section.

8.3 Consequence Reduction

Definition: Consequences of a contamination incident that are avoided due to deployment and operation of a CWS.

Analysis Methodology: Consequence reduction was evaluated using the results from the full ensemble of the simulation study. Three types of consequences are generated during simulations: illnesses, fatalities and miles of pipe contaminated. **Table 8-2** shows which consequences apply to each contaminant and indicates the primary and secondary consequence categories for each.

Table 8-2. Primary and Secondary Consequence Types for Each Contaminant

	Consequence Type		
Contaminant ID	**Illnesses**	**Fatalities**	**Miles of Pipe**
Nuisance Chemical 1	n/a	n/a	**P**
Nuisance Chemical 2	n/a	n/a	**P**
Toxic Chemical 1	S	**P**	S
Toxic Chemical 2	**P**	S	S
Toxic Chemical 3	**P**	S	S
Toxic Chemical 4	S	**P**	S
Toxic Chemical 5	S	**P**	S
Toxic Chemical 6	S	**P**	S
Toxic Chemical 7	S	**P**	S
Toxic Chemical 8	S	**P**	S
Biological Agent 1	**P**	S	S
Biological Agent 2	S	**P**	S
Biological Agent 3	S	**P**	S
Biological Agent 4	S	**P**	S
Biological Agent 5	S	**P**	S
Biological Agent 6	S	**P**	S
Biological Agent 7	S	**P**	S

P – primary consequence, S – secondary consequence, n/a – no consequences in this category

Consequences were simulated for a baseline case without a CWS and for the case in which the full Cincinnati CWS was in operation. The difference in consequences for these two cases represents the reduction in consequences that is attributable to the Cincinnati CWS. For the case without a CWS, individuals could still seek healthcare in response to their symptoms, and limited public health response actions were assumed to occur that would mitigate consequences to some degree. For the case with the CWS, consequences were further reduced through the following actions:

- **Improved public health response**. Information from the CWS can result in an earlier and more effective public health response, particularly if information from the CWS provides clues regarding the identity of the causative agent.

- **Operational response**. The utility can alter the flow of water in the distribution system, which can limit the spread of the contaminant, minimizing the number of individuals exposed to harmful levels of the contaminant. However, operational responses can have unintended consequences, such as maintaining a higher concentration of a contaminant in one area of the system, which could expose individuals to more harmful concentrations of the contaminant.
- **Public notification**. The utility, in cooperation with the local public health department, can issue a notice to the public advising them to not use the drinking water, which will further limit exposures to the contaminated water. Furthermore, the public notification could include guidance to symptomatic individuals seeking effective healthcare.

Results: Figure 8-19 is a timeline and consequence graphic for a distribution system attack scenario involving Biological Agent 4, which is representative of the timeline demonstrated by many of the scenarios involving biological agents. It shows the key timeline metrics relative to the start of the injection and the time series of fatalities for the case with and without the Cincinnati CWS in operation. In this scenario, the injection occurred at high demand (9:00 a.m.), and WQM was the first component to alert about eight hours after injection. A Possible determination was reached 41 minutes later. At this point, an SC team was deployed and water quality field testing results were available at 3 hours and 5 minutes after Possible.

At 20 hours and 14 minutes after injection, a PHS Astute Clinician alert occurred, which elevated the threat level to Credible and public notification was immediately issued. In all scenarios in the simulation study, after the first PHS alert occurs, the communicator protocol is invoked, which initiates a teleconference between the water utility and key representatives from public health agencies, which represents the current operational strategy for the PHS component. In the scenario depicted in Figure 8-19, the communicator teleconference contributed to raising the threat level to Confirmed 1 hour and 13 minutes after Credible determination. The public health response was initiated 27 hours and 46 minutes after the injection. Laboratory results for the water sample were available 34 hours and 12 minutes after Possible determination. While these results were available after the Confirmed determination, analytical confirmation of the contaminant’s identity would inform the later stages of response to an actual contamination incident.

The time series of fatalities for this simulated contamination scenario is also shown in Figure 8-19 with and without the CWS in operation. The time delays for onset and progression of symptoms and fatalities for this contaminant are in the range of 12 hours to 6 days, and in this scenario the first fatalities occurred about 39 hours after injection and continued rising for six more days. In the absence of a CWS, there would have been more than 1,600 fatalities as a result of this contamination incident. With the CWS in operation, the number of fatalities was reduced to 20, close to a 99% reduction. This reduction in consequences was largely attributable to the public notification being issued early in the response process, which dramatically reduced the number of individuals exposed to the contaminant. Additionally, prophylactic treatment provided as part of the public health response prevented a large number of potential fatalities.

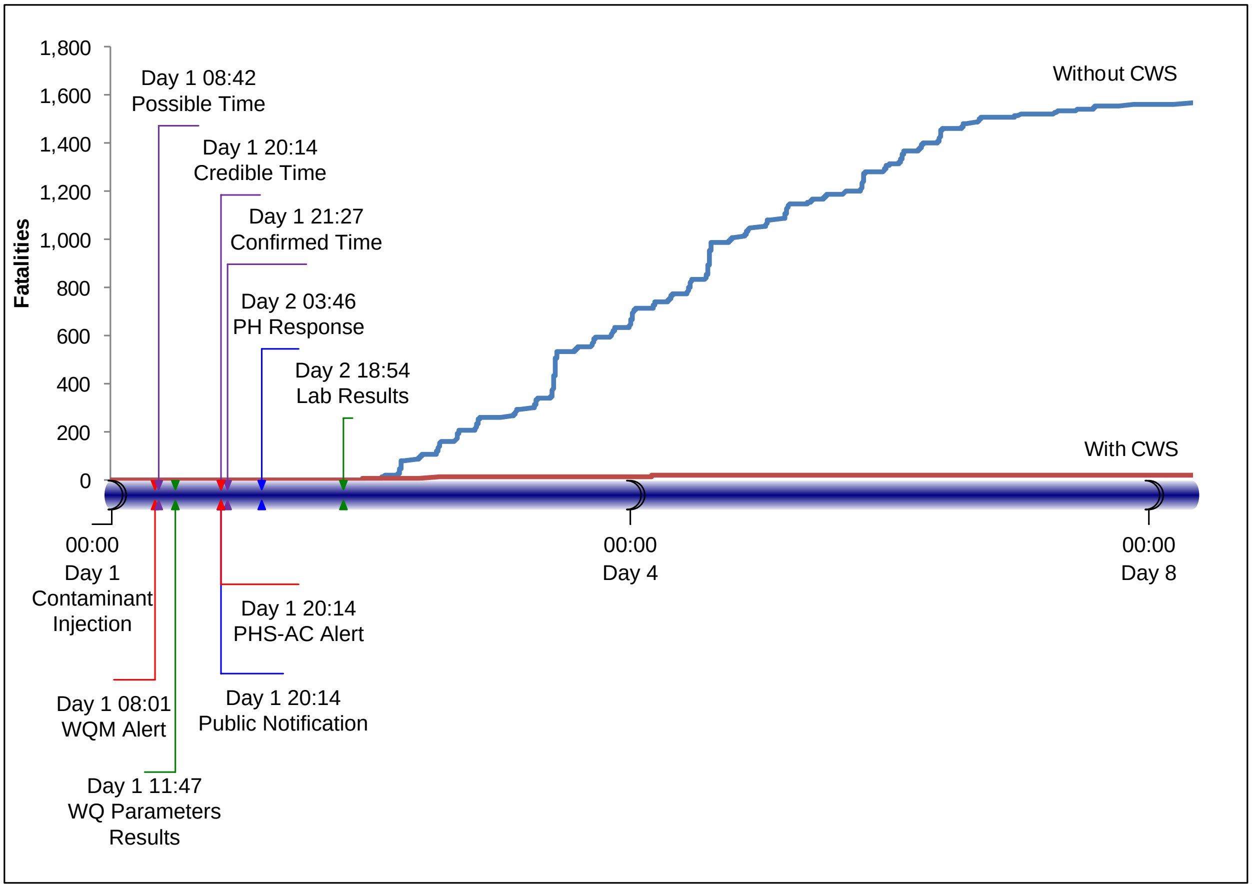

Figure 8-19. Timeline and Consequences for a Contamination Scenario Involving Biological Agent 4

Figure 8-20 is a timeline and consequence graphic for a distribution system attack scenario involving Toxic Chemical 6, which is representative of the timeline demonstrated by many of the scenarios involving toxic chemicals without a taste or odor. It shows the key timeline metrics relative to the start of the injection and the time series of fatalities for the case with and without the Cincinnati CWS in operation. In this scenario, the public health response occurred 1 hour and 27 minutes after injection but before the first CWS alert due to an unusually high number of cases seen in the emergency department, demonstrating that health departments will respond to an emerging health crisis even before the source of the exposure is known. The PHS Astute Clinician alert occurred 3 hours and 6 minutes after the start of the injection. Possible determination was reached 45 minutes later, following a teleconference between the utility and public health agencies, during which it was concluded that contaminated water could be a source of the exposure. The utility implemented an operational response 20 minutes after the Possible determination in an attempt to contain the contaminated water. The first WQM alert occurred 4 hours and 47 minutes after the start of the injection, and the threat level was elevated to Credible in the next 32 minutes. The public notification was issued 32 minutes after the Credible determination. Subsequently, a PHS-911 alert occurred and water quality field testing was conducted, which raised the threat level to Confirmed 1 hour and 20 minutes later. Laboratory results for the water sample were available five hours later. While these results were available after the Confirmed determination, analytical confirmation of the contaminant's identity would inform the later stages of response to an actual contamination incident.

The time series of fatalities for this simulated contamination scenario is also shown in Figure 8-20 with and without the CWS in operation. This contaminant has a short delay between exposure and onset of symptoms and rapid illness progression, which contributed to fatalities occurring early in the scenario, reaching about 750 in the first 10 hours. Moreover, the profiles for number of fatalities match closely for run types with and without the CWS in operation due to the time required to gather sufficient information during the investigation to conclude that contamination is Credible and subsequently issue public notification. At the time when a majority of individuals were in compliance with the public notification (approximately four hours after issuance of public notification), the number of fatalities stopped rising for the case in which the CWS was in operation. For the case without the CWS, the number of fatalities continued to rise until reaching about 1,750 approximately 36 hours after the start of the injection. In this example, the CWS would have reduced fatalities by about 1,000, which is more than a 55% reduction. This reduction in fatalities is primarily due to public notification, which sharply reduced the number of exposures once most individual began to comply with the notification. In comparison to the scenario described above for Biological Agent 4, a typical scenario involving a toxic chemical unfolds more quickly, with several alerts occurring early in the scenario due to the rapid onset and progression of symptoms.

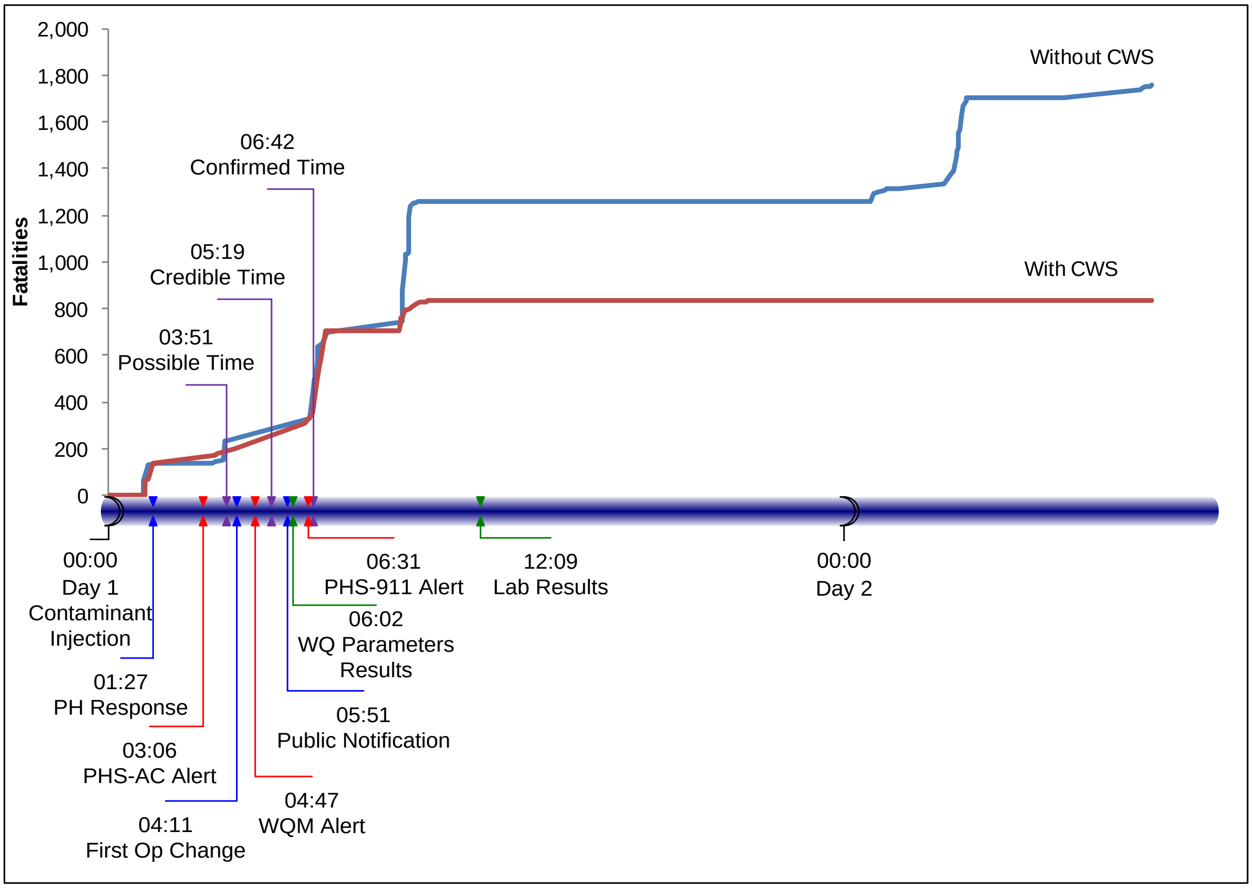

Figure 8-20. Timeline and Consequences for a Contamination Scenario Involving Toxic Chemical 6

Figure 8-21 is a timeline and consequence graphic for a distribution system attack scenario involving Toxic Chemical 4, which is representative of the timeline demonstrated by many of the scenarios involving toxic chemicals with a taste or odor. It shows the key timeline metrics relative to the start of the injection and the time series of fatalities for the case with and without the Cincinnati CWS in operation. In this scenario, CCS was the first component to detect with IVR and work order (WO) alerts occurring at 6 hours and 43 minutes and 7 hours and 16 minutes after the injection, respectively. Contamination was considered Possible 26 minutes after the first CCS alert and was followed by an operational response 10 minutes later. A PHS-DPIC alert occurred 8 hours and 28 minutes after the start of the injection, which immediately raised the threat level to Credible. The PHS-DPIC alert was followed by a PHS-911 alert three minutes later, which raised the threat level to Confirmed in the next 12 minutes. Public notification was issued 26 minutes after Confirmed determination, with the delay due to the two hours required to prepare a public notification following the determination that contamination is Possible. Public health response occurred 21 minutes after the public notification. The SC and LA results were available 2 hours and 27 minutes and 8 hours and 34 minutes after the Possible determination, respectively. While these results were available after the Confirmed determination, analytical confirmation of the contaminant's identity would inform the later stages of response to an actual contamination incident.

The time series of fatalities for this simulated contamination scenario is also shown in Figure 8-21, with and without the CWS in operation. The profiles for fatalities with and without the CWS in operation match closely for the first 13 hours when the fatalities reached about 475. The fatalities with the CWS reached 550 at about 16 hours after injection and then stopped rising, while the fatalities in the absence of a CWS kept increasing until they reached about 850 at about 38 hours. In this scenario, the CWS would have reduced fatalities by about 300, more than a 35% reduction. As with the previous scenario, the exposures avoided due to public notification were the main driver for the reduction in consequences.

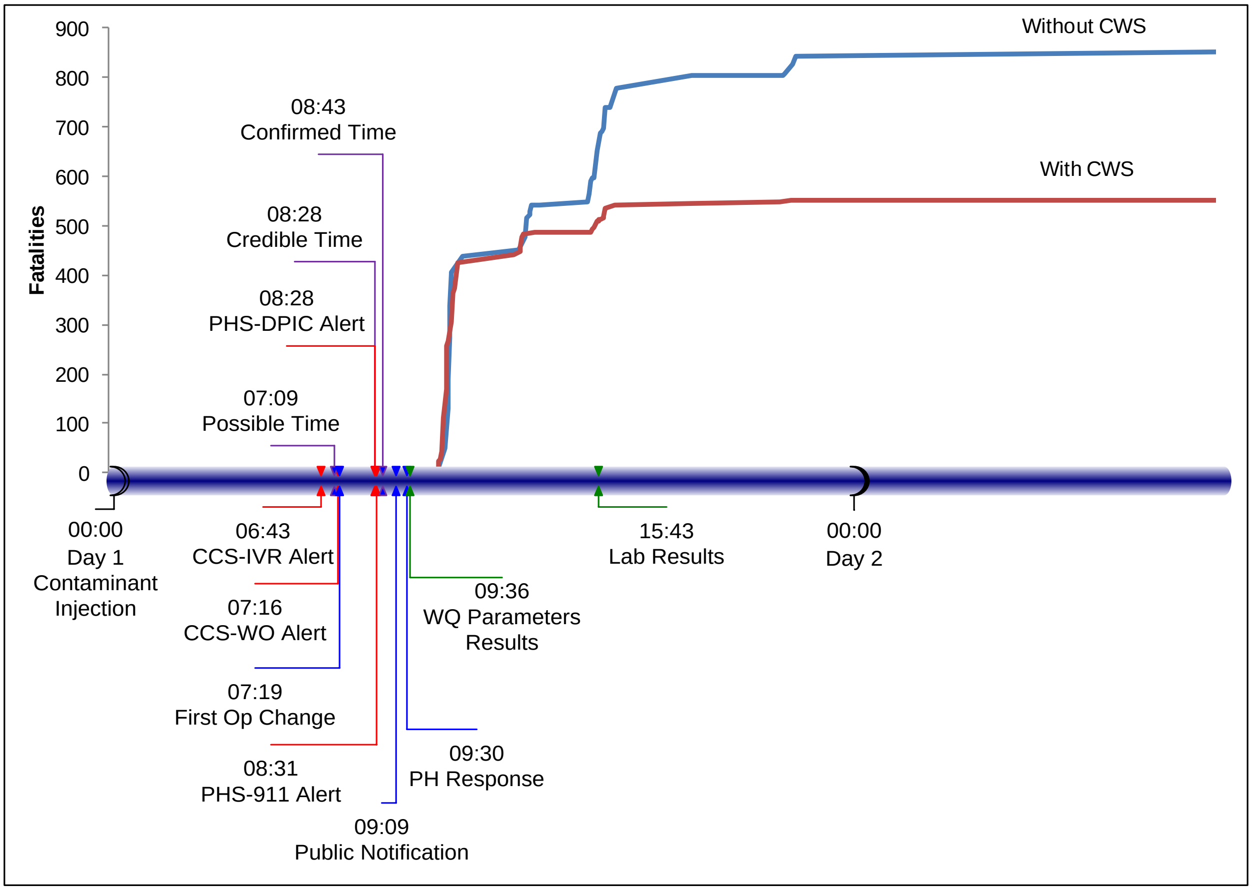

Figure 8-21. Timeline and Consequences for a Contamination Scenario Involving Toxic Chemical 4

The three timelines shown are intended to provide insight into how a contamination scenario unfolds, demonstrating timeline metrics and the primary consequences (fatalities) for three representative contaminants.

In the remainder of this section, a statistical summary of results from the entire ensemble of simulated contamination scenarios, excluding 100 scenarios in which there was no operational response or public notification, will be presented to illustrate the reduction in health-related consequences that might be realized under a wide range of scenarios. The 100 scenarios in which operational response or public notification were not implemented were excluded because without these response actions, there is no reduction in consequences attributable to utility response actions. The statistical summary of the reduction in consequences (i.e., fatalities, illnesses, healthcare burden and miles of pipe contaminated) attributable to the CWS is presented for individual contaminants in **Figures 8-22** through **8-25**. The figures show the 10th, 25th, 50th, 75th and 90th percentiles for the reduction in consequence in the form of box and whisker plots. Figures 8-22 through 8-24 are each broken up into three plots, each plot grouping contaminants with a similar range in consequence reduction, and are arranged in decreasing order of median consequence reduction. Note that in Figure 8-24, a reduction in the number of individuals receiving healthcare is beneficial as it indicates that fewer individuals were exposed to the contaminant (either through operational response or compliance with a public health notification) and, therefore, were not in need of medical treatment.

