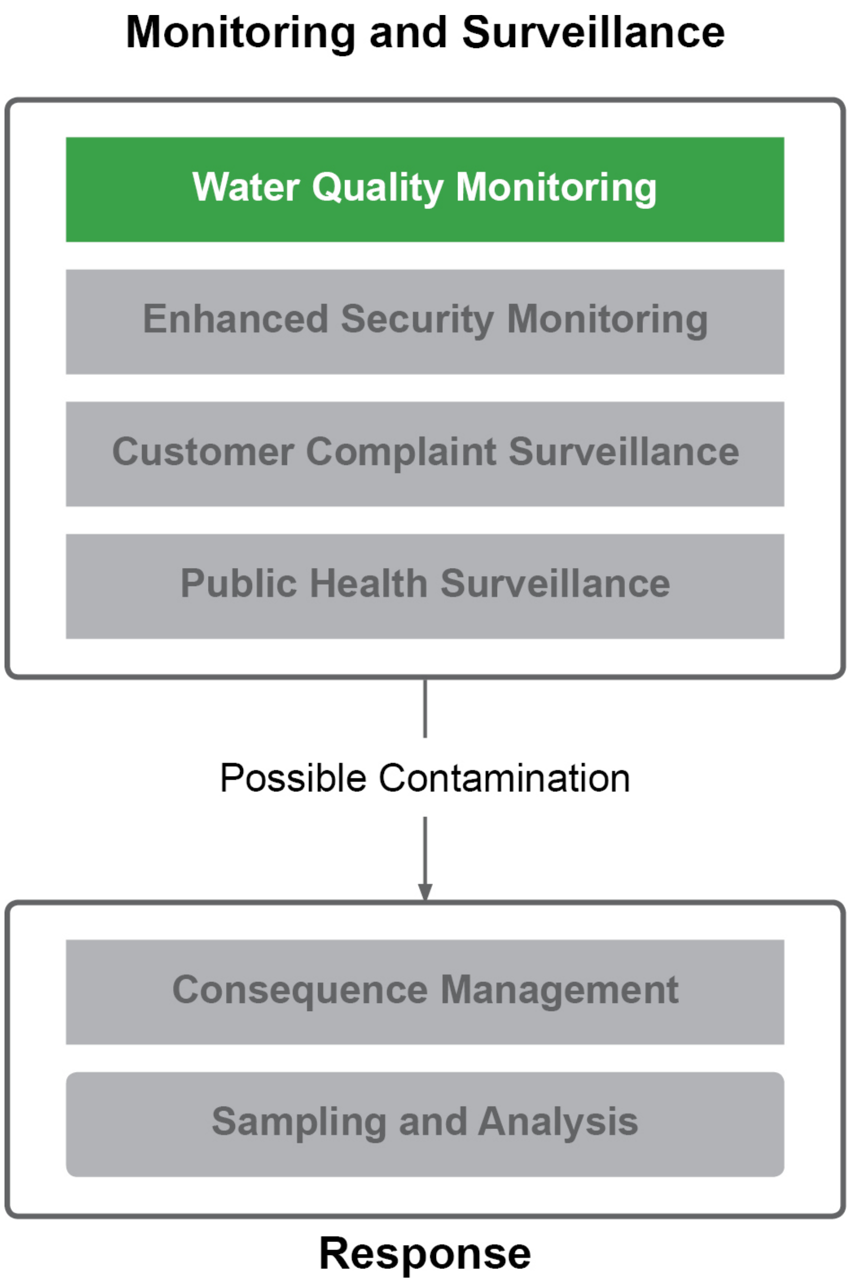
United States
Environmental Protection
Agency

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



Office of Water (MC-140) EPA-817-R-14-001B April 2014

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Acknowledgements

The Water Security Division of the Office of Ground Water and Drinking Water would like to recognize the following individuals and organizations for their assistance, contributions, and review during the development of this document.

- Yeongho Lee, Greater Cincinnati Water Works
- Jeff Swertfeger, Greater Cincinnati Water Works
- Mike Tyree, Greater Cincinnati Water Works
- Jennifer Hagar, Ohio Environmental Protection Agency
- Dr. Lindell Ormsbee, University of Kentucky

Executive Summary

The goal of the Water Security Initiative (WSI) is to design and demonstrate an effective multi-component warning 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 the water utility to possible contamination, and uses a consequence management plan (CMP) to guide response actions.