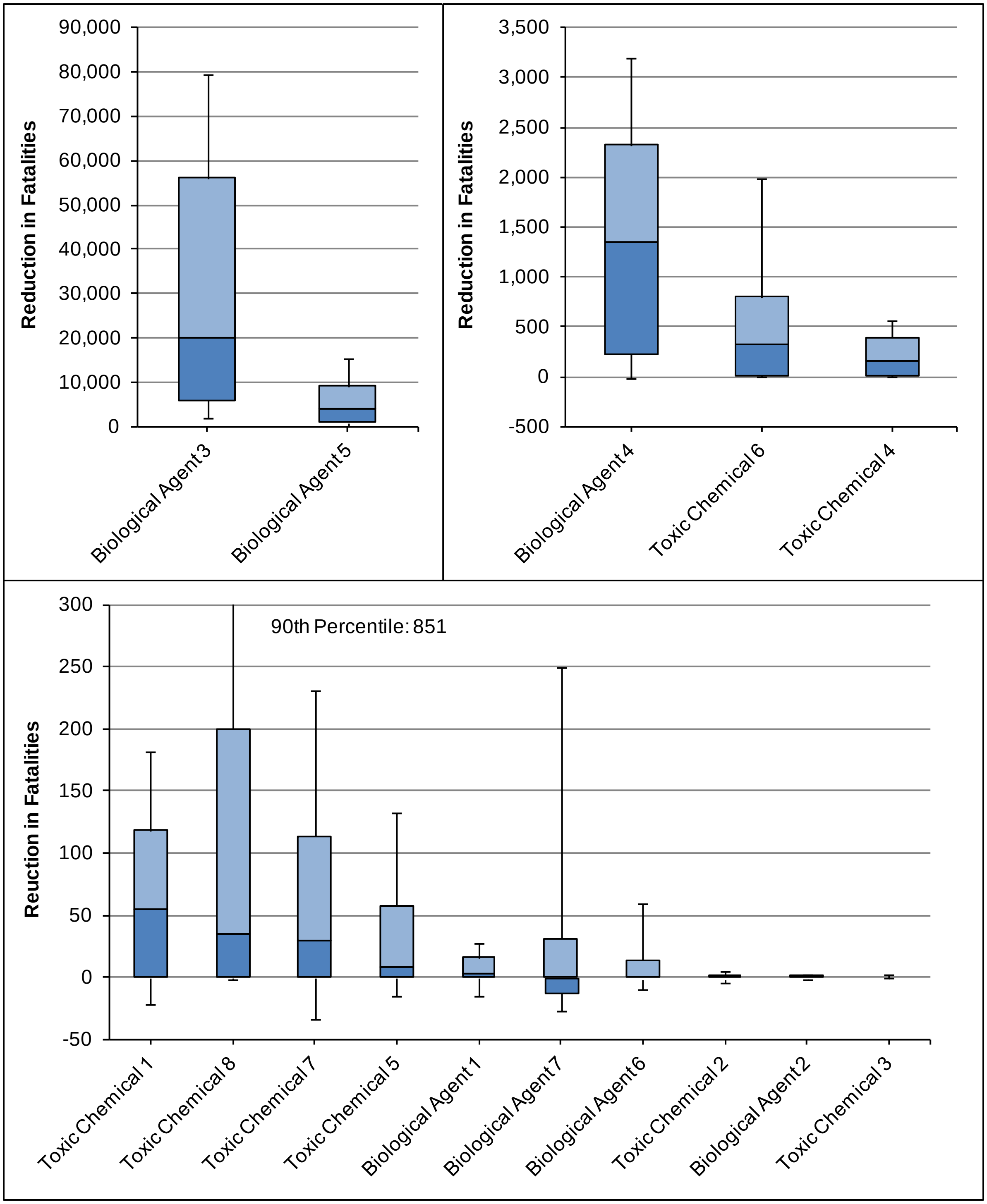

Figure 8-22. Reduction in Fatalities Attributable to the CWS

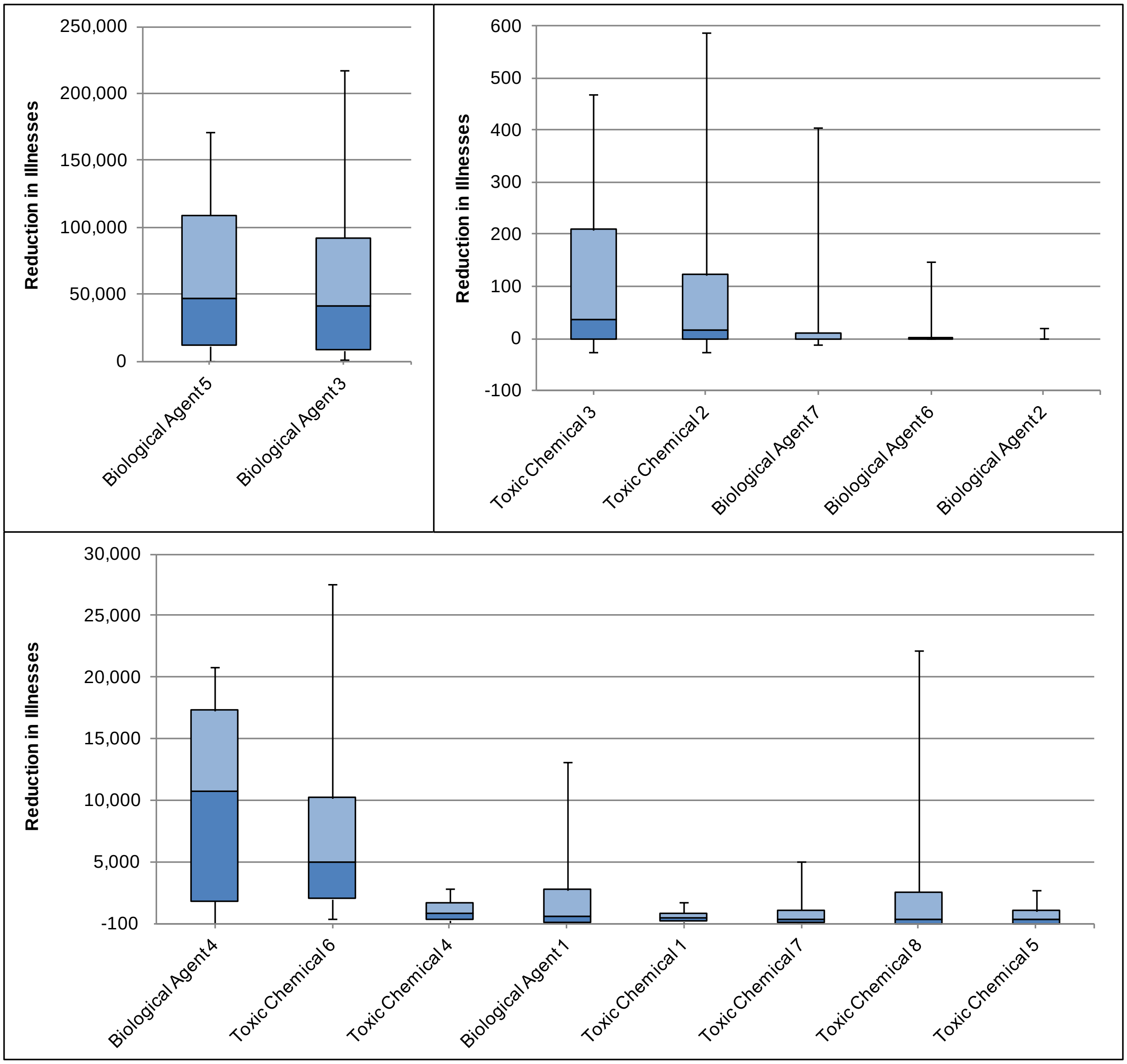

Figure 8-23. Reduction in Illnesses Attributable to the CWS

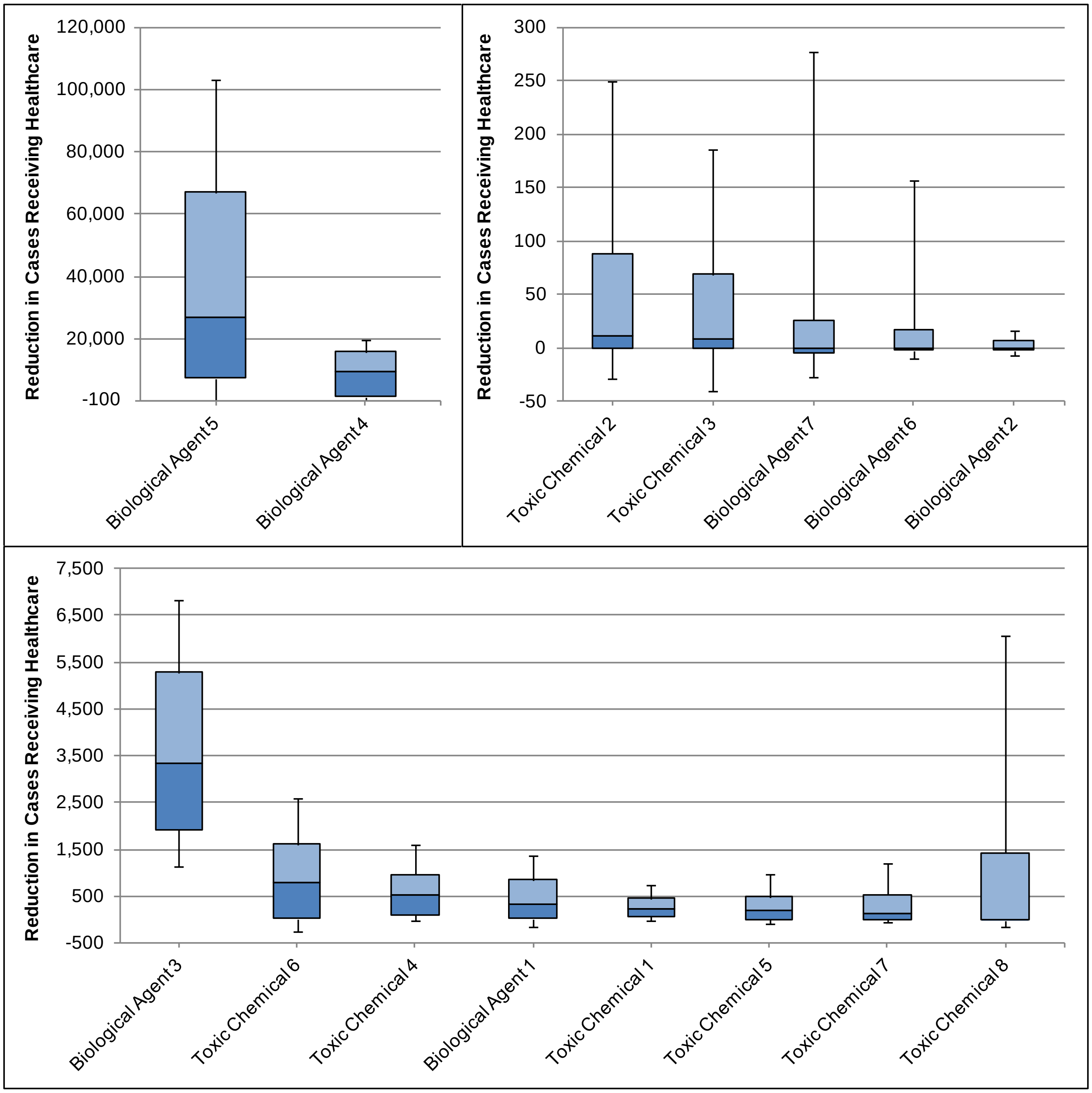

Figure 8-24. Reduction in Healthcare Burden Attributable to the CWS

Biological Agents 3, 4 and 5 showed the highest reduction in health-related consequences (fatalities, illnesses and healthcare burden). It is noteworthy that even though detections and response actions during scenarios involving Biological Agents 4 and 5 were among the slowest (Figures 8-8 and 8-9), they had the highest reductions in all three health-related consequence metrics. This demonstrates that while detection and response may be slow for some contaminants, a CWS can significantly reduce the public health consequences caused by these contaminants. In addition, Biological Agents 2, 6 and 7 and Toxic Chemicals 2 and 3 showed the smallest median reduction in all three health-related consequences. These contaminants produced relatively few health consequences in the baseline cases thereby limiting the extent of consequence reduction that could be achieved with a CWS.

The highest reduction in fatalities was seen for Biological Agent 3 with median and 90th percentile reductions around 20,000 and 80,000 respectively. The infectivity and virulence of Biological Agent 3 led to high fatalities and consequently a greater opportunity for the CWS to reduce those fatalities. Further, fatalities from exposure to Biological Agent 3 can be reduced through prophylactic treatment and proper medical care, both of which are generally implemented sooner due to information provided through the CWS. Although not as dramatic, the reduction in fatalities for Biological Agent 5 was also large, with median and 90th percentile reductions around 4,000 and 15,500 respectively. The reductions in fatalities for Toxic Chemicals 4 and 6 were in the hundreds for the majority of scenarios, and suggest that contaminants with rapid symptom onset and progression result in similar numbers of fatalities with or without a CWS in operation. In these cases, exposure to a lethal dose could result in rapid onset of symptoms and death sooner than it would be possible to seek effective medical treatment. Scenarios involving the ten contaminants shown in the bottom plot of Figure 8-22 had reductions in fatalities generally less than 100; however, these contaminants tend to generate low numbers of fatalities even in the baseline case, thus there is not much opportunity to further reduce fatalities in scenarios involving these contaminants.

Figure 8-25 shows box and whisker plots for reductions of miles of pipe contaminated. The reduction in miles of pipe contaminated represents areas of the distribution system that avoided contamination due to operational responses implemented by the utility. Not only would this reduction in contaminant spread reduce the number of potential exposures, it would also reduce the amount of pipe material (and number of buildings and homes) that would need to be remediated. The figure shows no discernible trend with contaminant type, which was expected given that operational responses are limited to a finite number of control points in the system and depend on the area suspected of being contaminated and not the identity of the contaminant. The largest reduction in consequences occurred for facility attack scenarios for which the spread of contamination was reduced drastically due to quick detection by ESM and the operational response that followed, which limited the spread of contaminated water. Consequence reduction was negative for a few scenarios, indicating the CWS consequence was greater than the baseline case. Incidents of negative consequence reduction are primarily due to a trade-off in the type of consequences that are reduced by operational response actions. For example, operational responses may be implemented that intend to limit the spread of contaminated water, which leads to a higher contaminant concentration in the impacted area. This can result in more individuals in the contaminated area being exposed to a lethal dose of the contaminant, rather than a diluted concentration that would have occurred if no operational changes were made. However, in a vast majority of scenarios across all contaminants, the reduction in miles of pipe contaminated was positive.

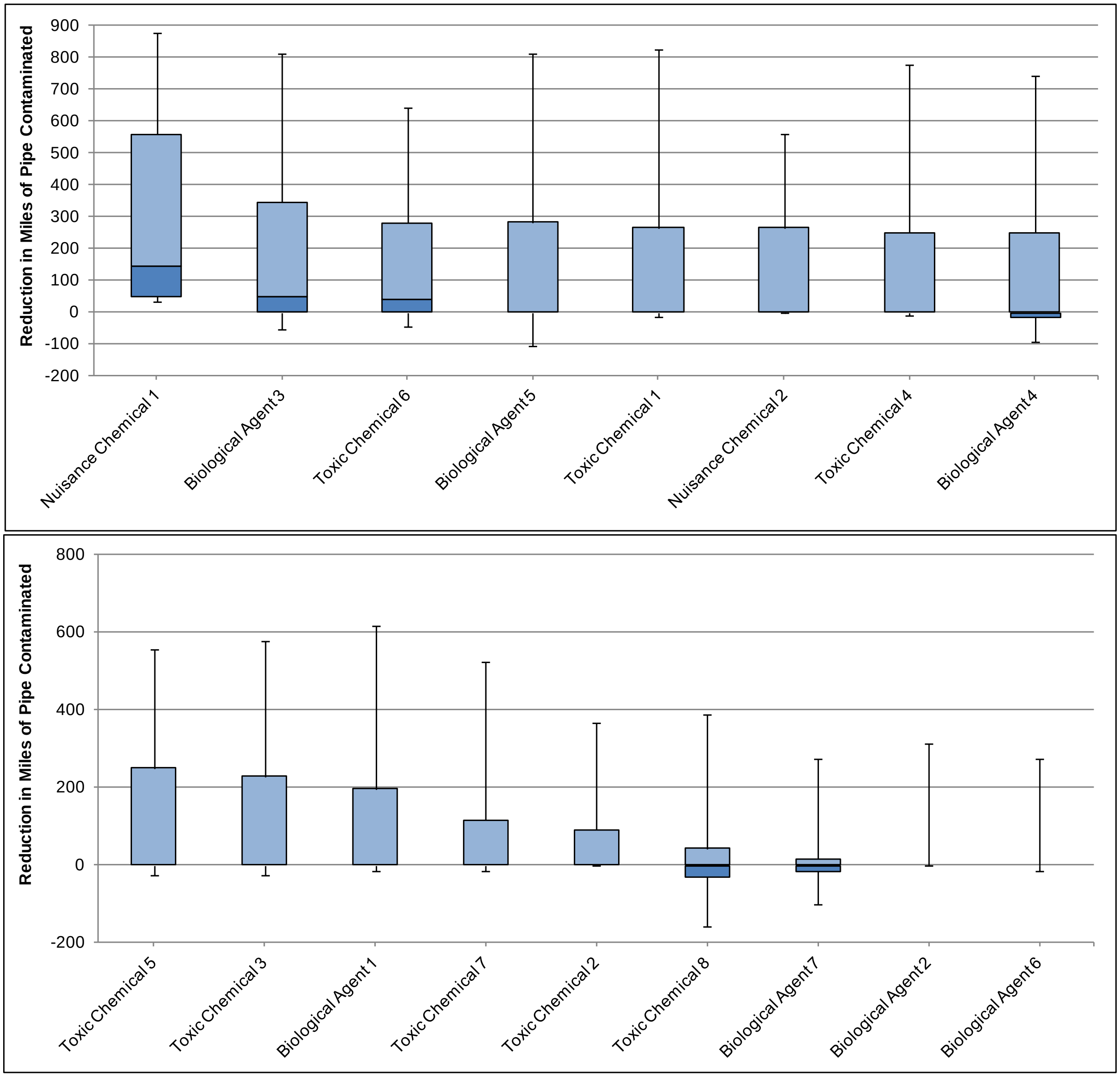

Figure 8-25. Reduction in Miles of Pipe Contaminated Attributable to the CWS

8.4 Summary

Empirical data collected from the Cincinnati CWS pilot, including results from 21 drills and exercises, were used to parameterize the Cincinnati CWS model, which was used to simulate a wide variety of contamination scenarios with varying contaminants, injection locations, and injection times. The results of the simulation study were used to quantify the timeliness and effectiveness of utility actions implemented in response to more than 2,000 simulated contamination scenarios. WQM, CCS and PHS all had median detection times of less than seven hours and the median time for Possible determination for all distribution system attack scenarios was 5.5 hours and just under 9.5 hours for Confirmed determination. Variability in the timeliness of PHS alerts was primarily driven by contaminant characteristics, particularly the delay between exposure and symptom onset. The timing of CCS alerts was driven by the injection time, with longer delays occurring for injections during low demand periods (12:00 a.m.). The timing of WQM alerts was found to be independent of contaminant type, but strongly dependent on the hydraulic travel time to the WQM station. Finally, it was observed that when multiple components detect contamination, threat level escalation and implementation of response actions occurred more quickly compared to scenarios where just one component detects contamination.

For contamination scenarios that produced a significant number of fatalities, the response stemming from detection by the CWS resulted in a large reduction in the number of fatalities when compared to the same scenario without CWS detection and response capabilities in place. Biological Agent 3 had the most significant reduction in fatalities with a median reduction in fatalities of 20,076 and a maximum of 231,448. Conversely, there were not significant reductions in health-related consequences observed for contaminants that did not result in significant health-related consequences in the baseline case.

Section 9.0: Sustainability

A key design objective for the CWS is to develop a sustainable system that provides an acceptable benefit-cost trade-off. The full cost of the CWS consists of two broad categories, capital expenditures to deploy the system and O&M expenses to keep the system functioning for its lifespan. Together they comprise the lifecycle cost of the system that can be compared with the benefits received over the lifespan of the system to determine if it is sustainable. The primary benefit of a CWS is the potential reduction in consequences in the event of a contamination incident; however, such a benefit may be rarely, if ever, realized. Thus, dual-use benefits to a utility, which are unrelated to detecting and responding to contamination incidents, will be an important driver for the sustainability of the system. Ultimately, the sustainability of the system can be demonstrated through utility and partner organization compliance with the protocols and procedures necessary to operate and maintain the CWS. To evaluate how well the CWS met this design objective, the following three metrics were evaluated: net present value, dual-use benefits, and willingness to maintain the CWS. The following subsections define each metric, describe how it was evaluated, and present the results.

9.1 Net Present Value

Definition: The difference between the present value of benefits and the present value of costs.

Analysis Methodology: A financial analysis was performed to quantify in dollars the lifecycle cost of the CWS and to similarly monetize the benefits that could be quantified in dollars using reasonable assumptions. Because costs occur over the assumed 20-year lifecycle of the system, all monetary values were adjusted to a common base year (2007) using a fixed rate of inflation and summed to represent the present value (PV) of the costs. The PV of the benefits was calculated using a common base year (2007) dollars. The benefit-cost analysis used these normalized costs to compute the net present value (NPV) of the Cincinnati CWS by subtracting the PV of the costs from the PV of the benefits.

The costs for deploying and operating the Cincinnati CWS were thoroughly documented and considered fixed in the benefit-cost analysis. However, there is more uncertainty regarding the benefits that would be accrued under the lifecycle of the Cincinnati CWS. Thus, the benefit-cost analysis was performed under two conditions: 1) assuming that a significant contamination incident occurred and 2) in the absence of a contamination incident. Given that no contamination incidents occurred during the evaluation period of the pilot, the Cincinnati CWS model, described in Appendix A, was used to estimate the consequences of contamination incidents with and without a CWS in place, with the difference in consequences under these two conditions providing an estimate of the reduction in consequences attributable to the CWS. The monetary value of this reduction in consequences was determined using a variety of assumptions about the costs to public health, water and wastewater utilities, and businesses served by the drinking water utility. These assumptions are described in detail in Appendix B. For the condition in which no contamination occurred, the benefit-cost analysis considered only those dual-use benefits that could be reliably monetized.

Results: This section first presents the total cost of the Cincinnati CWS. Next, the net present value is presented for the condition under which a significant contamination incident occurred, comparing the benefits of consequence reduction with the lifecycle cost of the Cincinnati CWS. Finally, the net present value is presented for the condition under which there is no contamination incident.

Table 9-1 presents the total cost of the Cincinnati CWS and each of its components broken out into the following categories: deployment, O&M, renewal and replacement, and salvage value. Deployment costs capture all labor costs for EPA, utility, and local partner personnel, as well as other direct charges for equipment, consumables and purchased services necessary to design and install the system. It also includes the costs (and savings) as a result of modifications to the system during the first year of operation. Lifecycle O&M costs represent the present value of all of the costs that GCWW and local partners incur each year to operate and maintain the CWS. Renewal and replacement costs represent all costs associated with replacing major pieces of equipment during the 20-year lifespan of the Cincinnati CWS based on the equipments' standard life expectancies. Finally, the salvage value is the estimated residual value of the system components after 20 years of operation. Appendix B describes the data sources and financial assumptions used to calculate the values presented in this table.

Table 9-1. Cost Elements used in the Calculation of Total Lifecycle Cost of the Cincinnati CWS

Cost Element	WQM	S&A	ESM	CM	PHS	CCS	Total
Deployment Costs	$4,229,000	$2,544,000	$1,389,000	$1,431,000	$1,306,000	$1,038,000	$11,936,000
Lifecycle O&M Costs	$2,515,000	$643,000	$568,000	$548,000	$241,000	$84,000	$4,598,000
Renewal and Replacement Costs	$1,556,000	$260,000	$257,000	$23,000	$242,000	$231,000	$2,569,000
Salvage Value	($97,000)	($11,000)	($19,000)	-	-	-	($127,000)
Lifecycle Cost	**$8,203,000**	**$3,436,000**	**$2,195,000**	**$2,001,000**	**$1,788,000**	**$1,353,000**	**$18,976,000**

Note: Any discrepancies in totals by element or component are a result of rounding.

The total lifecycle cost of the Cincinnati CWS is approximately $19 million. As anticipated, deployment cost ($11.9 million) is the largest element of the overall cost. The initial cost of equipment and contractor services accounted for the majority of the deployment costs, but these costs also include the effort required to optimize the system in the year following system deployment. The costs to operate and maintain ($4.6 million) and replace equipment ($2.6 million) over a 20-year lifespan constitute 37% of the overall cost of the system and are important expenditures to consider when deciding to deploy a CWS. The salvage value provides a small offset (less than 1%) to the total cost of the CWS.

Analysis of cost by component shows that WQM was the most expensive component, accounting for 43% of the total CWS costs. The deployment costs account for the majority (52%) of the total cost of the WQM component, which is expected given that this is an equipment intensive component. The O&M costs over the lifespan of the WQM component were also significant at 31% of the lifecycle cost for WQM and 55% of the total O&M costs for the CWS. The least expensive component is CCS because it was able to leverage existing call center software and capabilities at the utility, and therefore did not require large expenditures for new equipment. The lifecycle cost for CM was greater than that of two of the monitoring and surveillance components, PHS and CCS, even though CM required minimal equipment. The deployment cost for CM was driven by the large number of individuals from a variety of organizations who committed a great deal of time to development of Consequence Management Plan and other associated documentation. O&M costs are also significant for CM and include the expense of regularly exercising procedures, conducting drills and regularly updating documents.

The nature of the Cincinnati pilot is such that the cost of deploying this CWS are likely higher than those that would be incurred for a utility deploying a similar system. One reason for this is that the Cincinnati pilot was the first comprehensive CWS deployed, and the lack of previous experience to draw from resulted in additional costs during system design. This first pilot was both a demonstration and a research project; therefore, some aspects of the project were implemented to collect information about design alternatives. Furthermore, the research aspects of the project resulted in a substantial effort to document and evaluate system performance. Finally, this pilot was directly implemented by EPA and its contractors in collaboration with GCWW and local partner organizations. This implementation approach introduced substantial overhead costs that would not be incurred by a utility implementing a similar project independently. For these reasons, the costs of the Cincinnati CWS should not be directly extrapolated to projects at other utilities.

The benefits of the Cincinnati pilot were evaluated under the condition of a significant contamination incident occurring during the lifecycle of the Cincinnati CWS. To perform this analysis, 30 simulated contamination incidents were selected for a detailed cost analysis. Three scenarios were identified for each of 10 contaminants, which were selected to represent the range of water distribution system contamination threats. The contaminants include nuisance chemicals that do not cause acute health consequences, moderately toxic chemicals, and highly potent biological agents. The three scenarios evaluated for each contaminant were selected from a set of 119 scenarios to represent reductions in consequences at the 25th, 50th and 75th percentiles. More information about the scenarios selected for the benefit-cost analysis can be found in Section 3.4.

The reduction in consequences generated by the Cincinnati CWS model were used in conjunction with the methodology described in Appendix B to develop estimates of the monetary value of the reduction in consequences attributable to the CWS. For each of the 30 scenarios, **Table 9-2** presents the reduction in public health costs, lost revenue, distribution system remediation costs and total costs. Due to the selection of scenarios with widely differing consequence reductions, the associated cost savings also vary widely, from 0 to 414 billion dollars. With the exception of the three scenarios for Nuisance Chemical 1 and the 75th percentile scenario for Toxic Chemical 8, the reduction in the cost to public health was the most significant benefit. The results for Nuisance Chemical 1 are expected given that it does not cause acute health effects. For most scenarios, the value of the reduction in lost business revenue and remediation costs were within one order of magnitude of each another, with the notable exception of the 75th percentile scenario for Toxic Chemical 8, which had the largest reduction in remediation costs among the 30 scenarios. This is due to the expensive remediation techniques required to safely remove Toxic Chemical 8 from a contaminated distribution system.