System design objectives for an effective CWS are: spatial coverage, contaminant coverage, alert occurrence, timeliness of detection and response, operational reliability and sustainability. Metrics for the water quality monitoring (WQM) component were defined relative to the system metrics common to all components in the CWS, but the component metric definitions provide an additional level of detail relevant to the WQM component. 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 an analysis of lifecycle costs. This report describes the evaluation of data collected from the WQM component from the period of January 2008 – 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 pilot following the installation of all monitoring and surveillance components.
2. *Component Evaluations*, which include analysis of performance metrics for each component of the Cincinnati pilot.
3. *System Evaluation*, which integrates the results of the component evaluations, the simulation study, and the 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 2014).

WQM Component Design

A key monitoring component of a CWS is WQM, which consists of the following four design elements: sensor stations, a data collection system, an event detection system and component response procedures. Prior to implementation of the CWS, the Greater Cincinnati Water Works (GCWW) had sensors measuring basic water quality parameters (primarily free chlorine) at major utility facilities. Operators received alerts if the water quality values fell outside of an acceptable range defined by the utility, but there were no formal procedures for timely investigation of and response to these alerts. Thus, all four design elements were enhanced as part of the WSI pilot, including installation of water quality sensors at 15 new locations throughout the distribution system (new stations were also installed at two treatment plants), implementation of a dedicated data collection and management system, installation of an event detection system, and development of component response procedures. Free chlorine residual, conductivity, oxygen reduction potential (ORP), temperature, total organic carbon (TOC) and turbidity instruments were installed.

Each water quality sensor produces a data stream which is analyzed independently by the event detection system to identify anomalous patterns in WQM data. The CANARY software was used for event detection for this pilot. For the 15 monitoring stations in the distribution system for which alerts were produced and investigated, a total of 69 water quality data streams were analyzed by CANARY.

Once an anomaly is identified by the event detection system, a visual and audible alert is generated on the dedicated workstation in the utility control room. This workstation is monitored 24/7 by utility operators, who initiate an investigation according to the component response procedures when an alert occurs.

A summary of the evaluation results for each of the design objectives relevant to WQM is provided below. For more information on this topic, see Section 2.0.

Methodology

Several methods were used to evaluate WQM performance. Data was tracked over time to illustrate the change in performance as the component 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 16th 2008 and February 15th 2008. Additionally, three drills and one full-scale exercise 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 component. 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 for 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, which were assumed over a 20 year lifecycle of the CWS. Benefits included reduction in consequences (illness, fatalities and infrastructure damage) and dual-use benefits from routine operations.

Design Objective: Spatial Coverage

Spatial coverage is the percentage of the distribution system area that is covered by the WQM network. For WQM, this depends on the location and density of monitoring points in the distribution system and the hydraulic connectivity of each monitoring location to downstream regions and populations. Metrics evaluated under this design objective include area coverage and population coverage and are a superposition of the areas covered by the individual monitoring stations.

For the Cincinnati pilot, the WQM component has 72% area coverage. This translates to 84% population coverage, which is higher than area coverage because most of the uncovered portions of the distribution system have low population density.

While the area and population coverage were relatively high, results from the simulation study show that only 737 of 2,015 simulated scenarios (37%) had at least one WQM station that witnessed a potentially detectable contaminant concentration. The majority of the 1,278 scenarios that were not potentially detectable occurred in isolated sections of the distribution system and did not spread widely. Thus, while they were difficult to detect, the consequences of these contamination incident were also limited. For more information on this topic, see Section 4.0.

Design Objective: Contaminant Coverage

Contaminant coverage is the ability to detect a wide range of water contaminants and is measured by the contamination detection potential, contamination scenario coverage, and contaminant detection threshold metrics. Since there were no contamination incidents during the evaluation, water contamination was simulated with 17 contaminants to assess contaminant scenario coverage and the contaminant detection threshold. In order for a contaminant to be considered theoretically detectable by the WQM component, at least one of the measured water quality parameters must produce a statistically significant change in the presence of that contaminant. In order for a scenario to be practically detectable, a contaminant concentration sufficient to produce such a change must reach at least one WQM location. **Table ES-1** shows that all 17 contaminants simulated are theoretically detectable by the WQM component based on a bench-scale evaluation of the impact of various contaminants on measured water quality parameters. The table also presents the percentage of practically detectable scenarios that were actually detected by the WQM component. Note that the 17 contaminants being modeled in the simulation study were assigned generic IDs for security purposes. For more information on this topic, see Section 5.0.