Table 9-2. Benefits Attributable to the Cincinnati CWS due to the Reduction in Consequences from a Contamination Incident, in Millions of Dollars

Contaminant ID	CWS Model Analysis	Public Health	Revenue	Remediation	Total
Nuisance Chemical 1	25 Percentile	$0	$0	$0	**$0**
	50 Percentile	$0	$3	$4	**$6**
	75 Percentile	$0	$15	$38	**$52**
Toxic Chemical 1	25 Percentile	$1	$4	$1	**$6**
	50 Percentile	$456	$4	$1	**$462**
	75 Percentile	$932	$25	$6	**$963**
Toxic Chemical 5	25 Percentile	$0.0	$10	$4	**$14**
	50 Percentile	$72	$0	$0	**$72**
	75 Percentile	$425	$0	$0	**$425**
Toxic Chemical 6	25 Percentile	$222	$11	$1	**$225**
	50 Percentile	$2,556	$43	$6	**$2,605**

Contaminant ID	CWS Model Analysis	Public Health	Revenue	Remediation	Total
	75 Percentile	$5,736	$27	$7	**$5,770**
Toxic Chemical 7	25 Percentile	$1	$18	$2	**$21**
	50 Percentile	$252	$0	$0	**$252**
	75 Percentile	$891	$0	$0	**$891**
Toxic Chemical 8	25 Percentile	$0	$0	$0	**$0**
	50 Percentile	$252	$0	$0	**$252**
	75 Percentile	$1,466	$106	$3,390	**$4,962**
Biological Agent 3	25 Percentile	$42,391	$2	$0.3	**$42,393**
	50 Percentile	$145,008	$17	$1	**$145,027**
	75 Percentile	$413,678	$26	$2	**$413,706**
Biological Agent 4	25 Percentile	$1,411	$0	$0	**$1,411**
	50 Percentile	$9,785	$4	$1	**$9,789**
	75 Percentile	$16,659	$17	$1	**$16,677**
Biological Agent 5	25 Percentile	$7,743	$0	$0	**$7,743**
	50 Percentile	$30,093	$18	$3	**$30,115**
	75 Percentile	$66,322	$36	$5	**$66,364**
Biological Agent 6	25 Percentile	$0	$0	$0	**$0**
	50 Percentile	$14	$0	$0	**$14**
	75 Percentile	$114	$0	$0	**$114**

Note: Zero values in this table are actual values, not a result of rounding.

Figure 9-1 shows the total monetary value of the reduction in consequences, as reported in Table 9-2, for each of the ten contaminants. The bottom, middle, and top of each box corresponds to the 25th, 50th and 75th percentile scenarios for each contaminant, respectively. The ten box plots are divided among three charts to allow the y-axis (i.e., monetary value of the benefit) to be scaled appropriately for each group of contaminants. The chart on the top shows the five contaminants for which the lowest value was realized, while the chart at the bottom right shows the two contaminants for which the greatest value was realized. As a point of reference, the total lifecycle cost of the Cincinnati CWS is shown in Figure 9-1 as a red line.

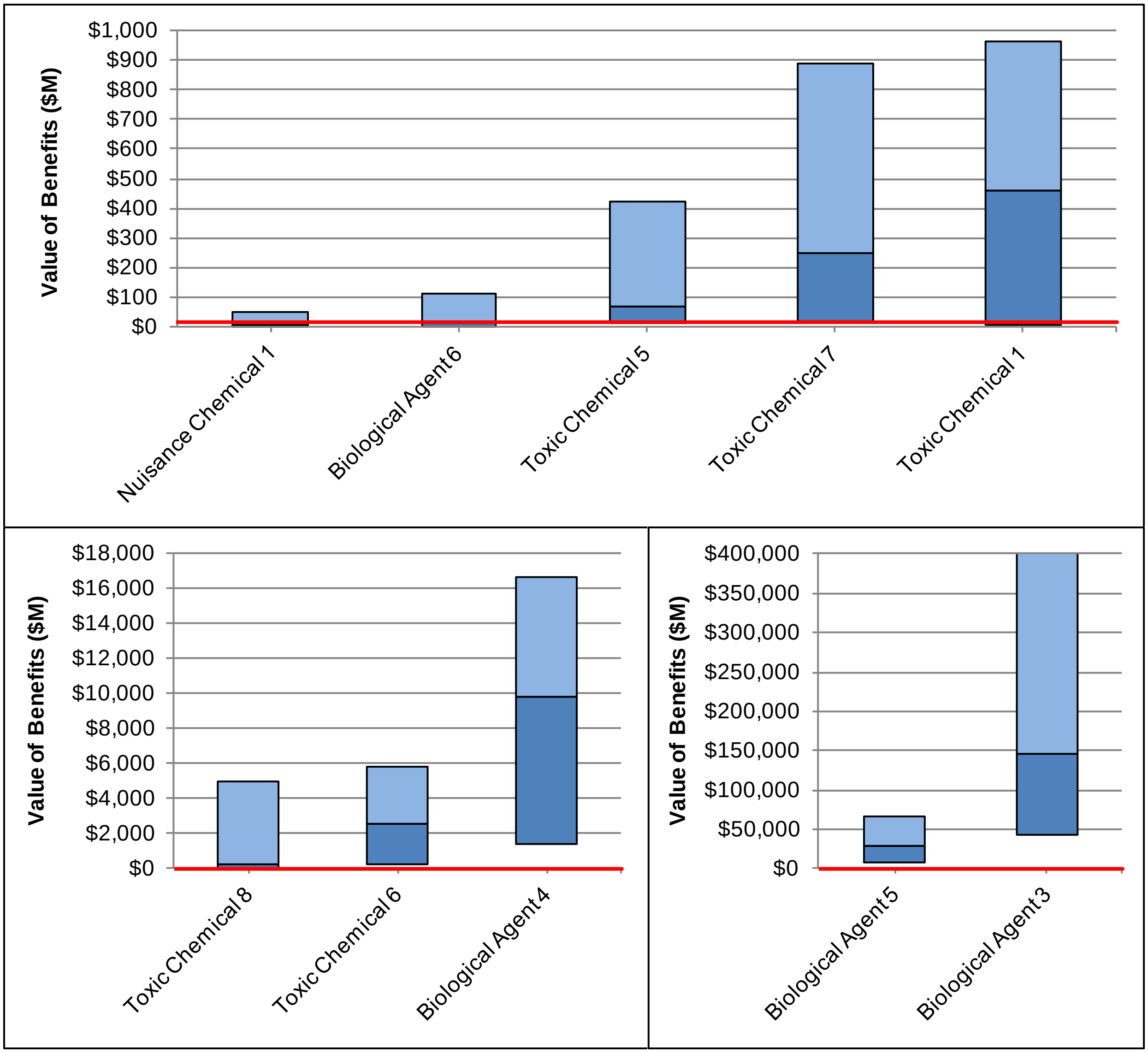

Figure 9-1. Benefit-Cost Analysis of the Cincinnati CWS
Note: Red line indicates the $19M lifecycle cost of the Cincinnati CWS

Of the 30 scenarios evaluated under the benefit-cost analysis, 23 had monetized benefits that exceeded the total lifecycle cost of the CWS. In 19 scenarios, the value of the benefits was more than 10 times the cost of the CWS, and in 11 scenarios the value of the benefits was more than 100 times the cost of the CWS. For all 10 contaminants, more than 25% of the scenarios generated benefits that were greater than the total lifecycle cost of the Cincinnati CWS. For eight contaminants, more than 50% the scenarios demonstrated benefits greater than costs, and for five contaminants, more than 75% of the scenarios demonstrated benefits greater than costs. These results demonstrate that the monetary value of consequences avoided due to early detection of and response to contamination incidents achieved through deployment of a CWS can far exceed the total lifecycle cost of the CWS.

While the analysis above can make a compelling business case for the Cincinnati CWS, the probability of a significant contamination incident, such as those considered in this study, is unknown but presumably very low. In this case, the potential benefits due to consequences avoided are not realized, and the benefit-cost analysis must consider the value of only dual-use benefits, which are benefits to routine utility operations. Benefits must be monetized to be included in the benefit-cost analysis. While many dual-use benefits were identified over the course of the evaluation period, only one could reliably be monetized. This monetized benefit was a reduction in chlorine utilization that was realized through information provided through the WQM component, which allowed utility operators to more accurately dose chlorine to meet distribution system residual targets. The resulting cost savings was estimated to be $4,410 per year. Assuming a steady cost for chlorine (i.e., its price increasing at the same rate as inflation), the PV of the benefit over 20 years is $88,200. Subtracting this benefit from the PV of the lifecycle cost of the CWS ($19 million) results in a large negative NPV, illustrating that in the absence of a contamination incident, a strict financial analysis is insufficient to make a business case for the Cincinnati CWS. However, there are significant dual-use benefits that cannot be monetized, which must be considered when evaluating the sustainability of the CWS.

9.2 Dual-Use Benefits

Definition: Subjective valuation of benefits that are not the primary reason for the system's deployment.

Analysis Methodology: Information collected from forums such as routine component review meetings, lessons learned workshops, and interviews were used to identify dual-use applications of the Cincinnati CWS. Section 3.5 provides a summary description of these data collection forums.

Results: The Cincinnati CWS resulted in benefits to GCWW's routine operations that go beyond the detection of contamination incidents. **Table 9-3** shows the dual-use benefits of the Cincinnati CWS identified by GCWW and partner organization personnel over the evaluation period of the pilot. None of these benefits could be quantified in a way that could be translated into a cost savings, and therefore required qualitative judgment regarding the value of the benefit provided. The benefits identified for the system and its components were grouped into the seven broad categories shown in Table 9-3. While non-monetizable, these benefits provide significant value to the utility and partner organizations, and thus to the customers served by the utility.

The total lifecycle cost of the Cincinnati CWS expressed as an annual cost is $1.28 million. Considering that GCWW supplies water to approximately 1.1 million people, the cost of the CWS is just higher than $1 per person per year. Given the significant value that the dual-use benefits of the CWS provides to the utility and its customers, it seems that a cost of $1 per customer per year could be justified.

Table 9-3. Dual-use Benefits of the Cincinnati CWS

Benefit	Description	WQM	S&A	ESM	PHS	CCS	CM
Ability to detect and respond to a wide range of distribution system water quality issues	A CWS allows the utility to quickly identify, diagnose and respond to undesirable water quality conditions resulting from operations or other activities not initiated by the utility, such as hydrant flushing by the fire department, thereby minimizing the impact on the customer.	X	X		X	X	X
Improved knowledge of distribution system water quality	A CWS provides the utility with nearly continuous information that can be used to develop an improved understanding of the water quality throughout the distribution system as it varies by time and location.	X	X			X	
Information to support activities related to regulatory compliance	A CWS supports compliance with drinking water regulations by providing spatial and temporal data about water quality, which enables a prompt response to developing water quality issues before they become compliance issues. Additionally, it provides information that can be used to assess the impact of potential future regulations on utility operations.	X	X			X	
Potential cost savings in operation and capital improvement	The monitoring components of a CWS provide the utility with data that can be used to modify operations for more efficient use of chemicals and power resulting in cost savings. Additionally, the data can be used to evaluate potential capital improvement projects intended to improve distribution system water quality and operations.	X					
Improved coordination and communication within the utility and with external partner organizations	Implementation of a CWS requires active participation from many divisions within the utility and from external partner agencies, such as public health agencies, police, fire (including HazMat), etc., which improves coordination and communication during both routine activities as well as emergency situations.	X	X	X	X	X	X
Improved relationship among public health agencies	Public health agencies that participated in the CWS improved relationships not only with GCWW but also with each other.				X		X
Increased public confidence in the water supply	The CWS demonstrates to the public the utility's efforts to provide a consistent, high quality product, thereby indicating its commitment to public health, resulting in improving the public confidence in the quality of their drinking water.	X	X	X	X	X	X
"All-hazards" preparedness	The CWS monitoring components, response infrastructure, and experience gained during drills and exercises can be utilized by the utility and its partner agencies to more efficiently and effectively monitor and respond to any emergency, such as natural disasters, public health emergencies, non-water related terrorist attacks, etc.	X	X	X	X	X	X

9.3 Willingness to Maintain the CWS

Definition: Behaviors that demonstrate the willingness and intent of an organization to maintain the CWS.

Analysis Methodology: The percentage of alerts that were investigated was tracked and used as a measure of the willingness of persons and organizations to monitor and maintain the CWS. Additionally, participation in drills, exercises, and other forums was tracked, which was used as a measure of the willingness of persons and organizations to participate in the CWS.

Results: **Figure 9-2** shows the percentage of alerts investigated relative to the number of alerts that occurred during each monthly reporting period over the entire evaluation period. Prior to June 2009, GCWW and local partner personnel were not expected to fully investigate all alerts because the rate of invalid alerts was deemed too high and the CWS was still being optimized to reduce the rate of invalid alerts. For this reason, the alert investigation rate was low during the first 14 months of the evaluation period; however, it gradually increased as the pilot transitioned to the real-time monitoring phase of the evaluation period.

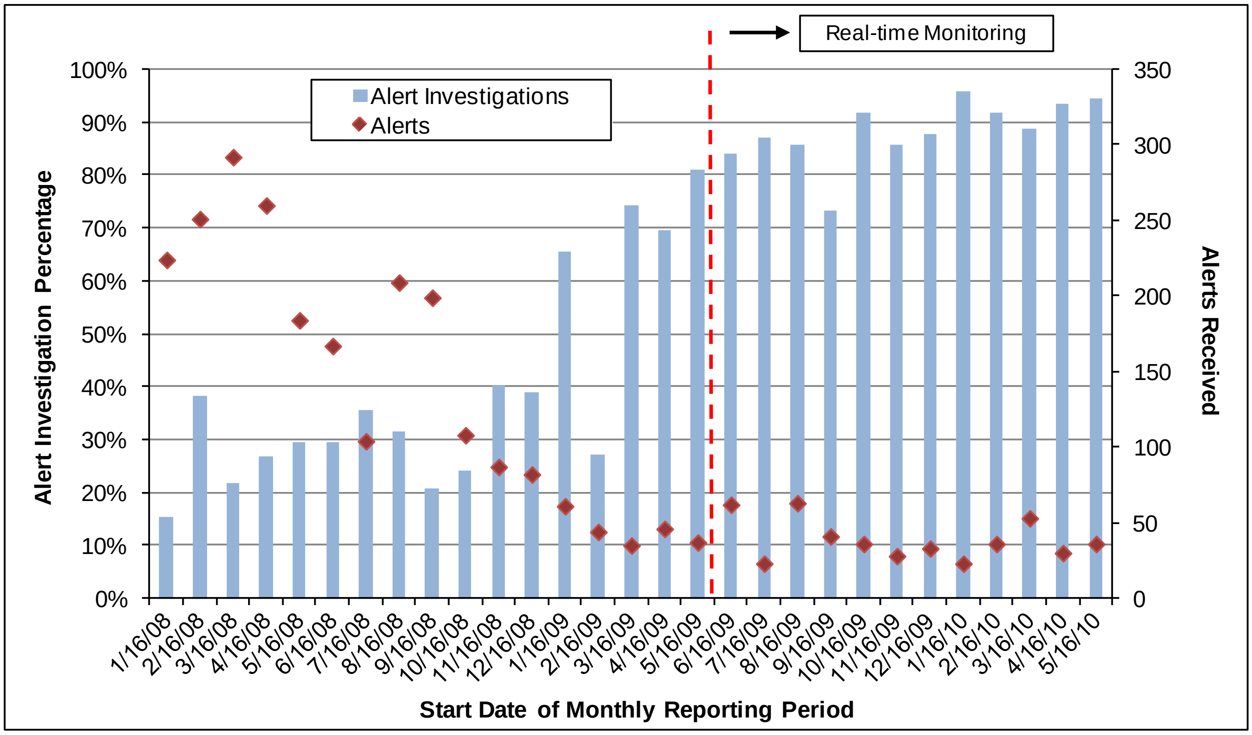

Figure 9-2. Percentage of CWS Alerts Investigated and the Number of Alerts Received

The alert investigation rate exceeded 90% during four of the last five reporting periods. The trend of increasing alert investigation rates correlates with improvement in the quality of the underlying data that generates alerts, thus reducing the number of invalid alerts as shown by the red diamonds in Figure 9-1. As discussed in Section 7.1, the optimization efforts that had the most significant impact on alert rates include improved performance of equipment and adjustment of alert thresholds to more accurately reflect normal system variability. Additionally, as more users became proficient with alert investigation procedures through exercises and training, the time and effort required to investigate alerts decreased, resulting in increased alert investigation rates. GCWW also reports that the number of alerts and the time required to investigate each alert has continued to decrease even three years after the end of the evaluation period.

Drills, exercises, component meetings, and lessons learned workshops were conducted routinely. These events were used to evaluate key aspects of component and system performance for particular activities or scenarios that could not be characterized via routine operations. Over the course of the evaluation period, 21 drills and exercises were conducted that collectively covered every component of the CWS. Participation in these drills and exercises by GCWW personnel and local partners was 100% for most activities. The continual participation in exercises indicates acceptance of the tools and procedures associated with the CWS.

Component meetings, including the PHS Users Group meetings, were initially conducted on a weekly to monthly basis early in the component development process. Once implementation was complete, the meeting schedule was adjusted to monthly or quarterly. Lessons learned workshops provided an open forum to gain feedback on the performance, operation and sustainability of components during the evaluation period. Personnel expressed specific feedback regarding the strengths and weakness of each surveillance tool in the context of their effectiveness in identifying possible contamination incidents. In general, GCWW and local partner personnel exhibited a high degree of participation and interaction in these forums, demonstrating a high degree of commitment to the project.

More than three years after completion of the WSI pilot, GCWW and local partners continue to operate and maintain the CWS. Engagement with external partners has also continued, as evidenced by continuation of PHS Users Group meetings twice a year and plans to conduct another full-scale exercise. Furthermore, GCWW has plans to upgrade the WQM component by standardizing the instruments at the existing WQM stations to a suite of instruments considered most valuable and sustainable. They are also considering the addition of more WQM locations and continue to pilot new sensor technologies.

9.4 Summary

A benefit-cost analysis was performed to evaluate whether the monetized benefits of a CWS were greater than the total lifecycle cost of the Cincinnati pilot ($18,976,000). If a contamination event occurs, the consequences can be significant, justifying the investment in a CWS. Thirty scenarios were evaluated under the benefit-cost analysis, of which 73% had monetized benefits that exceeded the total lifecycle cost of the CWS. Of the scenarios in which the benefits exceeded the CWS cost, half realized benefits that were valued at more than 100x the cost of the CWS. The primary driver of monetized benefits for most scenarios was the reduction in public health consequences of water contamination. While these results make a compelling business case for deployment of a CWS, the probability of contamination is unknown, but presumably very low.

Thus, the business case for deploying a CWS may rely on the value of dual-use benefits that were realized through the Cincinnati CWS. For example, GCWW was able to utilize WQM sensors to optimize chlorine residuals throughout the distribution system, reducing the overall chlorine dose and associated costs. Several non-monetizable benefits were realized across multiple CWS components including the ability to detect a wide range of distribution system water quality issues. Additionally, the Cincinnati CWS demonstrated benefits to business practices, such as improved communication and coordination within the utility and with its external partners. Overall, the investment in the CWS improved the response posture of GCWW and the local partners for “all-hazards,” which was demonstrated in GCWW’s response to the consequences of Hurricane Ike.

Management and personnel from GCWW and local partners demonstrated a strong willingness to maintain the CWS beyond the pilot. This was demonstrated in the high rate of alert investigations, greater than 90%, after the CWS was optimized. Furthermore, active participation in drills and exercises indicated a willingness of utility and response partner personnel to adopt the CWS components and procedures. Finally, the utility is considering upgrading the WQM component and continues to engage local partners through the Public Health Users Group.

Section 10.0: Summary and Conclusions

The evaluation of the Cincinnati CWS involved analysis of empirical data, observations from drills and exercises, results from modeling and simulations, qualitative observations gleaned from participants during forums, and a benefit-cost analysis. A set of performance metrics was defined for each of six design objectives, and results were presented showing how well the Cincinnati CWS performed relative to each metric. Highlights, limitations, and considerations for interpretation of this analysis are presented in this section.

10.1 Highlights of Analysis

Evaluation of the Cincinnati pilot produced a comprehensive assessment of the multi-component CWS design deployed under WSI. Through layers of redundancy built into the CWS and each of its components, the system achieved a high degree of operational reliability during the two-year evaluation period, with 95% data completeness and at least three of the four monitoring and surveillance components available >99% of the time. There was minimal multi-component downtime with the longest period involving two components concurrently down for 26 hours, and three components concurrently down for eight hours. While these periods of multi-component downtime may impact the timeliness of detection, they would not likely impact the overall ability of the CWS to detect a contamination incident, given that a detailed analysis of 30 simulated contamination scenarios in the simulation study showed that on average, contaminated water would remain in the distribution system at detectable levels for 5.3 days.

The multi-component Cincinnati CWS achieved comprehensive contaminant and spatial coverage by monitoring a variety of data streams and locations throughout GCWW’s distribution system. Results from a simulation study demonstrated a 98% detection rate for 2,015 simulated contamination scenarios involving a broad range of contaminant types (i.e., nuisance chemicals, toxic chemicals, and biological agents). The majority of the 44 scenarios that were not detected by the CWS involved a contaminant that does not cause acute health effects and is detectable by only a single component. This result emphasizes the value of a multi-component CWS, in which the detection capabilities of the monitoring and surveillance components are complementary and provide broad contaminant coverage. For example, while WQM covers only 72% of the distribution system area, it provides reliable detection capability for a wide range of chemical and biological agents. In comparison, CCS covers 100% of the distribution system area, but is able to detect only contaminants that cause a discernible taste or odor in water. Thus, the capabilities and limitations of the components balance out to provide a robust monitoring and surveillance system with broad spatial and contaminant coverage.

Results from the simulation study demonstrate that multiple components would generate alerts that are spatially and temporally related during a contamination incident. Co-occurring alerts from multiple components can increase a utility manager’s confidence that the alerts are valid and indicative of a potential water quality issue. Different contaminant types such as nuisance chemicals or those with rapid or delayed symptom onset trigger different combinations of component alerts, and the timing of those alerts occur in predictable patterns. The co-occurrence of two alerting components, especially the combination of PHS and WQM, was frequent in both simulated and empirical data. A combination of three components alerting was observed only once in the empirical data; however, alert clusters involving three or more components was common in the simulation study results. This would suggest that valid alert clusters involving alerts from multiple components are probably the result of a real water quality issue in the distribution system.

During real-time operation, most alerts were determined to be invalid; however, the CWS did detect 84 valid alerts involving main breaks, minor treatment process upsets, non-standard system operations or public health incidents that were unrelated to drinking water. Although invalid alerts initially occurred frequently, with more than 150 alerts during most reporting periods in the first year of operation, once the system was optimized by improving the quality of the underlying data and updating event detection system configurations to reflect normal variability, the number of invalid alerts was reduced to about 69 per reporting period.

A multi-component CWS also increases the timeliness of detection and response during a possible contamination incident. Results from the simulation study show median detection times less than seven hours for WQM, CCS and PHS, while ESM typically detected the incident before the start of contaminant injection. During the investigation, the median time for Possible determination was 5.5 hours and just under 9.5 hours for Confirmed determination. It was observed that when multiple components detect contamination, threat level escalation and implementation of response actions occurred more quickly when compared to scenarios in which just one component detects contamination. Timely detection and threat level determination lead to quicker implementation of response actions and a significant reduction in consequences.

10.2 Limitations of the Analysis

The fact that the CWS deployed in Cincinnati was the first of its kind has several implications for the evaluation presented in this report. Important considerations included:

- This was a pilot project and thus a variety of equipment, instrumentation and software applications were relatively novel when implemented. Some of the equipment that was installed proved unreliable and required an unsustainable level of effort to maintain. For some components, significant trial and error was necessary to achieve acceptable performance.
- Improved products are now available. In many cases, the Cincinnati pilot was the first real-time installation of hardware and software products for this specific application. Thus, many issues were encountered and resolved, and these improvements have been incorporated into many commercially available products. In addition, the increased awareness of the CWS application has motivated vendors to make their products more effective and reliable to implement.
- The planning and implementation approach, in which EPA took the lead role, was inefficient. Utility-led planning could potentially alleviate various pitfalls observed during implementation of the Cincinnati CWS and better leverage existing systems.

While an extensive amount of data from a variety of sources was available for evaluation of the Cincinnati pilot, there were some limitations of the analysis. Data completeness for the evaluation was relatively high, but there were some gaps in data collection. Specifically, some water quality data was lost during periods in which the data communications system was down. Also, there were some instances in which alert investigation checklists were incomplete or missing.

As noted earlier, no known contamination incidents occurred during the evaluation period of the Cincinnati pilot. Thus, it was necessary to use results from computer simulations of contamination incidents to evaluate certain performance metrics. While these simulations were very detailed and the supporting models were parameterized using data from real-world observations, the model is still only an approximation. Thus, the results of the simulation study should be considered only in the context of the design and assumptions intrinsic to the study.

10.3 Potential Applications of the Cincinnati CWS

The Cincinnati CWS was tailored to the capabilities and structure of GCWW and its local partners; therefore, extrapolation to other utilities should be performed carefully. However, the Cincinnati CWS revealed numerous applications and lessons that can be applicable to other CWSs.

The CWS design and implementation approach used in Cincinnati is just one of many possibilities. Based on the results presented here, and capabilities of other cities, it may be possible to refine elements of the design to reduce deployment costs while still achieving the utility's specific objectives. The results of the evaluation presented here may aid other utilities seeking to improve existing capabilities or add additional functionality as part of an effective CWS. Many utilities have existing capabilities that can be leveraged to build an effective CWS at a much lower cost than was incurred for the Cincinnati CWS.

At the start of the pilot, there was concern that the monitoring and surveillance components would generate too many alerts and that eventually these alerts would be largely ignored. In the early stages of the pilot, this was the case. However, once the system had been optimized to reduce the occurrence of invalid alerts, investigation rates approached 100%, indicating that the alert rate was acceptable to personnel responsible for monitoring the system. Furthermore, some staff members observed that the data and alerts generated by the system provided a deeper understanding of the impact of system operations on distribution system water quality. In addition, water quality anomalies and public health incidents not caused by contamination have been detected. This demonstrates that real-time monitoring and surveillance can provide valuable information for day-to-day operations.

Analysis of the simulation study results emphasizes the value of a multi-component CWS, in which the detection capabilities of the monitoring and surveillance components are complementary and provide broad contaminant coverage. With respect to the CWS design objectives (i.e., spatial coverage, contaminant coverage and timeliness of detection), limitation in the capabilities of one component are offset by the strengths of another. Additionally, co-occurring alerts from multiple components can increase the utility's confidence that the alerts are valid and indicative of a potential water quality issue.

The Cincinnati CWS demonstrated benefits to business practices, such as improved communication and coordination within the utility and with its external partners. Improved communication strategies and documented response procedures developed for the Cincinnati CWS are widely applicable to a variety of situations. In particular, the ability to respond to a wide variety of hazards, including extreme weather events such as the Hurricane Ike windstorm, is enhanced by CWS capabilities. Furthermore, these procedures are highly portable and can be adapted to meet the specific needs of a variety of applications. Given that improved communication and response protocols are relatively inexpensive to implement, they should be considered as one cost-effective strategy for improving any utility's monitoring and response capabilities. The overall success of a CWS depends not only on reliable data, but also requires the commitment of utility personnel and external partners who are aware of the possible causes of changes in observed water quality data, customer complaints or trends in public health data. Periodic drills and exercises can be an effective means of maintaining this commitment and knowledge.

The overarching goal of the CWS is to improve situational awareness such that potential water quality issues in the distribution system can be quickly detected and proactively addressed. The Cincinnati pilot demonstrated that this can be achieved through a multi-component monitoring and surveillance system combined with "all-hazards" response planning.

Section 11.0: References

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Section 12.0: Abbreviations

AWWA	American Water Works Association
CCS	Customer Complaint Surveillance
CI	Confidence Index
CL2	Free Chlorine Residual
CM	Consequence Management
COND	Conductivity
CPI	Consumer Price Index
CWS	Contamination Warning System
DPIC	Drug and Poison Information Center
ED	Emergency Department
EPA	Environmental Protection Agency
EMS	Emergency Medical Service
ESM	Enhanced Security Monitoring
FSE	Full-Scale Exercise
GCWW	Greater Cincinnati Water Works
HazMat	Hazardous Materials
IT	Information Technology
IVR	Interactive Voice Response
LA	Laboratory Analysis
NPV	Net Present Value
O&M	Operations and Maintenance
ORP	Oxidation Reduction Potential
PHS	Public Health Surveillance
PV	Present Value
QC	Quality Control
RFT	Rapid Field Test
S&A	Sampling and Analysis
SC	Site Characterization
SCADA	Supervisory Control and Data Acquisition
TLD	Threat Level Determination
TOC	Total Organic Carbon
WO	Work Order
WQM	Water Quality Monitoring
WQ&T	Water Quality and Treatment
WSI	Water Security Initiative
WUERM	Water Utility Emergency Response Manager

Section 13.0: Glossary

Alert. Information from a monitoring and surveillance component indicating anomalous conditions that warrant further investigation to determine if the alert is valid.

Alert investigation. A systematic, documented process for determining whether or not an alert is valid, and identifying the cause of the alert. If an alert cause cannot be identified, contamination is Possible.

Anomaly. Deviations from an established baseline. For example, a water quality anomaly is a deviation from typical water quality patterns observed over an extended period.

Baseline. Normal conditions that result from typical system operation. The baseline includes predictable fluctuations in measured parameters that result from known changes to the system. For example, a water quality baseline includes the effects of draining and filling tanks, pump operation, and seasonal changes in water demand, all of which may alter water quality in a somewhat predictable fashion.

Benefit. An outcome associated with the implementation and operation of a contamination warning system that promotes the welfare of the utility and the community it serves. Benefits can be derived from a reduction in the consequences of a contamination incident and from routine operations.

Benefit-cost analysis. An evaluation of the benefits and costs of a project or program, such as a contamination warning system, to assess whether the investment is justifiable considering both financial and qualitative factors.

Biotoxins. Toxic chemicals derived from biological materials that pose an acute risk to public health at relatively low concentrations.

Box-and-whisker plot. A graphical representation of nonparametric statistics for a dataset. The bottom and top whiskers represent the 10th and 90th percentiles of the ranked data, respectively. The bottom and top of the box represent the 25th and 75th percentiles of the ranked data, respectively. The line inside the box represents the 50th percentile, or median, of the ranked data. Note that some data sets may have the same values for the percentiles presented in box-and-whisker plots, in which case some lines will not be visible.

Bulk concentration (of contaminant). The concentration of a contaminant solution that is injected into the distribution system during a contamination scenario.

Bulk volume (of contaminant). The total volume of a contaminant solution that is injected into the distribution system during a contamination scenario.

Confidence index. In the Cincinnati contamination warning system model, a quantitative indicator of the reliability of the data used in the threat level determination process. The confidence index is calculated for each of the four monitoring & surveillance component, site characterization and laboratory analysis.

Confirmed. In the context of the threat level determination process, contamination is Confirmed when the analysis of all available information from the contamination warning system has provided definitive, or nearly definitive, evidence of the presence of a specific contaminant or class of contaminant in the distribution system. While positive results from laboratory analysis of a sample collected from the distribution system can be a basis for confirming contamination, a preponderance of evidence, without the benefit of laboratory results, can lead to this same determination.

Consequence management. Actions taken to plan for and respond to Possible contamination incidents. This includes the threat level determination process, which uses information from all monitoring and surveillance components as well as sampling and analysis to determine if contamination is Credible or Confirmed. Response actions, including operational changes, public notification, and public health response, are implemented to minimize public health and economic consequences, and ultimately return the utility to normal operations.

Consequence management plan. Documentation that provides a decision-making framework to guide investigative and response activities implemented in response to a possible contamination incident.

Contamination incident. The introduction of a contaminant in the distribution system with the potential to cause harm to the utility or the community served by the utility. A contamination incident may be intentional or accidental.

Contamination scenario. Within the context of the simulation study, parameters that define a specific contamination incident, including: injection location, injection rate, injection duration, time the injection is initiated and the contaminant that is injected.

Contamination warning system. An integrated system of monitoring and surveillance components designed to detect contamination in a drinking water distribution system. The system relies on integration of information from these monitoring and surveillance activities along with timely investigative and response actions during consequence management to minimize the consequences of a contamination incident.

Costs, implementation. Installed cost of equipment, IT components, and subsystems necessary to deploy an operational system. Implementation costs include labor and other expenditures (equipment, supplies, and purchased services).

Cost, lifecycle. The total cost of a system, component, or equipment over its useful or practical life. Lifecycle cost includes the cost of implementation, operation & maintenance and renewal & replacement.

Costs, operation & maintenance. Expenses incurred to sustain operation of a system at an acceptable level of performance. Operational and maintenance costs are reported on an annual basis, and include labor and other expenditures (supplies and purchased services).

Costs, renewal & replacement. Costs associated with refurbishing or replacing major pieces of equipment (e.g., water quality sensors, laboratory instruments, IT hardware) that reach the end of their useful life before the end of the contamination warning system lifecycle.

Coverage, contaminant. Specific contaminants that can potentially be detected by each monitoring and surveillance component, as well as sampling & analysis, of a contamination warning system.

Coverage, spatial. The areas within the distribution system that are monitored by, or protected by, each monitoring and surveillance component of a contamination warning system.

Credible. In the context of the threat level determination process, a water contamination threat is characterized as Credible if information collected during the investigation of Possible contamination corroborates information from the validated contamination warning system alert.

Data completeness. The amount of data that can be used to support system or component operations, expressed as a percentage of all data generated by the system or component. Data may be lost due to quality control failures, data transmission errors, and faulty equipment among other causes.

Distribution system attack scenarios. A simulated contamination incident in which the injection occurred at a distribution system node (and not at a utility facility). For every contaminant, one distribution system attack node was selected as an injection location for each of the 94 pito zones to ensure that the spatial extent of the distribution system was represented.

Distribution system model. A mathematical representation of a drinking water distribution system, including pipes, junctions, valves, pumps, tanks, reservoirs, etc. The model characterizes flow and pressure of water through the system. Distribution system models may include a water quality model that can predict the fate and transport of a material throughout the distribution system.

Dual-use benefit. A positive application of a piece of equipment, procedure, or capability that was deployed as part of the contamination warning system, in the normal operations of the utility.

Ensemble. The comprehensive set of contamination scenarios evaluated during the simulation study.

Event detection system. A system designed specifically to detect anomalies from the various monitoring and surveillance components of a contamination warning system. An event detection system may take a variety of forms, ranging from a complex set of computer algorithms to a simple set of heuristics that are manually implemented.

Evaluation period. The period from January 16, 2008 to June 15, 2010 during which data was actively collected for the evaluation of the Cincinnati contamination warning system pilot.

Facility attack scenarios. A simulated contamination incident in which the injection occurred at a utility facility (e.g., a distribution system storage tank or a pump station). The injection node set for the facility attack nodes included all GCWW facilities in the retail portion of the distribution system.

Flow rate. The volume of water moving past a fixed location per unit time.

Hydraulic connectivity. Points or areas within a distribution system that are on a common flow path.

Incident timeline. All significant activities that occur during a contamination incident, beginning with the start of contaminant injection. Elements of the incident timeline include: time for detection, time for alert investigation, time for threat level determination and time to implement response actions.

Injection duration. The cumulative time over which the bulk volume of a contaminant is injected into the distribution system at a specific location for a given scenario within the simulation study.

Injection location. The specific node in the distribution system model where the bulk contaminant is injected into the distribution system for a given scenario within the simulation study.

Injection rate. The mass flow rate at which the bulk volume of a contaminant is injected into the distribution system at a specific location for a given scenario within the simulation study, in units of mg/min or organisms/min.

Interactive voice response. An automated call management system that transfers utility customer calls to designated customer service representatives based on customer selected issues such as billing or water quality problems.

Invalid alert. An alert from a monitoring and surveillance component that is not due to an anomaly and is not associated with an incident or condition of interest to the utility.

Investigative component. Site characterization and laboratory analysis activities implemented as part of the threat level determination process for the purpose of determining if contamination is Credible or Confirmed, and for identifying the contaminant.

Metric. A standard or statistic for measuring or quantifying the performance of the contamination warning system or its components.

Model. A mathematical representation of a physical system.

Model parameters. Fixed values in a model that define important aspects of the physical system.

Module. A sub-component of a model that typically represents a specific function of the real-world system being modeled.

Monetizable. A cost or benefit whose monetary value can be reliably estimated from the available information.

Monitoring & surveillance component. Element of a contamination warning system used to detect unusual water quality conditions, including possible contamination incidents. The four monitoring & surveillance components of a contamination warning system include: 1) water quality monitoring, 2) enhanced security monitoring, 3) customer complaint surveillance and 4) public health surveillance.

Net present value. The difference between the present value of benefits and costs, normalized to a common year.

Node. A mathematical representation of a junction between two or more distribution system pipes, or a terminal point in a pipe in a water distribution system model. Water may be withdrawn from the system at nodes, representing a portion of the system demand.

Nuisance chemicals. Chemical contaminants with a relatively low toxicity, which therefore generally do not pose an immediate threat to public health. However, contamination with these chemicals can make the drinking water supply unusable.

Optimization phase. Period in the contamination warning system deployment timeline between the completion of system installation and real-time monitoring. During this phase, the system is operational but not expected to produce actionable alerts. Instead, this phase provides an opportunity to learn the system and optimize performance (e.g., fix or replace malfunctioning equipment, eliminate software bugs, test procedures and reduce occurrence of invalid alerts).

Pathogens. Microorganisms that cause infections and subsequent illness and mortality in the exposed population.

Pito zone. An area of the Greater Cincinnati Water Works distribution system in which water quality and pressure are fairly constant. There are 94 pito zones in the Greater Cincinnati Water Works distribution system model, ranging in area from 0.3 to 15 square miles.

Possible. In the context of the threat level determination process, a water contamination threat is characterized as Possible if the cause of a validated contamination warning system alert is unknown.

Priority contaminant. A contaminant that has been identified by EPA as a monitoring target under the Water Security Initiative. Priority contaminants may be initially detected through one of the monitoring and surveillance components and Confirmed through laboratory analysis of samples collected during the investigation of a Possible contamination incident.

Public health incident. An occurrence of disease, illness or injury within a population that is a deviation from the disease baseline in the population.

Public health response. Actions taken by public health agencies and their partners to mitigate the adverse effects of a public health incident, regardless of the cause of the incident. Potential response actions include: administering prophylaxis, mobilizing additional healthcare resources, providing treatment guidelines to healthcare providers and providing information to the public.

Public notification. A publicly released statement that includes a directive to utility customers, such as boil-water before use, do-not-drink the water, or do-not-use the water. The notification is prepared by the water utility and health department, and provided to media outlets to broadcast to the public when the safety of drinking water has been compromised.

Radiochemicals. Chemicals that emit alpha, beta, and/or gamma particles at a rate that could pose a threat to public health.

Real-time monitoring phase. Period in the contamination warning system deployment timeline following the optimization phase. During this phase, the system is fully operational and utility personnel and partners respond to alerts in real-time and in full accordance with alert investigation procedures. Optimization of the system still occurs as part of a continuous improvement process; however, the system is no longer considered to be developmental.

Remediation and recovery. The stage of a contamination incident following Confirmed contamination, which involves the implementation of system decontamination and return to service.

Risk communication. Communication activities within an organization and with external parties that address the consequences and outcome of an incident.

Routine operation. The day-to-day monitoring and surveillance activities of the contamination warning system that are guided by the component response procedures. To the extent possible, routine operation of the contamination warning system is integrated into the routine operations of the drinking water utility.

Salvage value. Estimated value of assets at the end of the useful life of the system.

Scenario subset. A group of scenarios that represent a portion of the full ensemble. Typically, scenario subsets will be defined by specific values or ranges of values for scenario parameters.

Security breach. An unauthorized intrusion into a secured facility that may be discovered through direct observation, an alert or signs of intrusion (e.g., cut locks, open doors, cut fences).

Simulation study. A study designed to systematically characterize the detection capabilities of the Cincinnati contamination warning system. In this study, a computer model of the Cincinnati contamination warning system is challenged with an ensemble of 2,015 simulated contamination scenarios. The output from these simulations provides estimates of the consequences resulting from each contamination scenario, including fatalities, illnesses, and extent of distribution system contamination. Consequences are estimated under two cases, with and without the contamination warning system in operation. The difference provides an estimate of the reduction in consequences.

Site characterization. The process of collecting information from an investigation site to support the investigation of a contamination incident during consequence management.

Threat level. The results of the threat level determination process, indicating whether contamination is Possible, Credible or Confirmed.

Threat level determination process. A systematic process in which all relevant information available from a contamination warning system is evaluated to determine whether the threat level is Possible, Credible or Confirmed. This is an iterative process in which the threat level is revised as additional information becomes available. The conclusions from the threat evaluation process are considered during consequence management when making response decisions.

Threat level index. In the Cincinnati contamination warning system model, a quantitative indicator of the threat level associated with a specific contamination scenario. The threat level index is calculated by the Cincinnati contamination warning system model by summing the confidence indices from all component models. A value greater than or equal to 1.0 represents Possible contamination, greater than or equal to 2.0 represents Credible contamination, and greater than or equal to 3.0 represents Confirmed contamination.

Time for Confirmed determination. A portion of the incident timeline that begins with the determination that contamination is Credible and ends with contamination either being Confirmed or ruled out. This includes the time required to perform lab analyses, collect additional information, and analyze the collective information to determine if the preponderance of evidence confirms contamination.

Time for contaminant detection. A portion of the incident timeline that begins with the start of contamination injection and ends with the generation and recognition of an alert. The time for contaminant detection may be subdivided for specific components to capture important elements of this portion of the incident timeline (e.g., sample processing time, data transmission time, event detection time, etc.).

Time for Credible determination. A portion of the incident timeline that begins with the recognition of a Possible contamination incident and ends with a determination regarding whether contamination is Credible. This includes the time required to perform multi-component investigation and data integration, implement field investigations (such as site characterization and sampling), and collect additional information to support the investigation.

Time for initial alert investigation. A portion of the incident timeline that begins with the recognition of an alert and ends with a determination regarding whether or not contamination is Possible.

Time-step. In the Cincinnati contamination warning system model, a set interval of time (i.e., every 15 minutes) at which the model performs calculations, reads inputs or generates outputs.

Toxic chemicals. Highly toxic chemicals that pose an acute risk to public health at relatively low doses.

Valid alert. Alerts due to water contamination, verified water quality anomalies (e.g., a change in water quality caused by work in the distribution system), or public health incidents.

Water Utility Emergency Response Manager. A role within the Cincinnati contamination warning system filled by a mid-level manager from the GCWW. Responsibilities of this position include: receiving notification of validated alerts, verifying that a valid alert indicates Possible contamination, coordinating the threat level determination process, integrating information across the different monitoring and surveillance components, and activating the consequence management plan.

Work Order. An internal record documenting the requirement for and execution of a utility-lead activity in the distribution system. For GCWW, water quality work orders, which are monitored by CCS, require the collection and testing of water samples from the location of a customer complaint.

Appendix A: Cincinnati Contamination Warning System Model

A.1 Overview of Contamination Warning System Model Architecture

To perform the simulation study, it was necessary to develop a detailed computer model of the Cincinnati Contamination Warning System (CWS). This model is comprised of sub-models representing the individual component of the CWS. The component models describe the data processing, decision logic, and sequencing steps that represent the activities executed by the corresponding component. Each component model consists of blocks referred to as modules. Modules represent a logical grouping of steps or a key function within the component model. Each module is parameterized using a variety of data sources as described in this appendix and operates on a set of inputs in order to produce a set of outputs that serve as inputs to a subsequent module.

To understand how the model functions, it is important to distinguish between model parameters, inputs and outputs:

- **Parameters**. Fixed values in the model that define important aspects of each component to accurately represent the physical system. Example parameters include the physical locations of monitoring stations and times necessary to complete various steps of the investigation process.
- **Inputs**. Values that will change during the course of the simulation study. An input may vary with respect to time, location or scenario. For example, an input is a contaminant concentration profile, which consists of concentrations at a particular location as a function of time for a specific scenario.
- **Outputs.** The results generated from a module or a model during the simulation. Some outputs are generated only once per scenario, while others are generated during multiple time-steps over the course of the scenario. Example model outputs include alerts generated by components or response actions implemented during consequence management.

The overall model architecture is depicted in **Figure A-1**. It includes a software application that models hydraulic and water quality conditions in a distribution system (EPANET), a Health Impacts and Human Behavior (HI/HB) model that simulates health consequences and human behaviors in response to various symptoms, models of the primary CWS monitoring and surveillance components (Enhanced Security Monitoring (ESM), Water Quality Monitoring (WQM), Customer Complaint Surveillance (CCS), and Public Health Surveillance (PHS), and a model of the Consequence Management (CM) process. The interconnecting lines depict how information flows among the models (e.g., outputs of each of the four monitoring and surveillance models serve as inputs to the CM model). The following sections describe each of the primary elements of the CWS model in greater detail.

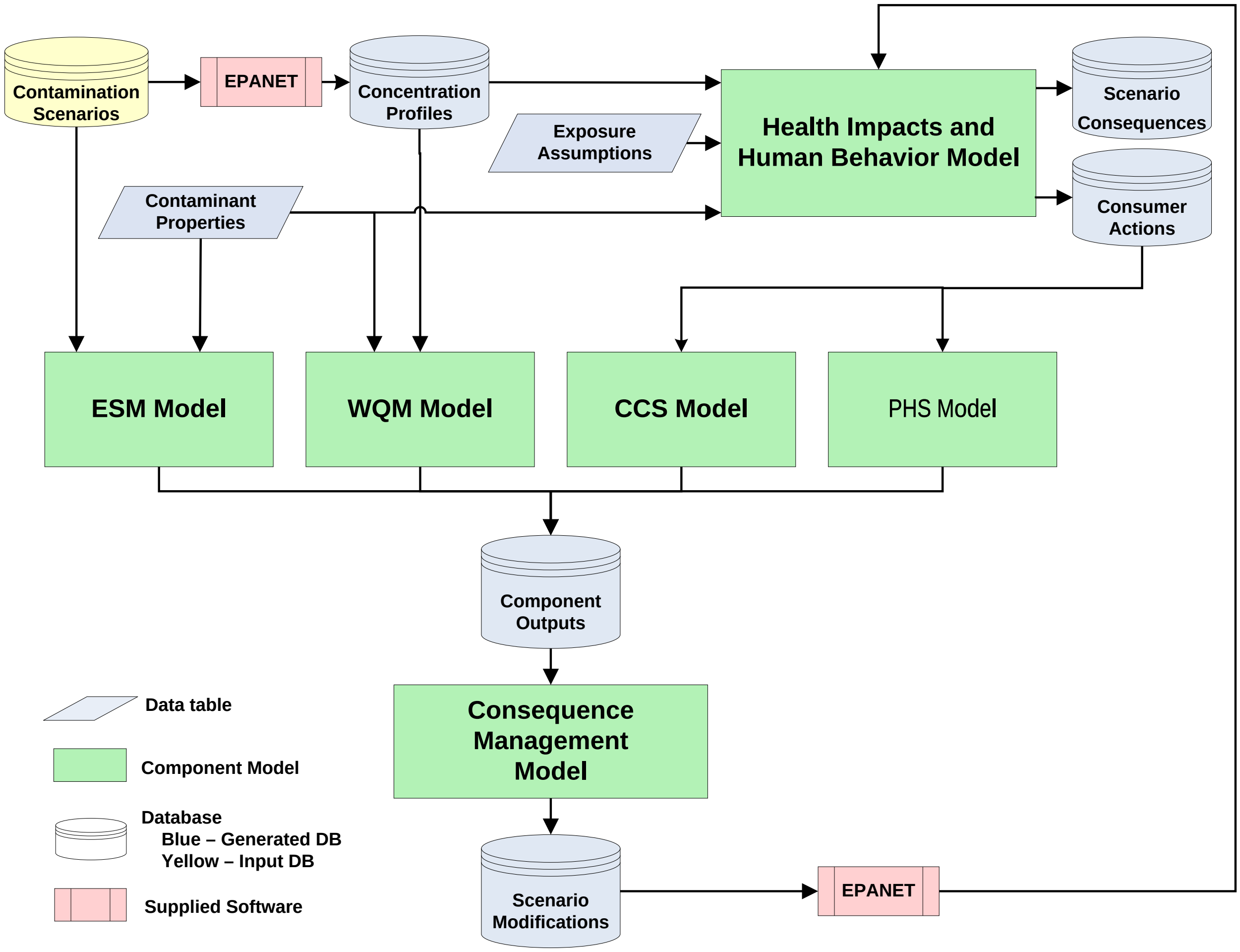

Figure A-1. CWS Model Architecture

This model operates in discrete time-steps (i.e., a set time interval) rather than continuously. While the inputs that govern operation of the CWS are changing constantly, it is impractical for the model to keep up with all the necessary calculations at every instant, and such data resolution does not produce more accurate predictions from the model. A practical solution to this challenge is to define a time-step at which point the most recent input values are used to calculate a new set of output values. For example, the concentration profile of a contaminant at a given point in the distribution system changes continuously, but usually in very small increments over very short time intervals. So instead of using every second of the contaminant concentration profile, it is approximated at a 15 minute time-step. Use of discrete time-steps reduces the quantity of data generated by the model by almost three orders of magnitude and drastically reduces run time without a significant loss in accuracy.