Table ES-1. Contaminant Coverage for the WQM Component

Contaminant	Theoretically Detectable?	% Practically Detected Scenarios Detected
Nuisance Chemical 1	Yes	94%
Nuisance Chemical 2	Yes	84%
Toxic Chemical 1	Yes	91%
Toxic Chemical 2	Yes	78%
Toxic Chemical 3	Yes	65%
Toxic Chemical 4	Yes	89%
Toxic Chemical 5	Yes	81%
Toxic Chemical 6	Yes	90%
Toxic Chemical 7	Yes	57%
Toxic Chemical 8	Yes	0%
Biological Agent 1	Yes	94%
Biological Agent 2	Yes	67%
Biological Agent 3[1]	Yes	93%
Biological Agent 4[1]	Yes	89%
Biological Agent 5[1]	Yes	94%
Biological Agent 6[1]	Yes	64%
Biological Agent 7[1]	Yes	80%

[1] For these contaminants, the co-contaminant was used to determine the practically detectable concentrations

Design Objective: Alert Occurrence

An alert is an indication from an event detection system that unusual water quality characteristics have been detected. In the case of the Cincinnati CWS, the CANARY event detection system was implemented and both visual and audible notifications were produced for each alert generated. Alert occurrence tracks the frequency of alerts to determine how well the event detection system can discriminate between true water quality anomalies (including contamination) and normal variability in the underlying data. Metrics for this design objective include invalid alerts, valid alerts and alert co-occurrence. Invalid and valid alert rates were characterized using empirical data gathered during the real-time monitoring phase. The number of alerts produced dropped significantly over the evaluation period as sensor and event detection system performance improved: 154 alerts were produced across the 15 distribution system monitoring stations for the first month of the evaluation period, compared with 19 for the final month of evaluation.

The data was also retrospectively analyzed using the final CANARY software and configurations in order to better characterize performance. For the final six months of the evaluation period, using these final configurations, an average of 15 alerts per month was produced. And while this is much higher than was originally expected, the utility found that this rate was sustainable, as the average time to complete an alert investigation by the end of the evaluation period was under 15 minutes with training and experience.

The utility staff found investigation of alerts to be useful in increasing distribution system knowledge and identifying water quality changes relevant to system operations or water quality management. During the evaluation period, 49 real incidents of unusual water quality were identified by reviewers and CANARY detected 69% of them. This accounted for 5% of all alerts.

The analysis of alert occurrence was supplemented through analysis of alerts generated during the simulation study, which provides an indication of the ability of the component to detect contamination incidents. Of the 737 simulated contamination scenarios that were practically detectable by the WQM component (see the discussion under the previous design objective), an alert was generated in 643 (87%) of them. For more information on this topic, see Section 6.0.

Design Objective: Timeliness of Detection and Response

The timeliness of detection refers to the time between the presence of unusual water quality in the distribution system and the start time of the first WQM alert. Metrics evaluated to characterize this design objective include time for initial detection and time to fully investigate an alert. The time for initial detection includes the hydraulic travel time from the injection point to the WQM location and the time for the CANARY event detection system to recognize the anomaly and generate an alert. For WQM, the time to collect and transmit data is negligible (less than 4 minutes). The time to fully investigate an alert captures the time to perform all activities necessary to fully investigate the alert and determine whether it is an indication of possible contamination.

During real-time operation, the time for initial detection could only be calculated for the four incidents that originated at the treatment plant. The source of the water quality changes was unknown for the other incidents, and thus the time that the unusual water quality originated in the distribution system could not be identified. For the four incidents originating at the treatment plant, it took between 6.3 and 11.3 hours for unusual water to flow from the treatment plant to a WQM location with a median travel time of 7.5 hours. The median time it took for CANARY to produce an alert once unusual water had reached a monitoring location was 1.6 hours. Overall, the time for initial detection of these four incidents ranged from 7.6 to 17.4 hours, with a median of 13.1 hours. Note that an alert was not always generated at the first WQM location reached.

The time of initial detection can be calculated precisely for simulated contamination incidents because the injection time is known. For the simulated contamination incidents that were detected by WQM, the hydraulic travel time ranged from 30 minutes to 35.5 hours with a median of 7 hours. The time between contaminated water arriving at a monitoring location and generation of an alert ranged from nine minutes to 120 hours with a median of 46 minutes. Overall the time for initial detection of simulated contamination incidents ranged from 26 minutes to 154 hours with a median of 10.8 hours.