A.2 EPANET Toolkit

EPANET is a common hydraulic and water quality modeling application widely used in the water industry to simulate hydraulics and water quality through the distribution system (http://www.epa.gov/nrmrl/wswrd/dw/epanet.html#content). EPANET is used in conjunction with a distribution system model that represents the arrangement of pipes, pumping facilities and storage facilities in a utility’s distribution system. In the simulation study, EPANET along with the Greater Cincinnati Water Works (GCWW) distribution system model was used to produce contaminant concentration profiles at every node in the GCWW distribution system model.

The EPANET Toolkit is a dynamic link library and is utilized in the simulation model for automation of parameter adjustments, automation of hydraulic and quality simulation, and customized extraction of concentration profiles. Instead of needing to mine output data after the EPANET model finishes, the Toolkit allows the extraction of concentration data needed for the ESM, WQM and HI/HB models. This ability reduces file size and optimizes the entire process of extracting EPANET outputs.

A conceptual configuration of the EPANET model is shown in **Figure A-2**. To generate the contaminant concentration profiles, EPANET used the inputs that define the contamination scenario, which are listed in the input database icon shown in the figure and described in detail in **Table A-1**.

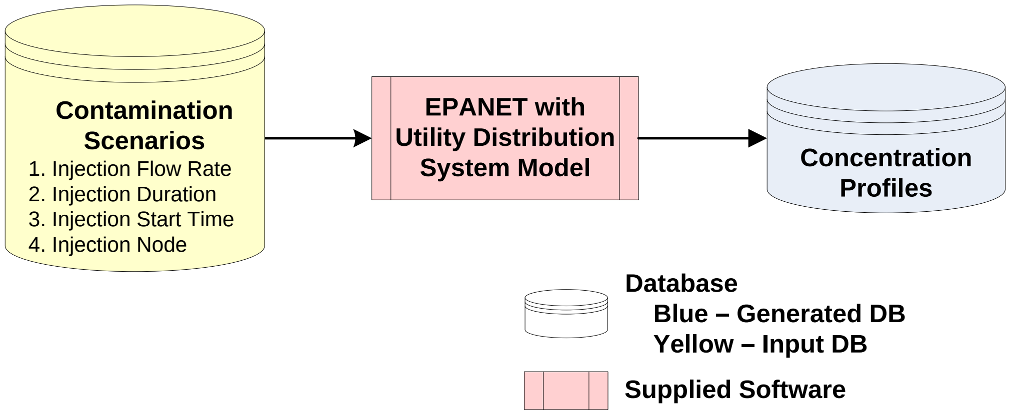

Figure A-2. EPANET Model

Table A-1. EPANET Inputs

Input	Description
Injection Node	The location of contaminant injection. It was assumed that all distribution system nodes in the system are potential injection locations with the exception of terminal points in the system and nodes that have no demand for water (i.e., they are not access points in the system).
Injection Time	The time at which a contaminant is injected into the distribution system at the injection node. Two injection times were selected: one representing a period of high demand and low pumping (9:00 a.m.), and the other representing a period of low demand and high pumping (12:00 a.m.).
Injection Rate	The mass flow rate of a contaminant being added to the distribution system at the injection location. Injection rates were selected to achieve a target concentration in the system that would result in harmful consequences (e.g., adverse public health or infrastructure contamination). Injection rates were calculated based on three typical flow rates in distribution pipes of various sizes.
Injection Duration	The continuous length of time the contaminant is injected into the distribution system at the injection node. The duration is calculated from the mass injection rate and the total mass of contaminant injected into the distribution system.

For each 15-minute time-step, concentrations at each node are recorded and stored as the model outputs shown in **Table A-2**.

Table A-2. EPANET Outputs

Output	Description
Node ID	Unique identifier for each node in the distribution system model.
Contaminant Concentration	The concentration of a contaminant (mg/L or organisms/L) at each node as a function of time.

Output	Description
Time of Concentration	The time at which a recorded contaminant concentration occurred at a specific node. Note that concentrations are recorded only at the times of exposure events, as described in Section A.3.

The concentration profiles generated by EPANET were used in the HI/HB model to determine the dose received by individuals exposed to contaminated water. The concentration profiles were also used as inputs to the WQM model to determine when and where WQM alerts are generated.

A.3 Health Impacts and Human Behavior

The HI/HB model was designed to simulate the health effects in the population served by the distribution system resulting from exposure to contaminated drinking water. The HI/HB model also simulates actions of individuals who either detect a problem with the drinking water or experience symptoms after being exposed to a harmful contaminant. This task is accomplished by tracking the health effects, actions and outcomes of each individual modeled in the simulation. The individual behaviors tracked in this model provide inputs for two of the contamination warning system components: calls to the utility provide inputs to the CCS model and health seeking behaviors provide inputs to the PHS model. Furthermore, the cumulative outputs from this model determine the overall public health consequences (illnesses, fatalities and healthcare burden) of each scenario.

Figure A-3 shows the relationships among the several modules and queues (shown as green rectangles and parallelograms) that comprise the HI/HB model, along with the outputs generated by the model (blue parallelograms). The HI/HB model first uses the output from EPANET to execute the exposure module, which determines the contaminant dose at each node in the distribution system model during each time-step of the simulation.

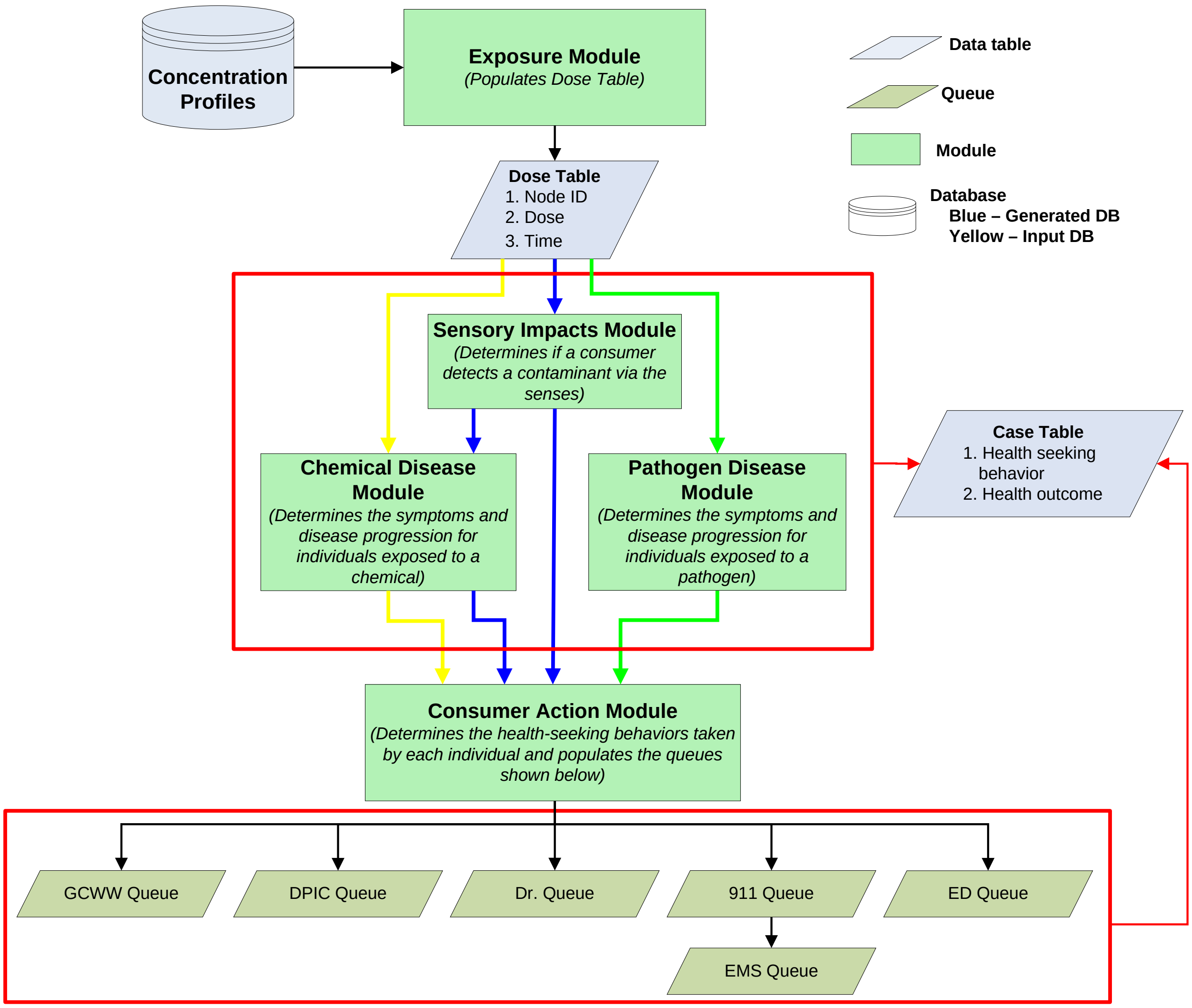

Figure A-3. Health Impacts and Human Behavior Model

The Exposure module calculates the cumulative dose for exposed individuals, which is then used by the Health Impact modules to determine the health impacts experienced by each exposed individual. In addition to the output from EPANET, the Exposure module also uses the time of public notification, which is outputted by the consequence management model. This time is used to determine the time when a compliant individual stops using the water and thus experiences no further increase in their cumulative dose. Three pathways are possible through these modules, depending on whether the contaminant is detectable by individuals through a taste or odor, and whether the contaminant is a chemical or a pathogen. Each individual who either detects the contaminant or receives a dose sufficient to produce health effects becomes a “case” in the Case Table. The disease progression timeline and ultimate outcome of each individual are tracked in the Case Table.

The HI/HB model includes three health impacts modules: Sensory Impact, Chemical Disease and Pathogen Disease. The Sensory Impact module is used to determine whether or not an exposed individual detects the contaminant through the senses, based on the concentration in the water at the time of the exposure event and a detection threshold for the specific contaminant. The two disease modules include the logic and parameters to determine the disease progression timeline, expression of symptoms, and ultimate health outcome based on the cumulative dose received.

The various symptoms and sensory perceptions experienced by each affected individual are inputs to the Consumer Action module, which determines the actions taken by each individual in response to their condition. Available actions include: doing nothing, calling GCWW, calling the Drug and Poison Information Center (DPIC), calling 911, visiting a primary healthcare doctor, visiting the emergency department (ED) or administering self-treatment (not shown in the figure). Individuals may also receive prophylactic treatment for some contaminants once the contaminant identity is known. The specific actions selected by an individual are based on the contaminant type, symptom level, and demographic characteristics of each individual. Data from literature reviews was used to estimate the percentage of symptomatic individuals in each demographic group that would pursue each of the available options at each stage of disease progression (Bertakis et al., 2000; Schappert and Bert, 2006).

For each time-step, individuals are processed up to the number that can be handled by the available capacity of the queues at that time. With one exception, the queues operate on a first in first out basis. The ED queue includes a triage function such that individuals with more serious symptoms are automatically moved ahead of individuals with less serious symptoms. When an individual is processed, the queue and treatment information is added to their record in the Case Table, and then one of the following occurs:

- Each individual is automatically moved to a new queue due to a referral or queue logic. For example, a call to 911 always results in an Emergency Medical Service (EMS) response, which represents the policy of the City of Cincinnati Fire Department. Therefore, when someone is processed in the 911 queue, they automatically move to the EMS queue.
- Individuals will take another action if they wait too long in their current queue (e.g., they will drive themselves to the ED if an EMS unit has not arrived in a specified amount of time), or, if their symptoms worsen while waiting in one queue, they may be switched to another queue (e.g., if a person waiting for prophylactic treatment becomes symptomatic, they leave the prophylaxis queue and enter the ED queue).
- The individual is done taking action and has been processed through the appropriate queues. All cases eventually arrive at this point, where logic within the queue processing routine is used to determine if the individual received effective medical treatment.

All queues are defined by two ceilings on capacity: one representing normal, non-emergency conditions, and the other representing mobilization of additional resources during response to a recognized public health crisis. The capacity ceiling of some queues is fixed over a 24/7 period, while other ceilings vary with the time of day and day of the week. Each queue also has an associated mean processing time that quantifies the length of time that a particular resource is committed to a specific individual. Finally, some queues have a maximum wait tolerance that defines the length of time that an individual will remain in the queue before they exit the queue and pursue another option.

The model executes all the routines depicted in Figure A-3 to initially populate the Case Table. The model does not operate on each time-step over the duration of the simulation, as this would result in unnecessary computing overhead. Instead, the model determines when the next action takes place and produces outputs only during those time-steps. This approach reduces the model run time significantly.

The primary inputs to the HI/HB model, shown in **Table A-3**, are the contaminant concentration profiles at each distribution system model node, attributes of each node (e.g., population at the node), and attributes of the contaminant used in the scenario (e.g., health effects parameters). This input data is passed to the Exposure module, which includes parameters that define exposure events, such as the time of consumption or showering events and the volume of water used during each event. The Exposure module calculates the cumulative dose for exposed individuals, which is then used by the Health Impacts modules to determine the health effects experienced by each exposed individual.

A pre-defined sequence of exposure events is used by this model, which establishes central tendencies in the timing of consumption and showering. The central tendency in the timing of the consumption events, as well as the volume consumed, is based on surveys of drinking water usage in the United States (Davis and Janke, 2008; USEPA, 2007). Based on the results of these studies, the model uses five consumption events per day, roughly corresponding to three meals and two breaks between the meals. In addition, children and adults are assumed to take one shower per day in the morning hours (USEPA, 1997), during which there is the potential for inhalation of aerosolized water droplets containing the contaminant. In the model, it was assumed that infants do not take showers. While one time of day is selected for each of these exposure events, these times represent a central tendency in consumption behavior. The actual time at which individuals consume water (or take a shower) is governed by a normal distribution around the central tendency.

Table A-3. HI/HB Model Inputs

Input	Description
Contaminant ID	Sanitized identifier for the contaminant used in the scenario. Linked to the appropriate contaminant attributes described in Table A-4.
Contaminant Concentration	The concentration of a contaminant (mg/L or organisms/L) at each node as a function of time. These values are outputs from EPANET.
Time of Exposure	The time that an individual is exposed to drinking water during consumption or showering events. The timing of the consumption events is based on surveys of drinking water usage in the United States (Davis and Janke, 2008; USEPA, 2007). Based on the results of these studies, the model uses five consumption events per day (07:00, 09:30, 12:00, 15:00, 18:00), roughly corresponding to three meals and two breaks between the meals. The model uses one showering event per day at 07:00.

Parameters for the HI/HB Model are listed in **Table A-4**. Key parameters include detection threshold concentrations, as well as the cumulative dose that would produce mild, moderate and severe symptoms in an exposed individual. There are also model parameters that govern the probability of infection in the case of a pathogen, or fatality in the case of a toxic chemical or biotoxin, as a function of cumulative dose received.

Once the threshold is surpassed for a specific age group at a specific node, all individuals at that node who are still using the water will experience the symptoms associated with that threshold. Each individual will likely take action based on the symptoms they experience, as determined by the Consumer Action module, and these actions can vary for each individual assigned to that node.

Table A-4. HI/HB Model Parameters

Parameter	Description
Node ID	Unique identifier for each node in the distribution system.
Population	The number of consumers at each node in the distribution system, including the distribution of this population among the following five demographic groups: children (younger than 18 years, further subdivided into infants younger than 1 year and older children); adult females (18 to 65 years); adult males (18 to 65 years); senior females (older than 65 years) and senior males (older than 65 years). Population was calculated by Threat Ensemble Vulnerability Assessment using nodal demands from the GCWW distribution system model.

Parameter	Description
Consumption Volume	The volume consumed by an individual over a 24-hour period, specifically defined for infants, children, and adults. The total volume consumed by an infant in the model is 0.30 L/d, by a child is 0.595 L/d and by an adult is 1.41 L/d distributed over five ingestion events. The volume inhaled by a child or an adult during the showering event is 0.00006 L/d. The model assumes no exposure due to showering for infants. The volume consumed during a consumption event is based on surveys of drinking water usage in the United States (Davis and Janke, 2008; USEPA, 2007).
Detection Threshold and Probability	The concentration of a specific contaminant, above which it can be detected through the senses (taste, odor, or irritation), and the probability that an individual exposed to a contaminant at concentration at or above the threshold will detect it. The threshold and probabilities for detecting a contaminant are based on data reported in the literature for each specific contaminant. In cases where such data was not available, it was assumed that between 90 and 100% of the population would detect the contaminant.
Threshold Doses for Symptoms	The dose of each contaminant that produces mild, moderate, and severe symptoms. All thresholds are contaminant-specific attributes that determine the type and severity of symptoms based on the cumulative dose received. Values were derived from expert judgment of medical specialists and toxicologists, October 13, 2009.
Symptom Onset Delays	The time delay between exposure to a contaminant above a threshold dose and the onset of symptoms. Specific onset delays are defined for each contaminant and each symptom level: mild, moderate, and severe. Values were derived from expert judgment of medical specialists and toxicologists, October 13, 2009.
Threshold Doses for Fatality	Points distributed along the dose response curve that relate the cumulative dose received by an individual to the probability of death. Values were derived from an extensive review of contaminant databases and peer reviewed literature.
Fatality Onset Delay	The time delay between exposure to a lethal dose of a contaminant and death. Values were derived from an extensive review of contaminant databases and peer reviewed literature. The dose is cumulative over the simulation duration, but the model does include metabolic degradation of contaminants post-exposure.
Probability of Fatality with Medical Treatment	The probability that an individual exposed to a lethal dose of a contaminant will die after receiving effective medical treatment. Values were derived from expert judgment of medical specialists and toxicologists, October 13, 2009.
Probability of Fatality if Untreated	The probability that an individual exposed to a lethal dose of a contaminant will die at the end of the disease (after the fatality onset delay) in the absence of medical intervention. Values were derived from an extensive review of contaminant databases and peer reviewed literature.
Queue Capacity	A time series for each queue showing the maximum number of individuals that can be processed simultaneously based on the available resources at the current time-step (e.g., available operators, open hospital beds, etc.). Two capacity ceilings are defined for each queue: one reflecting normal, non-emergency conditions; and the other reflecting mobilization of additional resources in response to an emerging public health crisis. The capacity ceiling parameters were provided by each department for normal business hours, non-business hours, and emergency conditions.
Processing Times	The time it takes to process an individual in a queue (e.g., call processing time, EMS transport time, etc.). Along with the queue capacities, this determines when resources are available to process additional individuals. The processing time for an individual to complete each queue was provided by each department.
Treatment Window	The amount of time, relative to the onset of disease, within which treatment must be received in order to be effective. The size of the treatment window is specific to each contaminant. Values were derived from expert judgment of medical specialists and toxicologists, October 13, 2009.
Effective Treatments	An indicator regarding which of the following treatment alternatives may prove effective following exposure to a specific contaminant: self-treatment, treatment by a primary care physician, treatment by an EMS technician, and treatment by an ED physician. The parameter also indicates whether or not the treatment alternative is limited due to a finite resource. Values were derived from expert judgment of medical specialists and toxicologists, October 13, 2009.
Threshold Number of Cases for a Differential Diagnosis	For each contaminant and associated symptom level, the number of individuals experiencing those symptoms that must be seen in the ED to cause public health officials to tentatively identify the causative agent. Values were derived from expert judgment of medical specialists and toxicologists, October 13, 2009.

Parameter	Description
Threshold Number of Cases for Public Health Response	For each contaminant, the total number of individuals that must been seen in the ED before public health officials recognize an emerging public health crisis. Values were derived from expert judgment of medical specialists and toxicologists, October 13, 2009.
Health Seeking Behaviors	The probability that an individual will pursue each of the following health seeking behaviors: do nothing, self treat, call GCWW, call DPIC, call 911, visit a doctor, or visit the ED. Unique probabilities are assigned to each combination of contaminant, symptom level, and demographic group. The probabilities change after public notification has been issued to better align healthcare choices with effective treatments. Information obtained from literature reviews was used to estimate the percentage of symptomatic individuals in each demographic group that would pursue each of the available options based on the specific symptoms they experience (Bertakis et al., 2000; Schappert and Bert, 2006).

The HI/HB model executes the Exposure module, the appropriate Health Impact module, and the Consumer Action module to populate the Case Table. The Consumer Action module generates information about the action taken by each individual and saves this information to the appropriate record in the Case Table. If an individual receives effective medical treatment, the time of treatment is recorded. If the individual does receive effective medical treatment in a defined window of opportunity relative to the time of disease onset, that individual's probability of dying is reduced, and their outcome is determined using this lower mortality rate. The efficacy of various treatment options, as well as the window of opportunity for treatment, is dependent upon the contaminant and associated disease.

The Case Table records the outputs shown in **Table A-5**, including: the timeline of the health impacts, actions taken by each individual, and outcome of each individual. The fully populated Case Table provides information used as inputs to the other models shown in Figure A-1.

Table A-5. HI/HB Model Outputs

Output	Description
Case ID	A unique identifier for each individual exposed to contaminated water during a contamination scenario.
Location ID	The specific distribution system model node that the individual is assigned to for all exposure events (i.e., home location).
Time of Stop Use Compliance	The date and time that an individual stops using contaminated water due to compliance with a "do not use" notice from the water utility. A distribution of times ranging from 30 min to 10 hours after issuance is assumed for compliance with a "do not use" notice, and the model assumes that approximately 10% of the population will never comply. Also, individuals will immediately stop using water if they detect the contaminant through the senses.
Time of Detection	The date and time that an individual detects contaminated water via the senses.
Time of Infection	The date and time that an individual is either infected with a pathogen or becomes symptomatic due to chemical exposure.
Time of Symptoms	The date and time that an infected individual experiences each discrete level of symptoms: mild, moderate, and severe.
Time of Health Seeking Behavior	The date and time that an individual takes various actions in response to their current condition. Times are recorded for each health-seeking behavior option that an individual takes over the course of the scenario.
Time of Medical Treatment	The date and time that an individual receives health care that effectively treats their condition. If effective medical treatment is received in time, the individual's prognosis improves.
Time of Death	The date and time that an individual dies due to exposure to the contaminated water. This field is blank if the individual recovers or never receives a fatal dose of contaminant.
Differential Diagnosis Confidence	A time series of values between 0 and 2 indicating the confidence of public health officials in the identity of the contaminant responsible for illnesses observed in the ED. Confidence in the identity of the contaminant can range from nil (0) to absolute certainty (2).
Times Public Health Response is Activated	The date and time when each effective public health response (e.g., instructions provided to health partners, mobilization of additional hospital personnel, etc.) has been implemented. These times establish when expanded queue capacities and improved medical referrals will be in effect.

Other key outputs from the HI/HB model include the time that additional resources are available to healthcare providers for the purpose of treating patients. Specifically, the output from the Public Health Response module will determine when the expanded queue capacities are in effect.

A.4 Enhanced Security Monitoring

The ESM model was designed to simulate the systems, equipment, and procedures that detect and respond to security breaches at distribution system facilities (e.g., pump stations, storage tanks, etc.) that are vulnerable to contamination. For each distribution system facility considered, the model uses site-specific information about the path between an assumed point of entry and an assumed point of contaminant introduction, the steps required to introduce the contaminant, and the path of egress from the facility following the completion of the attack. The model assumes that all attacks would use a pump to inject the contaminant, and that the attacker would leave as soon as they started pumping the contaminant into the distribution system.

The model also simulates the physical security alerts and monitoring systems for the facility that have been breached in order to generate the alert that would be displayed to security personnel. Following alert recognition, the model simulates the alert investigation process based on the procedures used by GCWW personnel.

Figure A-4 provides an overview of the ESM model showing the relationships among the three modules, shown as green rectangles, which comprise the model: ESM Intrusion module, ESM Alert Generation module and ESM Alert Investigation module. The inputs to and outputs from each module of the ESM model are shown as blue parallelograms.

The first module that operates is the Intrusion module. Here, location-specific attack and retreat times are used for each ESM location, based on site-specific factors such as intrusion entry points, access points to drinking water, and feasible injection volumes. Attack and retreat times serve as inputs to the Alert Generation module, which accounts for processing time for monitoring devices, as well as alert and video transmission times.

The ESM alerts are transmitted to the Alert Investigation module, which simulates the actions that would be taken by GCWW personnel in response to ESM alerts. This module is based on alert investigation procedures developed for the ESM component and timeline metrics characterized during drills, exercises, and routine operation of the CWS. These metrics account for the time required to recognize the alert and perform a variety of investigative functions, including a review of video clips, if available, and on-site inspection of the ESM site. The outputs from this module include the time of key notifications, the time investigators arrive on site, the time that contaminant injection is interrupted and the ESM confidence index.

The ESM confidence index is an overall indicator of the reliability of the information from the ESM component, considering all available data from all ESM alerts and the ongoing investigation. The value of the ESM confidence index will change over time as the investigation progresses. An ESM alert could result in Possible, Credible, or Confirmed contamination without additional information from another component. Under the model assumptions, an ESM alert can result in a Possible determination if there is no employee call-back following a brief waiting period after the alert is received. ESM can result in a Credible determination under either of the following conditions: 1) observation of signs of tampering during site investigation, and 2) conclusive video evidence of an intrusion and pumping equipment at a utility facility. Finally, ESM can provide sufficient information to Confirm contamination if GCWW responders observed an ongoing injection during a site inspection.

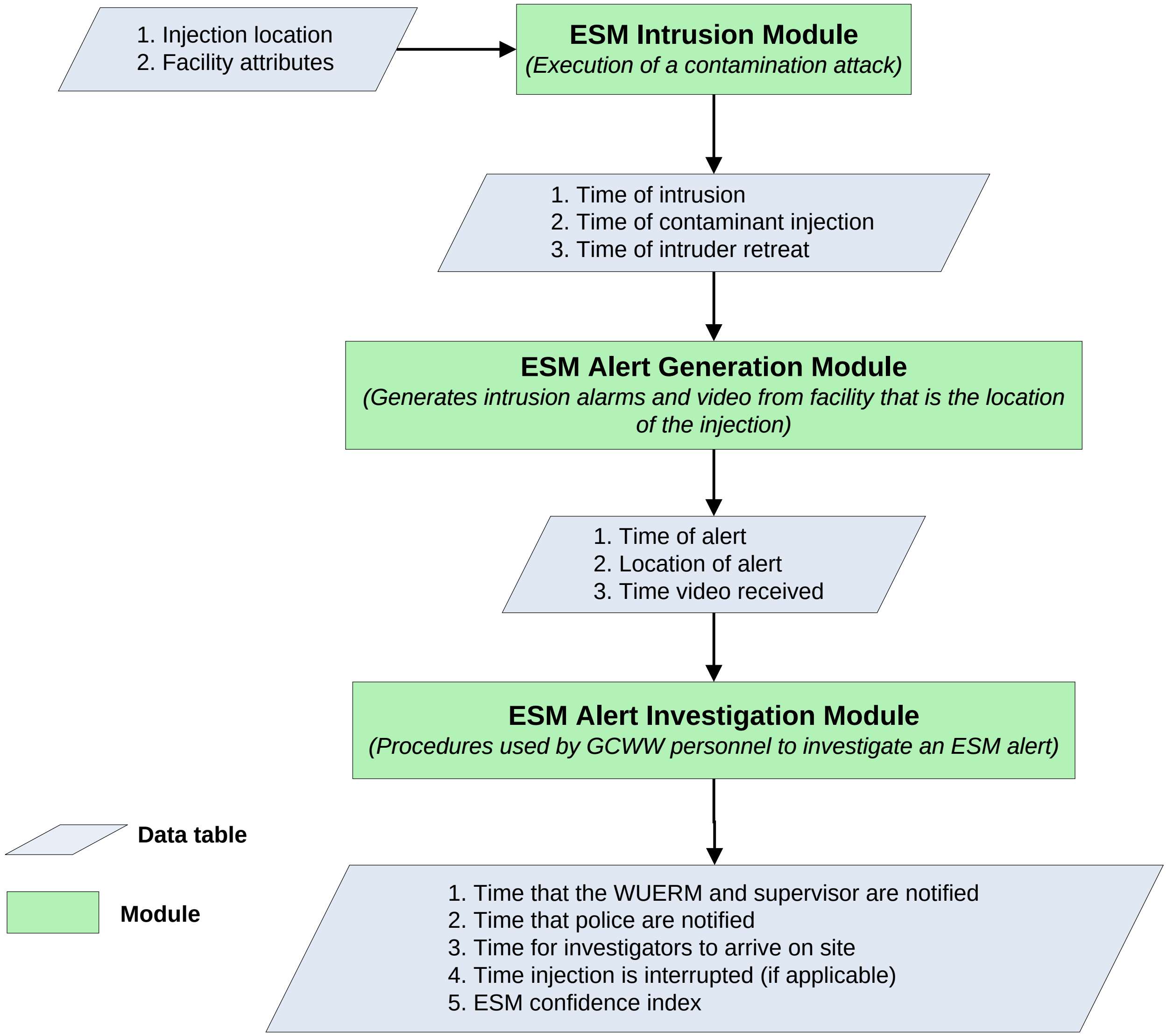

Figure A-4. Enhanced Security Monitoring Model

The primary inputs to the ESM model are shown in **Table A-6** and include: the intrusion location, injection start time, and injection duration. The ESM model will be activated only if the injection location (node) occurs at one of the ESM sites.

Table A-6. ESM Model Inputs

Input	Description
Location of Intrusion	The node at which the contaminant is introduced under the conditions of the scenario. The ESM model will be activated only if the attack node is associated with a utility facility with ESM capabilities.
Scenario Start Time	The date and time that the scenario starts, at which point the perpetrators start introducing the contaminant into the distribution system from the location of intrusion.
Duration of the Injection	The total time that the equipment is actively injecting the contaminant into the distribution system at the location of intrusion. The injection duration was determined using EPANET to ensure that the contaminant is spread through the distribution system at potentially harmful concentrations.

Parameters for the ESM model are listed in **Table A-7**. Key parameters include attack and retreat times, as well as the response times for GCWW security personnel and law enforcement personnel to travel to the location of the ESM alert.

Table A-7. ESM Model Parameters

Parameter	Description
Attack and Retreat Times	Specific attack and retreat times were derived for each ESM site. The time to attack and retreat was based on the specific layout of each facility and the specific location in the facility from which the injection would occur. Times to execute various actions were provided by Sandia National Labs, the American Water Works Association (AWWA), and estimates from security experts.
Video Surveillance	The location-specific information regarding the presence/absence of video equipment at the ESM site. This information is based on the physical design of the ESM component of the Cincinnati CWS.
Alert Transmission Time	Time to transmit an alert intrusion signal from the remote programming logic controller to the SCADA user interface at the control center (five seconds). Times were directly measured from the physical system.
Employee Call in Wait Time	The time for an operator to wait for an employee to call in after entering a remote GCWW facility. Time is documented in GCWW procedures.
Video Clip Transmission Time	Time to transmit a video clip from the remote facility to the SCADA user interface at the control center (three minutes). Times were directly measured from the physical system.
Time to Contact Local Law Enforcement	The time it takes for the utility control center operator to dial 911 and inform the 911 dispatcher of the intrusion event. The values for this parameter were obtained from drills and exercises performed during the evaluation period of the Cincinnati pilot.
Time to Contact GCWW Security	The time it takes for the utility control center operator to dial GCWW Security and inform the guard of the intrusion event. The values for this parameter were obtained from drills and exercise performed during the evaluation period of the Cincinnati pilot.
Law Enforcement Response Time	The time it takes for local police to reach the location of the ESM alert. The values for this parameter were obtained from average law enforcement response times.
GCWW Security Response Time	The time it takes for GCWW Security to reach the location of the ESM alert. The values for this parameter were obtained from online mapping software.
Site Investigation Time	The site-specific time it takes for the Plant Supervisor to conduct an investigation at the location of the ESM alert. The values for this parameter were obtained from drills and exercises performed during the evaluation period of the Cincinnati pilot.

The primary outputs from the ESM model are shown in **Table A-8**, and include the time the alert is received, the time at which various responders arrive on site, and the time at which the site investigation is completed. If responders arrive on site in time to interrupt the injection, that time is also outputted by the model. Another important output, which is an input to the downstream Consequence Management model, is the ESM confidence index.

Table A-8. ESM Model Outputs

Output	Description
Time of Alert	The date and time when the ESM equipment detects intrusion into a utility facility, generates an alert, and transmits that alert to the SCADA user interface.
Time of WUERM Notification	The date and time when the utility control center operator or Plant Supervisor contacts the WUERM after completing the ESM investigation.
Time of Law Enforcement Response	The date and time when local law enforcement arrives on-site.
Time of GCWW Security Response	The date and time when GCWW Security arrives on-site.
Time of Site Investigation	The date and time when the Plant Supervisor completes their investigation of the site of the suspected intrusion.

Output	Description
Time the Injection is Interrupted	The date and time when the injection is stopped by investigators from GCWW, if the time that responders arrive at the injection location occurs prior to the time the injection would be completed.
ESM Confidence Index	A time series of values from the ESM component indicating the reliability of information available from the investigation of the ESM alert and the degree of confidence in the suspicion that the drinking water has been contaminated.

A.5 Water Quality Monitoring

The WQM model was designed to simulate the network of monitoring stations throughout the GCWW drinking water distribution system and the associated investigative procedures designed to detect unusual water quality conditions. The network consists of fifteen WQM stations in the distribution system, which monitor for the following parameters: free chlorine (CL2), specific conductivity (COND), oxidation reduction potential (ORP), pH and total organic carbon (TOC).

Data generated by the network of monitoring stations is transmitted to an operations center where it is continuously analyzed for potential anomalies by an event detection system. When an anomaly is detected, an alert is generated and displayed on a user interface. GCWW personnel follow a standardized alert investigation procedure to determine the cause of the alert. If the alert cannot be attributed to a benign or known cause, contamination is considered Possible.

Figure A-5 provides an overview of the WQM model, showing the relationships among the modules and software applications that comprise the model. The three modules, shown as green rectangles, which constitute the WQM model include: Contaminant Profile Simulator module, WQM Alert Processing module, and WQM Alert Investigation module. Additionally, the WQM model incorporates the CANARY software application, shown as a pink rectangle, which is the event detection system used at the Cincinnati pilot. The inputs to and outputs from each module of the WQM model are shown as blue parallelograms.

The Contaminant Profile Simulator uses contaminant-specific correlation factors to simulate the change in water quality due to the presence of a specific contaminant. The inputs to this module include the baseline water quality data from the GCWW pilot as well as the simulated contaminant concentrations produced by EPANET. By applying the correlation factors to the contaminant concentration profiles, the Contaminant Profile Simulator generates a time series of changes in each water quality parameter. These changes are superimposed on GCWW baseline water quality data to generate water quality parameter values that reflect the impact of the contaminant concentration at each monitoring location.

The Contaminant Profile Simulator provides the input water quality parameter dataset analyzed by CANARY, which uses a linear filter algorithm to search for anomalies. Specifically, this algorithm uses historic water quality data to predict water quality at the next time step. Differences between the current water quality value and the predicted value are recorded and compared to a threshold value. Additionally, the differences across all sensors can be joined to create a combined difference value. If the threshold value is exceeded, CANARY generates an alert.

Once an alert is generated, the WQM Alert Processing module simulates the time delay between detection of the anomaly at the monitoring station and display of the alert on the SCADA user interface. The delay is due to data transmission and event detection processing time, and while on the order of only a few minutes, it is still accounted for.

The alert investigation process begins when the Water Quality and Treatment (WQ&T) Chemist is notified of the alert. The investigation includes a decision point where the investigation of the alert may be terminated unless a priority water quality parameter, specifically TOC or CL2, is included in the trigger parameters for the alert. The prioritization of trigger parameters and relative changes that warrant further investigation are based on data collected from WQM alert investigations during the Cincinnati pilot. The investigation continues with a simultaneous review of water quality data (by the WQ&T Chemist) and distribution system operations (by the Operator). After completion of these reviews, distribution system work orders are reviewed to determine whether recent or ongoing work in the system could have caused the water quality that generated the alert.

Once the review of water quality data, operational data, and distribution system work orders has been completed, three actions are implemented: 1) the Water Utility Emergency Response Manager (WUERM) is notified of the WQM alert, 2) a remote sample is collected at the WQM station that produced the alert, and 3) all downstream WQM stations are set to automatically collect a sample after any subsequent alert is generated. If no cause for the alert has been identified thus far, the WQM station that generated the alert is inspected by a technician. The model accounts for the time required for the technician to gather equipment and drive to the location of the WQM station. The model further assumes that the technician verifies that all instrumentation is functioning properly, and thus faulty readings are ruled out as a potential cause of the alert. The outputs from this module include the time when results from the investigation are reported to the WUERM, the time of sample collection, and the WQM confidence index.

The WQM confidence index is an overall indicator of the reliability of the information from the WQM component and the degree of confidence in the suspicion that the drinking water has been contaminated. The value of the WQM confidence index will change over time as the investigation progresses. Under the model assumptions, the following conditions can lead to a determination that contamination is Possible:

1. Completion of the investigation of a single WQM alert for which no benign cause is identified,
2. During the investigation of the first WQM alert, a second WQM alert occurs at a WQM station that is hydraulically connected to the first, or
3. During the investigation of one WQM alert, the WUERM discovers that other component(s) have detected potential indicators of contamination that are consistent with the information from the WQM alert.

The WQM component can also produce information sufficient to establish that contamination is Credible if two hydraulically connected WQM stations alert due to low chlorine residuals and the site inspection has been completed for the first alert.

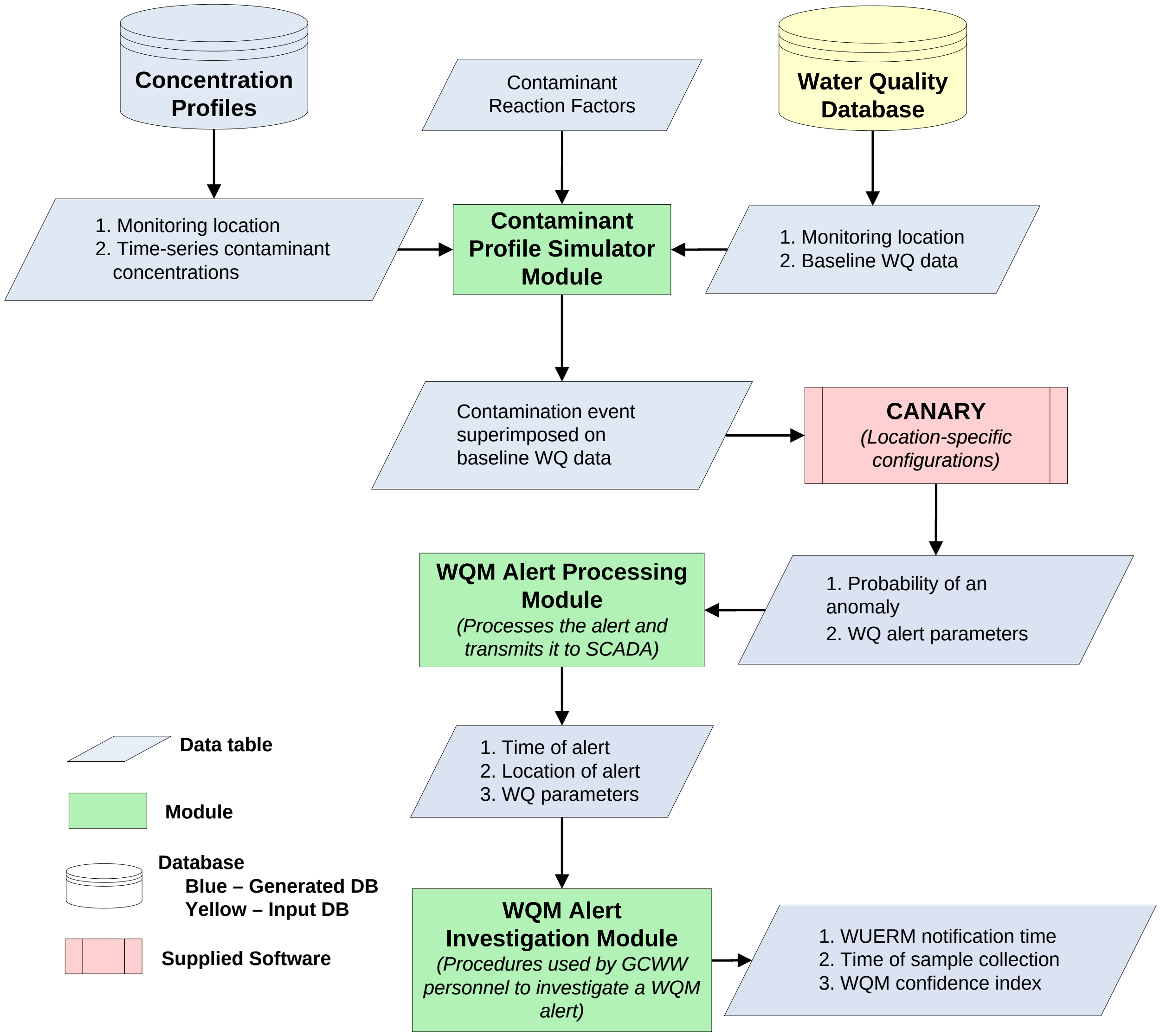

Figure A-5. Water Quality Monitoring Model

The primary inputs to the WQM model are shown in **Table A-9** and include: the contaminant identification, contaminant concentration profiles, and baseline water quality data. This information, along with key parameters described below, is used to create a dataset for each monitoring station that simulates the change in water quality resulting from contamination superimposed on baseline water quality data.

Table A-9. WQM Model Inputs

Input	Description
Contaminant ID	Sanitized identifier for the contaminant used in the scenario. Linked to the appropriate contaminant attributes described in Table A-4.
Contaminant Concentrations	For each scenario, the concentration of the contaminant (mg/L or organisms/L) at each WQM location as a function of time. These values are outputs from EPANET.
Baseline Water Quality Data	The baseline data captures CL2 (mg/L), TOC (mg/L), pH, ORP (mV) and COND (uS/cm) values that were reported for each time-step during the time period being modeled in the simulation study for each monitoring location. The same baseline water quality data is used for all scenarios. This baseline data was obtained from WQM instrumentation during the evaluation period of the Cincinnati pilot.

Parameters for the WQM model are listed in **Table A-10**. Key parameters include alert processing time, time for initial investigation, the time to conduct a WQM site investigation, and the contaminant-specific reaction factors.

Table A-10. WQM Model Parameters

Parameter	Description
Polling Interval	Established time between WQM data collection events by the SCADA system (2 minutes).
Alert Processing Time	Time for data transmission and processing time between CANARY and SCADA. The values for these parameters were obtained from direct measurements of SCADA system performance.
Time for Initial Investigation	Time required for GCWW staff to review water quality data and distribution system operations during investigation of a WQM alert (first alert only). In the case of subsequent alerts, an abbreviated investigation is performed that evaluates the connectivity among alerting stations. The values for this parameter were obtained from drills and exercises performed during the evaluation period of the Cincinnati pilot.
Time to Conduct WQM Site Investigation	For each monitoring station, the time needed to perform the complete set of instrument checks and rapid field tests on water collected at the WQM station. Note that the WQ&T Technician keeps in constant contact with the WUERM, so results are reported to the WUERM immediately. The values for this parameter were obtained from drills and exercises performed during the evaluation period of the Cincinnati pilot.
Contaminant-Specific Reaction Factors	For the given contaminant, empirical factors relating the concentration of the contaminant to a subsequent change in the value of the following water quality parameters: CL2, TOC, pH, ORP, and COND. These correlation factors were derived from the results of bench-scale contaminant spiking studies (Hall, et al., 2007).

The primary outputs from the WQM model are shown in **Table A-11**, and include the time the alert is received, WUERM notification time, field safety screening results, water quality testing results, and the WQM confidence index.

Table A-11. WQM Model Outputs

Output	Description
WQM Location ID	Unique identifier for each WQM location that produces an alert during the simulated scenario.
WQM Alert Start Time	The date and time at which each unique WQM alert is first displayed on the SCADA user interface.
WUERM Notification Time	The date and time at which the WUERM is notified of each unique WQM alert.
WQM Sample Collection Time	The date and time when a water sample was collected (using a remote controlled sampling system) from an alerting WQM station.
Field Safety Screening Results	The date, time, and results (“normal” or “abnormal”) for all field safety screening performed during site investigations within the WQM component. Based on scenario assumptions, the results of field safety screening will be “normal” at locations other than the site of contaminant injection.
Water Quality Testing Results	The date, time, and results (“normal” or “abnormal”) for all water quality testing performed during site investigations in response to a WQM alert. The design of the model assumes that the results of water quality testing demonstrate that the monitoring station is performing correctly.
WQM Confidence Index	A time series of values from the WQM component indicating the reliability of information available from the investigation of the WQM alert and the degree of confidence in the suspicion that the drinking water has been contaminated.

A.6 Customer Complaint Surveillance

The CCS model was designed to simulate the systems and procedures used by GCWW to detect contamination through calls from customers reporting aesthetic changes to the quality of their drinking water. Customers may detect contaminants with characteristics that impart an odor, taste, or visual change to the drinking water, or that result in instantaneous yet minor symptoms, such as a mild irritation.

In the CCS model, all customers in the GCWW service area have the potential to detect contaminants that change the aesthetic characteristics of the drinking water. Customers exposed to water contaminated at concentrations above the contaminant-specific detection threshold may detect the contaminant, and may call the utility. Calls to the utility are tracked through an interactive voice response system (IVR), which includes a menu option specific to water quality issues.

Figure A-6 provides an overview of the CCS model showing the relationships among the three modules, shown as green rectangles, that constitute the model: a Work Order (WO) Generation module, CCS Event Detection module, and CCS Alert Investigation module. The inputs to and outputs from each module of the CCS model are shown as blue parallelograms.

Calls to the utility reporting water quality problems are generated by the HI/HB model, as described in Section A.3, and are one of the primary inputs to the CCS model. The first module that operates is the WO Generation module. In this module, work orders are created in response to customer calls reporting water quality concerns. The model assumes that each call reporting a water quality issue is converted into a new WO, which is consistent with GCWW’s procedures. The customer calls that are tracked through the IVR and WOs are inputs to the Event Detection module.

The Event Detection module simulates the event detection systems used in the CCS component of the Cincinnati CWS, which analyzes both the IVR and WO data streams using the following three algorithms:

- **One Day, Weekday Scan.** Monitors current data and evaluates it against recent historic data. If the number of IVR selections or WOs in the previous 24 hours equals or surpasses the threshold, an alert is generated. Does not operate between 12:00 a.m. Saturday morning through 11:59 p.m. Sunday night.
- **One Day, Weekend Scan.** The same as the One Day, Weekday Scan, but applies only to the hours between 12:00 a.m. Saturday morning through 11:59 p.m. Sunday night.
- **Two Day Scan.** Monitors current data and evaluates it against recent historic data. If the number of IVR selections or WOs in the previous 48 hours equals or surpasses the threshold, an alert is generated.

The one day scans have a reset function such that if an alert is generated, the algorithm begins counting from zero again starting at the time of alert. Any data contributing to previous alerts cannot contribute to the count triggering subsequent alerts, even if it falls in the 24 hour period. Thus, many one day alerts could result from a surge of IVR selections or WOs. The two day scan is continuous and will not alert until the number of calls or WOs in the previous 48 hours falls below the threshold before surpassing it again. Thus, a surge of IVR selections or WOs would likely result in only one alert from the two day scan, as the algorithm would remain above the threshold during the event. The alerts generated by the Event Detection module serve as the inputs to the CCS Alert Investigation module.

The Alert Investigation module simulates GCWW’s procedures for investigating a CCS alert, which includes an assessment of the underlying complaints for clustering and similar problem descriptions as well as possible benign explanations for the alerts such as distribution work or operational changes. Additionally, recent water quality data in the area of the complaints is reviewed, which is simulated in the model by checking the WQM component confidence index. The investigation process follows one of two paths depending on whether the alert is from the IVR or the WO data stream. However, the investigations of both types of alerts are eventually turned over to the WQ&T Chemist, who makes the determination whether contamination is Possible. The outputs from this module include the time when results from the investigation are reported to the WUERM and the CCS confidence index.

The CCS confidence index is an overall indicator of the reliability of the information from the CCS component, considering all information available from the alert investigation at any given time. The value of the CCS confidence index will change over time as the investigation progresses and as more alerts are generated. Under the model assumptions, a fully investigated CCS alert will result in a Possible determination. Subsequent CCS alerts are not fully investigated but incrementally increase the CCS confidence index up to a maximum of value of 1.5. However, information from another monitoring and surveillance or investigative component is necessary to elevate the threat level to Credible.

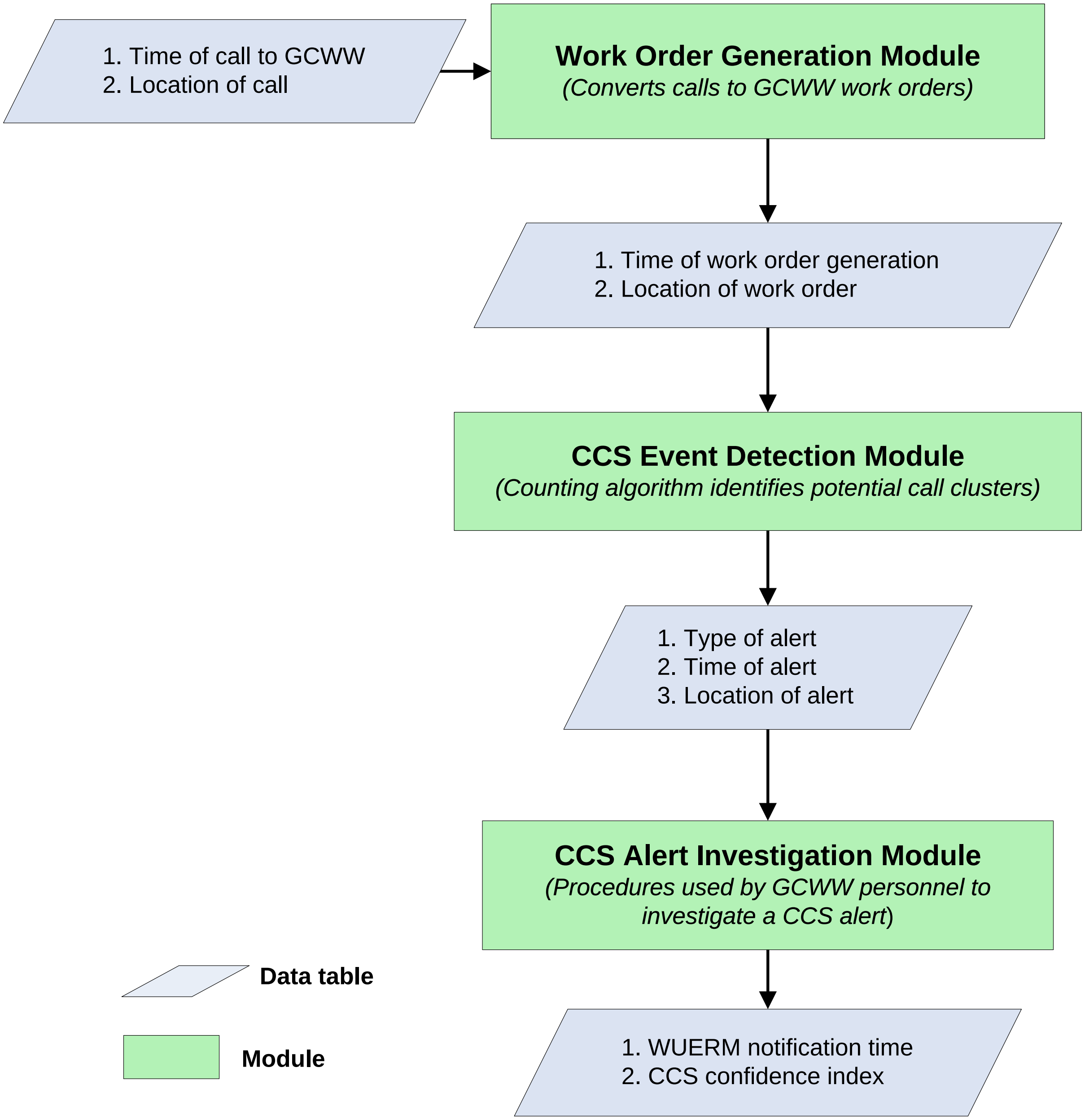

Figure A-6. Customer Complaint Surveillance Model

The primary inputs to the CCS model are shown in **Table A-12** and include the date and time of utility calls generated by the HI/HB model, the time and date of WOs, the number of customers in the call queue waiting to talk to a customer service representative, and the WQM confidence index from the WQM model described in Section A.5.

Table A-12. CCS Model Inputs

Input	Description
Utility Call Time	The date and time a customer who has detected the contaminant calls the utility. These values are created in the HI/HB model and reside in the Case Table.
Work Order Generation Time	The date and time that a WO is generated by the WO Generation module of the CCS model.

Input	Description
Customer Service Representative Call Queue	The number of callers waiting to talk to a customer service representative at each time-step. This value is the number of individuals waiting in the GCWW queue from the HI/HB model.
WQM Confidence Index	Generated by the WQM model, is used as a proxy for water quality data in the area of a CCS alert. It is used during the investigation of a CCS alert to determine if degraded water quality is spatially correlated with customer complaints.

Parameters for the CCS model are listed in **Table A-13**. Key parameters include event detection system scan times and thresholds as well as the time to investigate a CCS alert.

Table A-13. CCS Model Parameters

Parameter	Description
WQ&T Chemist Capacity	The number of WQ&T Chemists handling customer complaints during business and non-business hours. The values for this parameter are based on GCWW staffing practices.
CCS Event Detection System Scan Time and Thresholds	The size of the window (i.e., one day scan and two day scan) utilized to monitor current data and evaluate it against recent historical data to generate CCS alerts. If the number of utility calls or work orders in the scan window equals the threshold (four water quality calls or three WOs), an alert will be generated. The values for the thresholds were obtained from the CCS event detection system configuration file utilized by the GCWW CCS in June 2010.
CCS Event Detection System Alert Transmission Time and Data Processing Delay	The CCS event detection system processes data at least 2 minutes old and runs every minute. Thus, alert generation is typically delayed 3 minutes from the last event in the window. The values for this parameter were obtained from the CCS event detection system configuration file utilized by the GCWW CCS in June 2010.
Call Queue Threshold	The number of calls waiting to be answered by customer service representatives that is necessary to cause the utility to increase suspicion that there may be a problem with the water quality. This value was provided by GCWW and was confirmed in one of the drills held during the evaluation period Cincinnati pilot.
Time to Investigate a CCS Alert	The time necessary to query customer service representatives (business hours) or dispatchers (non-business hours), evaluate the calls for clustering, check for active or recent distribution work in the area of the calls, and review recent water quality data in the area of the calls. The values for this parameter were obtained from drills and exercises performed during the evaluation period of the Cincinnati pilot.

The outputs from the CCS model include the alert start time, WUERM notification time, and CCS confidence index for alerts, and are described in **Table A-14**.

Table A-14. CCS Model Outputs

Output	Description
CCS Alert Start Time	The date and time the CCS alert is generated.
CCS Alert Location	The pito zone(s) that contain the calls that caused the alert.
WUERM Notification Time	The date and time at which the WUERM is notified of each unique CCS alert.
CCS Confidence Index	A time series of values from the CCS component indicating the reliability of information available from the investigation of the CCS alert, and the degree of confidence in the suspicion that the drinking water has been contaminated.

A.7 Public Health Surveillance

The PHS model was designed to simulate new and existing syndromic surveillance systems and procedures used by Cincinnati area public health partners to detect unusual clusters of illness and disease. The component operates by analyzing health seeking behaviors and identifying unusual trends that may be an early indicator of an emerging outbreak.

PHS monitors a number of data streams, and there is a unique mechanism for event detection for each data stream that involves automated analysis of the data or standard procedures to identify anomalies or deviations from the base state of disease/illness within the population. If an alert is generated through one of these systems, the local health partners work collaboratively with GCWW utility personnel to conduct an investigation to determine whether or not the public health alert is related to contaminated drinking water. A communicator protocol was implemented as a part of the alert investigation process to facilitate discussions among GCWW and the public health partners regarding the possibility of water contamination. During the discussions, representatives from each partner organization provide real-time updates to further the investigation process.

Figure A-7 provides an overview of the PHS model showing the relationships among the three modules, shown as green rectangles, which comprise the model: PHS Pre-processing module, PHS Event Detection module and PHS Alert Investigation module. The inputs to and outputs from each module of the PHS model are shown as blue parallelograms.

The first module to operate in the PHS model is the Pre-processing module. The inputs to this module are located in the case table generated by the HI/HB model and include the time and action associated with the health seeking behaviors taken by each exposed individual. The Pre-processing module converts these actions into the format required by the event detection systems used to analyze the various data streams: 911, EMS, DPIC, ED, and primary care physicians. In general, all data streams capture the following information: case ID, location, symptom category, and the date and time that information from the case entered the data stream,

The Event Detection module uses the outputs from the Pre-processing module to search for unusual clusters of health seeking behavior. Each of the data streams uses a unique algorithm for event detection, and the model was parameterized with the event detection system configurations used in the Cincinnati pilot:

- **911:** SaTScan™ analyzes 911 calls generated by the HI/HB model against a 21-day baseline dataset of 911 calls generated during a portion of the evaluation period of the Cincinnati pilot. 911 calls will always generate an EMS response, so customers that call 911 will always be placed in the EMS queue.
- **EMS:** The Early Aberration Reporting System analyzes EMS run records generated by the HI/HB model against a 21-day baseline dataset of EMS runs generated during a portion of the evaluation period of the Cincinnati pilot. Each case uses the zip code of the location of the run and the associated syndrome.
- **DPIC:** Two unique surveillance methods are approximated in the DPIC module: volume-based statistical surveillance and human surveillance. Both of these simple algorithms are based on fixed thresholds for the number of DPIC calls generated within the HI/HB model.
- **ED:** An algorithm analyzes ED visits generated within the HI/HB model. The algorithm generates alerts when pre-established thresholds, determined for each syndrome category, are exceeded.
- **Primary care physician:** An algorithm analyzes primary care physician visits generated within the HI/HB model. The algorithm generates alerts when pre-established thresholds are exceeded, which are assigned on a contaminant-specific basis.

The PHS alerts generated by the Event Detection module provide the inputs to the Alert Investigation module, which simulates the investigation process implemented by GCWW and its public health partners.

This module is based on alert investigation procedures developed for routine operation of the PHS component of the Cincinnati CWS. This module accounts for the time required to recognize the alert and perform a variety of investigative functions, including activating the communicator protocol, holding a call to discuss the PHS alert investigation, and contacting frontline healthcare providers for more information about individual cases. The outputs from this module include the time when results from the investigation are reported to the WUERM and the PHS confidence index.

The PHS confidence index is an overall indicator of the reliability of the information from the PHS component, considering all available data from all PHS alerts and the ongoing investigation. The value of the PHS confidence index will change over time as the investigation progresses. Under the model assumptions, PHS can result in a Possible determination in one of two ways: 1) completion of a single PHS alert in which water contamination cannot be ruled out as a potential cause, or 2) receipt of multiple PHS alerts that increase the confidence index to 1.0 and an indication of potential contamination from another component. While the PHS confidence index can increase above the threshold for Credible (2.0), information from another component is necessary for a PHS alert to be considered a Credible indicator of drinking water contamination. This additional information can come from another monitoring and surveillance component (WQM or CCS) or an investigative component (site characterization (SC) or laboratory analysis (LA) and is necessary to draw a potential connection between the PHS alert and the drinking water.

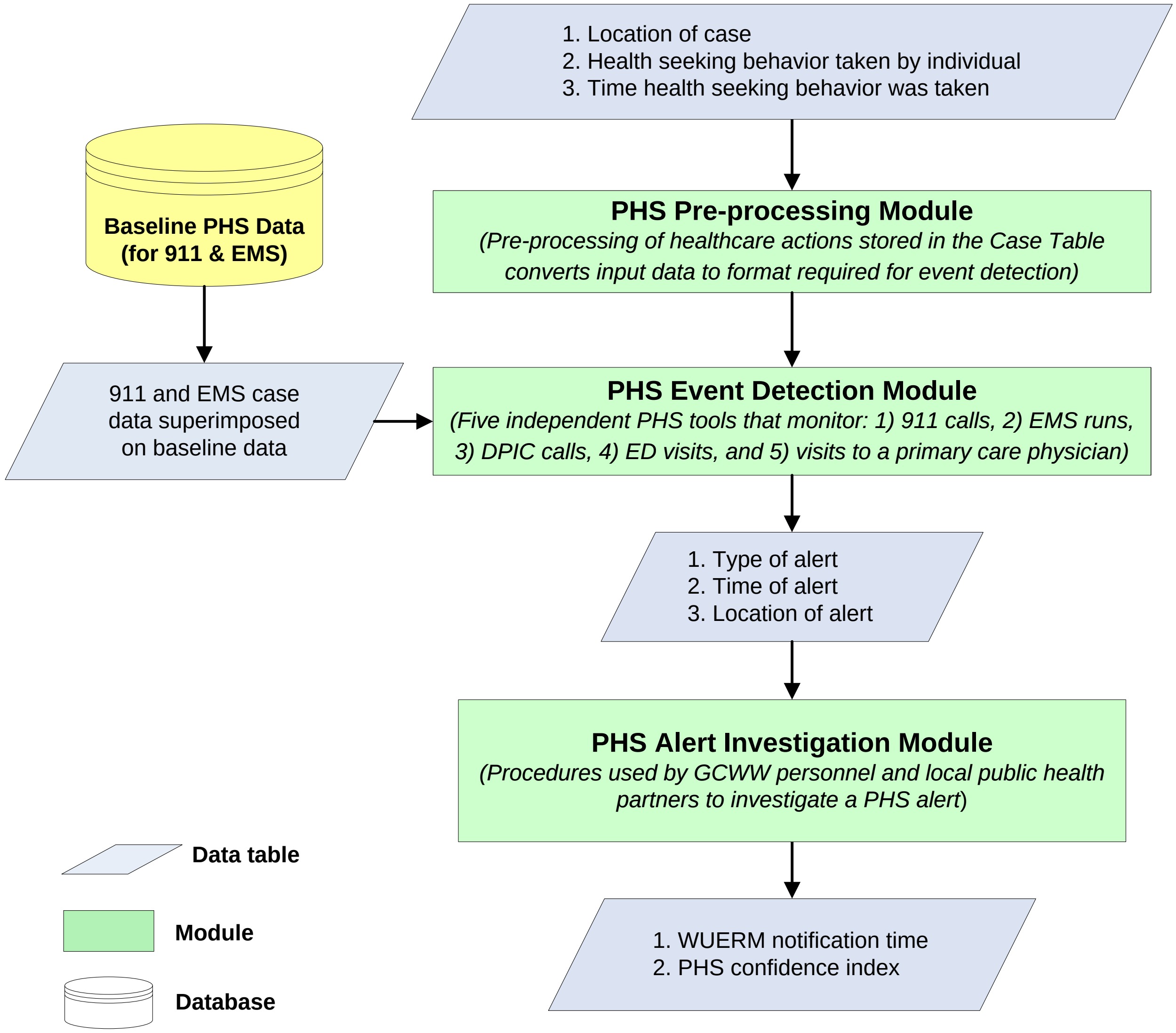

Figure A-7. Public Health Surveillance Model

The primary inputs to the PHS model are shown in **Table A-15** and include location, symptom level, and the times of individual health seeking behaviors. These are the primary outputs generated from the HI/HB model and recorded in the case table.

Table A-15. PHS Model Inputs

Input	Description
Case ID	A unique identifier for each individual exposed to contaminated water during a contamination scenario. Case IDs are assigned in the HI/HB model and reside in the Case Table.
Location ID	The specific distribution system model node that the individual is assigned to for all exposure events (i.e., home location).
Symptom Level	Contaminant-specific category for symptoms experienced by an exposed individual. Values were derived from an extensive review of contaminant databases and peer reviewed literature.
911 Call Time	The date and time the customer calls 911 in response to their current symptoms.
Emergency Medical Service Run Time	The date and time an EMS unit responds to and treats a symptomatic individual.

Input	Description
DPIC Call Time	The date and time the customer calls DPIC to seek medical advice in response to their current symptoms.
ED Visit Time	The date and time the customer is admitted to a hospital ED to seek medical assistance in response to their current symptoms.
Primary Care Physician Visit Time	The date and time the customer visits a primary care physician to seek medical assistance in response to their current symptoms.

Parameters for the PHS model are listed in **Table A-16**. Key parameters include event detection system alert parameter, the time to investigate a PHS alert, and the time to activate the communicator protocol.

Table A-16. PHS Model Parameters

Parameter	Description
Analysis Frequency	A parameter used in PHS event detection systems that determines how frequently data is analyzed for anomalies. This scheduled time varies for the different surveillance tools of the PHS model. The values for this parameter replicate the configuration of the PHS event detection systems used in the Cincinnati CWS.
911 Alert Parameters	The parameters for determining the conditions that must be met to generate a 911 alert. These include the minimum p-value (.025) for an alert cluster and the number of 911 cases in the cluster (17 calls) for the cluster to be considered anomalous. The values for these parameters replicate the configuration of the 911 event detection system used in the Cincinnati CWS.
Emergency Medical Service Alert Parameters	The parameters for determining the conditions that must be met to generate an EMS alert. These include the number of minutes of historical data used to establish the baseline (10,080 minutes) and the ratio of EMS runs to zip codes in the alert (1.5). The values for these parameters replicate the configuration of the EMS event detection system used in the Cincinnati CWS.
EpiCenter Alert Parameters	Unlike the 911 and EMS event detection systems, EpiCenter could not be used directly in the PHS model. The behavior of EpiCenter is replicated by applying syndrome-specific thresholds for daily number of simulated cases to generate the alert. The thresholds were determined through an analysis of historical emergency department data and established at four standard deviations above the mean daily totals for the syndrome.
Primary Care Physician and Emergency Department Physician Disease Reporting Alert Parameters	Threshold for the number of visits to primary care physicians or ED physicians above which the health department is notified about the unusual frequency of patients expressing similar symptoms. Reporting thresholds are contaminant-specific. The values for this parameter are based on consultation with DPIC subject matter experts.
DPIC Statistical Surveillance Alert Parameters	The parameters for determining the conditions that must be met to generate a DPIC statistical surveillance alert. These include the analysis window (24 hours) and the threshold for calls to DPIC from within the same zip code (four calls) to trigger an alert. The values for these parameters replicate the configuration of the DPIC's statistical surveillance event detection system.
DPIC Human Surveillance Alert Parameters	The parameters for determining the conditions that must be met to generate a DPIC human surveillance alert. This simple algorithm assumes that DPIC will suspect water contamination if two calls to DPIC originate from the same node within 4 hours of each other. The values for these parameters were determined through consultation with DPIC subject matter experts.
Time to Investigate Alert	The time to investigate a PHS alert and identify if the underlying cases are clustered and potentially due to a common exposure route. The value of this parameter varies based on the type of alert and was obtained from drills and exercises performed during the evaluation period of the Cincinnati pilot.
Time to Activate Communicator	The time (minutes) after local health partners complete their preliminary investigation, initiate the communicator protocol, and convene a conference call to discuss the alert. The value for this parameter was obtained from drills and exercises performed during the evaluation period of the Cincinnati pilot.
Time for Communicator Discussion	The time for GCWW and local public health partners to discuss active PHS alert(s) and determine whether water contamination is Possible. The value for this parameter was obtained from drills and exercises performed during the evaluation period of the Cincinnati pilot.

The outputs from the PHS model include the alert start time, WUERM notification time, and PHS confidence index for alerts shown in **Table A-17**.

Table A-17. PHS Model Outputs

Output	Description
PHS Alert Start Time	The date and time the PHS alert is generated and the appropriate public health agency is notified.
PHS Alert Location	Pito zone containing the initial underlying case(s) that generated the alert.
WUERM Notification Time	The date and time at which the WUERM is notified of each unique PHS alert.
PHS Confidence Index	A time series of values from the PHS component indicating the reliability of information available from the investigation of the PHS alert, and the degree of confidence in the suspicion that the drinking water has been contaminated.

A.8 Consequence Management

The CM model was designed to simulate the actions taken to investigate and respond to Possible water contamination incidents in the distribution system. These actions are meant to minimize response and recovery timelines through a pre-planned, coordinated effort. Investigative and response actions are implemented to establish credibility, minimize public health and economic consequences, and ultimately return the utility to normal operations. The model is largely based on the series of decision trees documented in the GCWW Consequence Management Plan that guide the threat level determination process and various response actions.

Figure A-8 shows the relationships among the modules that constitute the CM model, shown as green rectangles, along with the outputs generated by the model, shown as blue parallelograms. The CM model consists of five modules: Threat Level Determination (TLD) module, Site Characterization module, Laboratory Analysis module, Public Notification module, and the Operational Response module.

Data generated by the monitoring and surveillance components are the primary inputs to the CM model, and include: WUERM notification, component confidence indices, alarm types and alarm locations. Location information is expressed in terms of pito zones, which are specific pressure zones identified within the GCWW distribution system.

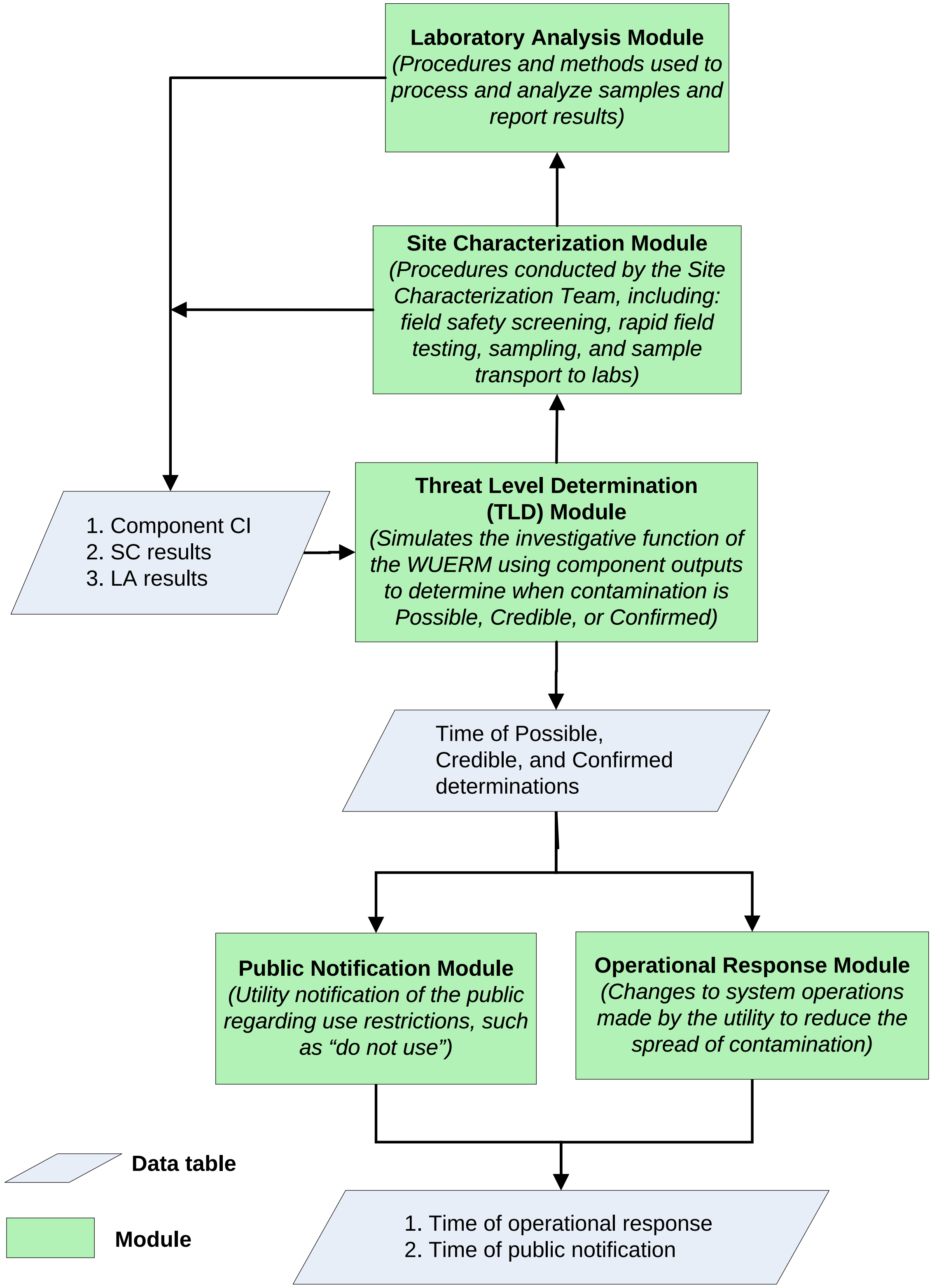

Figure A-8. Consequence Management Model

The TLD module steps through each time-step of the simulation and considers data that would be available at that time to establish if/when contamination is deemed Possible, Credible or Confirmed. This module simulates the investigative functions of the WUERM using information generated by the monitoring and surveillance component models (ESM, CCS, WQM and PHS), SC, and LA to determine the level of confidence in the possibility that a contamination incident has occurred. These TLD outputs are the primary drivers for implementation of response actions such as a public notification and operational response.

The SC module is initiated in response to Possible contamination as determined through the investigation of an alert from one or more of the monitoring and surveillance components. Once the threat level reaches Possible, one SC team will begin mobilization and will deploy to the location of the first validated alert. This module includes SC team mobilization, travel time, deployment, site approach, field safety screening, sample retrieval, rapid field testing, sampling for laboratory analyses, and transport to GCWW for disposition of samples to method laboratories. This is a critical step in the investigation process and involves collecting information from an investigation site to support the threat level determination process. SC activities start with performing a site hazard assessment when approaching a suspected contamination site(s) and ends when water samples are collected and sent to a laboratory for analysis.

The LA module is based on procedures and methods GCWW and partner laboratories use to process and analyze samples collected during the investigation of a Possible contamination incident. LA includes mobilization of laboratories to prepare for sample receipt and analysis, sample delivery to laboratories, sample analysis, data review, and reporting analytical results to the WUERM. There are two types of labs that may be mobilized in the LA module: auto and triggered laboratories. Any samples collected over the course of the investigation are always sent to all auto laboratories, where they collectively analyze the samples for an established suite of contaminants. Triggered laboratories are used only in situations where there is evidence to suggest that a potential contaminant is outside of the established suite of contaminants analyzed by the auto laboratories. Typically, this evidence will come from one of the monitoring and surveillance components (CCS, WQM, or CCS), the differential diagnosis generated by the HI/HB model (see Table A-5), or SC results.

Each of the monitoring and surveillance components, along with SC and LA, produce a time series of confidence indices, a numeric indicator of the strength of the signal from the component that contamination has occurred, which are used by the TLD module to determine the overall threat level. The confidence indices (CIs) for each component at each time-step are monitored and summed by the TLD module to represent the overall threat level index (TLI):

$$\mathrm{TLI} = \mathrm{CI}_{\mathrm{ESM}} + \mathrm{CI}_{\mathrm{WQM}} + \mathrm{CI}_{\mathrm{CCS}} + \mathrm{CI}_{\mathrm{PHS}} + \mathrm{CI}_{\mathrm{SC}} + \mathrm{CI}_{\mathrm{LA}}$$

The threat level determination process classifies a contamination threat to be Possible when one of the following two conditions are met: 1) the investigation of an alarm from a single component is completed and uncovers no benign explanation for the alarm, or 2) information from an ongoing alarm investigation is supplemented by information from additional component alarms that are related spatially and temporally. The threat level reaches Possible when:

- The TLI ≥ 1.0 and
- The WUERM has been notified and informed of the results of the investigation, which results in the continuation of the investigation of the Possible contamination incident.

In general, contamination is determined to be Credible when indicators of contamination from two or more independent components is related temporally and/or spatially; however, in some cases, information from only WQM or only ESM may be sufficient to establish that contamination is Credible. The threat level reaches credible when:

- The incident has met the criteria for Possible as described above and

- TLI ≥ 2.0 and
- In the case of a PHS alarm, at least one of the other data streams has a confidence index > 0.0.

Contamination is Confirmed when definitive laboratory analysis results are available, or when a preponderance of evidence indicates that contaminated drinking water poses a direct threat to public health. As described previously in Section A.4, an ESM alert can lead to a Confirmed contamination if the site investigation catches the contaminant injection in progress. The threat level reaches Confirmed when:

- The incident has met the criteria for Credible as described above and
- TLI ≥ 3.0

The threat level is an input to the Operational Response and Public Notification modules. These modules generate the time, location, and type of response actions, which are ultimately used to revise parameters within EPANET and the HI/HB model to determine revised consequences of each scenario with the CWS in place. The consequences from the baseline condition (without CWS in place) can then be compared with those from the CWS condition to determine the reduction in consequences attributable to deployment of the CWS.

Once contamination is deemed Possible, the Operational Response module is executed. Operational responses are changes to system operations that attempt to minimize the spread of contaminated water by physically or hydraulically isolating portions of the distribution system.

Public notification is the series of notifications the utility, either by itself or in concert with public health partners, makes to the public regarding use of drinking water. The Public Notification module is designed to simulate the activities that lead up to issuance of a “do not use” notice to the public, which is intended to prevent future exposures to the contaminated water. Preparation of a public notification begins once contamination is deemed Possible and can be issued as soon as contamination is deemed Credible. Logic in the HI/HB model determines if and when each individual complies with the use restriction (see the parameter “time of stop use compliance” in Table A-5).

The primary inputs to the CM model, shown in **Table A-18**, are the confidence indices, alert times, and the WUERM notification times. These inputs come from the component models and are used to determine the threat level and the contaminant identification.

Table A-18. CM Model Inputs

Input	Description
Component Type(s)	Indicator of the component that produced the alert. Options: ESM, WQM, CCS, and PHS.
Alert Location ID	The node associated with the location of the component alert. The values for this parameter are generated by the component models.
Alert Start Time	The date and time assigned to the component alert by the component models.
WUERM Notification Time	The date and time at which the WUERM is notified about a component alert. The values for this parameter are generated by the component models.
Sample ID	A unique identifier for each sample collected during a scenario, which can be traced back to a sample location and collection time. The values for this parameter are generated by the component in the model where the sample was collected.
Sampling Location	The node from which samples were collected.
Component Confidence Indices	A time series of values from each component indicating the reliability of information available from the investigation of the component alert and the degree of confidence in the suspicion that the drinking water has been contaminated.

Parameters for the CM model are listed in **Table A-19**. Key parameters include thresholds for threat level determination, time to mobilize and deploy the SC team, time for laboratory analysis of samples, time to evaluate and implement operational responses, and time to prepare a public notification.

Table A-19. CM Model Parameters

Parameter	Description
Threshold for Threat Level Determination	The minimum threat level index for Possible, Credible, and Confirmed determinations to be declared. The values for this parameter were obtained from drills and exercises performed during the evaluation period of the Cincinnati pilot.
SC Team Mobilization Time	The time it takes the SC team to mobilize, which begins with the time the WUERM directs the SC team to deploy and ends with the time they leave for the site. Different values for this parameter are established for normal business hours and non-business hours. The values for this parameter were obtained from drills and exercises performed during the evaluation period of the Cincinnati pilot.
Time to Deploy the SC Team	The time it takes the SC team to deploy their equipment and prepare for the site approach once they arrive at the investigation site. The values for this parameter were obtained from drills and exercises performed during the evaluation period of the Cincinnati pilot.
Time for Laboratory Mobilization	The time it takes the laboratories to prepare to analyze samples from the time they are notified by GCWW. The value for this parameter varies by method, laboratory, and whether initial notification of the labs occurs during business or non-business hours. The values for this parameter were obtained from utility and external lab procedures.
Time for Sample Receipt, Disposition, and Delivery to Contract Labs	The time required for GCWW to receive and inventory samples collected in the field, prepare chain of custody forms, deliver samples to in-house chemists, package samples for shipment, and deliver samples to external labs. For laboratory analyses that are part of the baseline suite, drive time was provided by GCWW or documented during drills performed during the evaluation period of the Cincinnati pilot. For laboratory analyses that are performed by triggered labs, drive time estimated based on the location of laboratory that was assumed to be used.
Time to Analyze Samples and Perform QC Data Review	The time required to analyze samples, review QC information, and prepare the results for reporting. This is a laboratory-specific parameter and was estimated based on laboratory method analysis time requirements.
Reporting Limits	The minimum reporting limit (i.e., concentration) for each contaminant simulated in the study. The values for this parameter were obtained from actionable concentrations for each contaminant provided by GCWW.
Time to Prepare Public Notification	The time necessary to prepare and distribute a public notification through broadcast media (e.g., television, radio, text notifications, etc.) such that it is available for public viewing. The values for this parameter were obtained from drills and exercises performed during the evaluation period of the Cincinnati pilot.
Time to Implement Operational Response	The time necessary to evaluate operational response options and select, plan, and implement the operational response action that best protects the public and utility infrastructure from exposure to contaminated water. Operational response actions modeled include isolation of tanks and reservoirs and manipulation of pumps and valves. The values for this parameter were obtained from drills and exercises performed during the evaluation period of the Cincinnati pilot and discussions with utility operators.

The primary outputs from the CM model are shown in **Table A-20**, and include the threat level index, the zone of impact, the time and action for an operational response, and the time of public notification. The zone of impact is an output from the TLD module that identifies all pito zones that may be contaminated at a given time-step based on information generated by the various components.

Table A-20. CM Model Outputs

Output	Description
Threat Level Index	A numeric indicator of the threat level associated with a potential contamination incident at each time-step, which relates to the Threat Level as described below.

Output	Description
Threat Level	A discrete indicator of the level of confidence in the assertion that the distribution system has been contaminated. There are three threat levels: Possible, Credible, or Confirmed. The Threat Level is determined from the value of the Threat Level Index and other criteria, such as notification of the WUERM.
Contaminant Identification Confidence Index	A numeric indicator of the confidence of utility officials in the identity of the contaminant, which is based on information from all components (including SC and LA). Note that this parameter considers input from local public health partners, as modeled by the Differential Diagnosis module generated by the HI/HB model.
Zone of Impact	A running list of all the pito zones that could be contaminated according to the information available to the WUERM, updated at each time-step.
Field Safety Screening Results	The date, time, and results ("normal" or "abnormal") for all field safety screening performed during SC activities. Based on scenario assumptions, the results of field safety screening will be normal at locations other than the site of contaminant injection.
Rapid Field Test Results	The date, time, and results ("normal" or "abnormal") for all water quality testing performed during SC activities. The results from rapid field testing are based on the contaminant concentration at the time and node from which the sample was collected for field testing. If the contaminant concentration is above a specified minimum detection level for a given test, the results are reported as abnormal.
Time Samples Delivered to Laboratories	The date and time when samples are delivered to the specified laboratory for sample disposition and analysis.
Laboratory Results	The date, time, and results ("normal" or "abnormal") for a specific laboratory analysis. The results from laboratory analysis are based on the contaminant concentration at the time and node from which the sample was collected for laboratory analysis. If the contaminant concentration is above a specified minimum detection level for a given analysis, the results are reported as abnormal.
Operational Change	The date and time at which the operational change is implemented. The operational change is translated to a specific EPANET operational rule that is changed to model the response.
Time of Public Notification	The time that a "do not use" notice is issued to the public.

Appendix B: Benefit-Cost Analysis Methodology

B.1 Introduction

To evaluate the sustainability of the Cincinnati Contamination Warning System (CWS) in a quantitative fashion, a benefit-cost analysis was conducted. This type of financial analysis compares the benefits and costs to determine which value is larger. Therefore, it requires a complete and transparent accounting of the actual costs of deploying the Cincinnati CWS and estimated benefits derived from operation of the system expressed in comparable terms, which for this analysis are U.S. dollars in 2007 (the year the system was deployed). The benefits and costs were assessed over a 20-year lifecycle. The basis for selecting a 20-year lifecycle is the heavy reliance of the system on sensor technology, information technology (IT) systems, and human processes that will likely be obsolete and thus need to be replaced or updated within 20 years.

The remainder of this document presents the systematic benefit-cost analysis methodology in the following two subsections:

- **Identification of Monetizable Costs and Benefits**. This section describes the approach and sources used to determine the overall costs and benefits associated with the deployment and operation of the Cincinnati CWS.
- **Financial Analysis**. This section presents the methodology used to compare the benefits and costs. It also presents the methodology used to determine the lifecycle costs of the CWS, and to estimate the monetary value of benefits associated with identifying and responding to a contamination incident.

B.2 Identification of Monetizable Costs and Benefits

To conduct the benefit-cost analysis, a comprehensive list of costs and benefits was compiled from which only those that could be monetized were considered. The costs of deploying and operating the Cincinnati CWS were readily monetized as the cost data had been tracked during implementation of the system. However, benefits of the CWS were more challenging to identify and, with one exception, depended on the reduction in consequences resulting from early detection and response to a contamination incident using CWS capabilities, which was monetized using assumptions discussed in Section B.3.

B.2.1 Identification of Monetizable Costs

The costs considered in the benefit-cost analysis included all costs associated with the implementation and operation of the CWS during the 20-year lifecycle; however, they did not include those associated with pre-existing resources or operations, even if those capabilities were leveraged for the CWS. The main source of the cost data used in performing this analysis was the *Water Security Initiative: Cincinnati Pilot Post-Implementation System Status* report (USEPA, 2008). This report describes the configuration and cost of the pilot CWS as it was deployed in Cincinnati, Ohio as of December 2007. The total cost of the Cincinnati CWS over an assumed 20-year lifecycle was determined by summing all costs associated with implementation and operation of the CWS. The major cost elements for the Cincinnati CWS are described in **Table B-1**.

Table B-1. Cost Elements for Implementation and Operation of the Cincinnati CWS

Cost Element	Description
Deployment Costs	The total costs for designing and implementing the CWS. Deployment costs include all US Environmental Protection Agency (EPA), extramural, Greater Cincinnati Water Works (GCWW) and local partners' labor costs as well as other direct charges for equipment, consumables, and purchased services.
Modification Costs	The cost of modifications to the Cincinnati CWS after system implementation was completed in January 2009 through the end of the evaluation period in June 2010. The costs were tracked by EPA and GCWW over the evaluation period of the pilot, and include all appropriated equipment and labor costs associated with the modification.
Equipment Renewal and Replacement Costs	The costs associated with replacing equipment during the 20-year lifecycle of the Cincinnati CWS. The costs were identified for major pieces of equipment, generally with a replacement value of $500 or more. The useful life of the equipment was estimated using field experience with the equipment, manufacturer-provided data, and the recommendations of subject matter experts.
Salvage Value	The salvage value is the estimated value of the system components at the end of the 20-year lifecycle of the Cincinnati CWS. The salvage value was estimated using straight line depreciation for all equipment with an initial value greater than approximately $1,000 and represents a credit against the system costs in the benefit-cost analysis. The useful life of the equipment was estimated from experience with equipment at the Cincinnati pilot along with professional judgment.
Operation and Maintenance (O&M) Costs	The costs incurred to operate and maintain the CWS over the 20-year lifecycle of the Cincinnati CWS. The O&M costs represent all EPA, extramural, GCWW, and local partners' labor costs as well as other direct charges for consumables and purchased services for maintaining the CWS. Additionally, the annual cost to maintain and update CWS documentation was extrapolated from the costs incurred to update documents following drills and exercises conducted during the pilot evaluation period using an assumed frequency of future drills and exercises over the 20-year lifecycle of the CWS.

B.2.2 Identification of Monetizable Benefits

The benefits considered in the benefit-cost analysis include all improvement in GCWW's capability to detect and respond to unusual water quality conditions realized through operation of the CWS. Benefits were grouped into one of two broad categories: those resulting from the reduction in consequences from a contamination incident and those related to day-to-day utility operations (dual-use benefits).

Information about dual-use was obtained directly from GCWW and local partner staff through a variety of forums, including routine component review meetings, lessons learned workshops, and exit interviews as described in Section 3.5. These forums provided an opportunity for front line personnel, supervisors, senior managers and representatives from partner organizations with an opportunity to provide feedback on the Cincinnati CWS in areas such as the value of various enhancements implemented during the pilot, application of the CWS to activities other than contaminant detection, and long-term plans for the CWS. With only one exception, there was insufficient information to monetize dual-use benefits. The one dual-use benefit that could be monetized was the reduction in chlorine applied to maintain the target disinfectant residual throughout the distribution system, which was realized through the chlorine residual data generated by the Water Quality Monitoring (WQM) component.

The other category of benefits considered in the benefit-cost analysis is the reduction in the consequences of a contamination incident due to early detection and response realized through operation of the CWS. Because there were no contamination incidents in the GCWW distribution system over the course of the pilot, the Cincinnati CWS model, described in Appendix A, was used to estimate the consequences of simulated contamination incidents both with and without the CWS in operation. The difference in consequences under these two conditions was calculated to determine the benefits due to consequences avoided that were attributable to the CWS.

The Cincinnati CWS model allows for the evaluation of various consequences that could result from intentional contamination. **Table B-2** describes three types of benefits, expressed in terms of reduced consequences, attributable to early detection and response to a contamination incident through the CWS. These benefits were monetized using various assumptions described in Section B.3.

Table B-2. Monetizable Benefits Attributable to the Cincinnati CWS due to the Reduction in Consequences from a Contamination Incident

Benefit in terms of Consequence Reduction	Description
Public health	The reduction in fatalities, number of people requiring medical treatment, and lost leisure time attributable to early detection and response through operation of the CWS.
Revenue	The reduction in lost water revenue, lost wastewater revenue, and lost business revenue attributable to early detection and response through operation of the CWS.
Remediation	The reduction in distribution system remediation cost and the cost of an alternate water supply attributable to early detection and response through operation of the CWS.

B.3 Financial Analysis

The financial analysis required the benefits and costs identified to be expressed in terms of the value of a dollar in a common reference year. Because the Cincinnati CWS was substantially complete in 2007, it was decided to express the present value (PV) of all costs and benefits in 2007 dollars, allowing for an unbiased comparison.

B.3.1 Overview of Present Value Calculations

With the costs and benefits occurring over the 20-year lifecycle of the CWS, their values required adjustment to reflect the time-value of money (i.e., one dollar in the future is worth less than one dollar today due to the investment potential of that dollar). As discussed earlier, 2007 was selected as the reference year for all PV calculations because most of the deployment costs were incurred in that year. All costs incurred prior to 2007 were adjusted to 2007 dollars by using the change in the Consumer Price Index (CPI) between 2007 and the year that the cost was incurred. Future costs were adjusted to 2007 dollars by using a 2.1% annual discount rate. The general assumptions used to calculate the PV of the CWS costs and benefits are presented in **Table B-3**.

Table B-3. Cincinnati CWS Present Value Assumptions

Description	Cost Basis	Source
Term of Analysis	20 years	Subject matter expert judgment regarding the useful life of the CWS
Present Value	2007 dollars (no inflation)	Year in which most of the implementation costs of the Cincinnati CWS were incurred
Discount Rate for PV	2.1%	Office of Management and Budget, 2010

B.3.2 Monetization of Costs

The lifecycle cost analysis for the Cincinnati CWS was performed using the costs incurred to design, deploy, operate and maintain the Cincinnati pilot CWS and includes the items described in Section B.2.1. The modification costs were combined with the deployment costs for the purpose of the lifecycle cost analysis. The lifecycle cost was determined by calculating the PV of the annualized O&M costs, the periodic renewal/replacement costs, the salvage value of the equipment, and combining these annualized costs with the deployment and modification costs. As indicated above, the monetized costs and benefits were adjusted to 2007 dollars using the change in the Consumer Price Index between 2007 and the year that the cost was incurred.

While a 20-year lifecycle was assumed for the entire CWS, individual pieces of equipment and subsystems would need to be replaced or updated more frequently; thus, costs to update the CWS would occur over the entire 20-year lifecycle rather than as one lump sum at the end of that period. The useful life assumptions used for major pieces of CWS equipment are presented in **Table B-4**.

Table B-4. CWS Component Useful Life

CWS Equipment	Useful Life (years)	Cost Assumptions
Water Quality Sensors	3 to 7	$3,700 to $24,950, per sensor
ESM Contact Alarms	7	$260, per contact alarm
Security Lighting	15	$311, per lighting fixture
Fixed Cameras	7	$1,037, per camera
Video System	5	$11,000 for the entire system
Laboratory Instruments	10	$585 to $56,122, per instrument
Field Instruments	7	$645 to $7,750, per instrument
Information Technology (IT) Systems	5	$35,822 for all CWS-specific IT systems
Documentation	2 to 7	$7,280 for all documents, if updated in-house

B.3.3 Monetization of Dual-use Benefits

The only dual-use benefit of the Cincinnati CWS that was monetizable was a reduction in chlorine usage resulting from the utilization of chlorine data from the WQM component. To calculate the cost savings, the utility provided six months of chlorine dose data, indicating the changes in the dosages that occurred as a result of chlorine sensor data (10,011 lbs), and their cost for chlorine ($470 per ton.) The cost saving from this period was doubled to represent an annual value, and it was assumed to represent a typical year.

B.3.4 Monetization of Benefits during a Contamination Incident

The general approach and key assumptions used to estimate the monetary value of the consequence avoided due the operation of the CWS included:

- **Fatalities.** The fatalities cost was calculated by multiplying the number of lives lost by a unit value per life estimated to be $7.1 million.
- **Medical Treatment.** The medical treatment cost was determined by multiplying the number of individuals who received medical treatment by the respective treatment costs. Treatment costs were estimated from the Healthcare Cost and Utilization Project using either the International Classification of Diseases, ninth revision code or the clinical classification category for treatment of the specific contaminant and the estimated length of hospital stay required for that contaminant. These figures include the cost of hospitalization, medicine, supportive care, and

prophylactic treatment but not the cost of treatment for chronic illness resulting from the exposure. The contaminant-specific medical treatment costs are reported in **Table B-5**.

- **Lost Leisure Time.** The lost leisure time due to illness was determined by multiplying the number of individuals who experienced illness by half of the average hourly wage rate in Hamilton County ($11.34 per hour), times 16 hours per day for the remediation period. Note that lost wages are included under Lost Business Revenue.
- **Alternate Water Supply.** It was assumed that a temporary alternate water supply would be provided using bottled water. The cost of bottled water was multiplied by the gallons consumed per person per day (1.28 gallons), multiplied by the number people affected, multiplied by the duration of the outage.
- **Water System Remediation.** The remediation cost was determined by calculating the cost of all labor, equipment, and treatment chemicals needed to treat the contaminated water prior to disposal, and remediate distribution system pipes and storage tanks. The remediation process was considered from planning through demobilization. An overview of the assumed remediation strategy for each contaminant considered in the benefit-cost analysis is presented in **Table B-6**.
- **Lost Drinking Water Revenue.** The water revenue lost was determined by calculating the demand at the affected nodes for the duration of the remediation period and multiplying it by the average water service revenue of $2.53 per 1,000 gallons.
- **Lost Wastewater Revenue.** The wastewater revenue lost was calculated by prorating the average daily revenue for the utility ($423,871) by the percentage of the service area affected and multiplying by the duration of the remediation period in days.
- **Lost Business Revenue.** The business revenue lost was estimated by assuming that all businesses in zip codes affected by the contamination incident would be shut down for the duration of the remediation period. U.S. 2000 Census data reports the yearly revenue generated per zip code, which is converted into a value for daily revenue generation by dividing by 365. The daily revenue value was then multiplied by the number of days in the remediation period. For zip codes that were partially contaminated, the daily revenue value was proportionally adjusted by the percentage of the zip code affected.

Table B-5. Contaminant-specific Medical Treatment Cost per Illness

Contaminant	Value (2007 dollars)	Assumed Medical Treatment[1]
Toxic Chemical 1	$9,098	3.2 days of supportive therapy
Toxic Chemical 5	$11,728	3.8 days of supportive therapy and agent-specific medication
Toxic Chemical 6	$11,728	3.8 days of supportive therapy and agent-specific medication
Toxic Chemical 7	$11,728	3.8 days of supportive therapy and agent-specific medication
Toxic Chemical 8	$11,896	3.8 days of supportive therapy
Biological Agent 3	$55,663	11 days of supportive therapy
Biological Agent 4	$7,426	4.8 days of supportive therapy and agent-specific medication
Biological Agent 5	$7,665	5.2 days of supportive therapy and agent-specific medication
Biological Agent 6	$9,240	5.2 days of supportive therapy and agent-specific medication
Nuisance Chemical 1	$0	Not applicable. Acute illnesses do not occur from exposures to doses assumed in this study.

[1] Supportive therapy includes any form of treatment intended to relieve symptoms or help the patient live that does not directly address the causative agent for the illness. Supportive therapy may include administration of intravenous fluids and mechanically assisted breathing.

Table B-6. Contaminant-specific Remediation Methods and Significant Cost Factors

Remediation Method	Significant Cost Factors	Contaminants
Application of chlorine with contact time of two hours followed by flushing and discharging to combined sewer	Chemical feeders ($10,000 each) Sodium Hypochlorite ($0.91/gal)	Toxic Chemical 5 Toxic Chemical 6 Biological Agent 3 Biological Agent 4 Biological Agent 5 Biological Agent 6
Application of chlorine with contact time of two hours under acidic conditions followed by flushing and discharging to combined sewer	Chemical feeders ($10,000 each) Sodium Hypochlorite ($0.91/gal) Hydrochloric Acid ($1.57/gal)	Toxic Chemical 7
Application of chlorine with contact time of two hours under alkaline conditions followed by flushing and discharging to combined sewer	Chemical feeders ($10,000 each) Sodium Hypochlorite ($0.91/gal) Sodium Hydroxide ($1.71/gal)	Toxic Chemical 1
Application of dispersant with contact time of two hours followed by flushing and discharging to combined sewer	Chemical feeders ($10,000 each) Dispersant ($1.91/lb)	Nuisance Chemical 1
Application of acidified water with a contact time of two hours followed by flushing to reverse osmosis treatment unit	Chemical feeders ($10,000 each) Hydrochloric Acid ($1.57/gal) Reverse Osmosis Treatment Units ($500,000 ea) Concentrate Disposal ($20/gal)	Toxic Chemical 8