The time to investigate alerts received in real-time monitoring was between one and 23 minutes, with a median of 4.5 minutes. However, none of these resulted in full implementation of the component response procedures and thus do not illustrate how long a full WQM investigation would take. Therefore, the values from drills and exercises were used to quantify the time to fully investigate a WQM alert. Total investigation times from these drills and exercises ranged from 118 to 191 minutes. **Figure ES-1** shows the timeline from the first drill, in which it took 118 minutes to fully investigate this alert. Much of the time during the exercise was for site inspection and characterization. For more information on this topic, see Section 7.0.

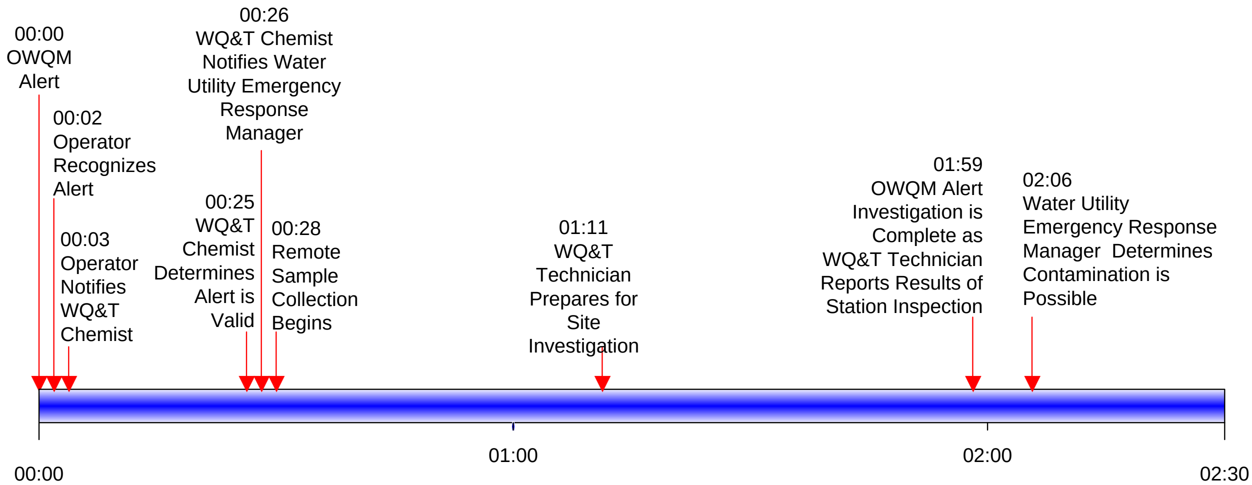

Figure ES-1. Timeline Progression of the WQM Alert Investigation During Drill 1

Design Objective: Operational Reliability

Operational reliability metrics quantify the percentage of time that the four WQM design element – WQM stations, data collection system, event detection system and component response procedures – were operating and producing accurate outputs. Overall, the component had 81.7% availability.

Causes of downtime included malfunctioning sensors producing no data or inaccurate data, loss of power to monitoring stations, failure of the communication system and the event detection system being turned off for maintenance or trouble shooting. The WQM station, data collection, and event detection design elements were unavailable for 28.2, 110, and 3,795 hours respectively. The event detection system element was by far the biggest contributor to component unavailability. For more information on this topic, see Section 8.0.

Design Objective: Sustainability

Sustainability is a key objective in the design of a CWS and each of its components, which for the purpose of this evaluation is defined in terms of the cost-benefit trade-off. Costs are estimated over the 20 year life-cycle of the system to provide an estimate of the total cost of ownership and include the implementation costs, enhancement costs, operation and maintenance (O&M) costs, renewal and replacement costs and the salvage value. The benefits derived from the system are defined in terms of primary and dual-use benefits. Metrics that were evaluated under this design objective include costs, benefits, and compliance. The costs used in the calculation of costs for the WQM component are presented in **Table ES-2**. These costs were tracked as empirical data during the design and implementation phase of project design, and were analyzed through a benefit-cost analysis. It is important to note that the Cincinnati CWS was a pilot research project, and as such incurred higher costs than would be expected for a typical large utility installation.

Table ES-2. Cost Elements used in the Calculation of Cost

Parameter	Value
Implementation Costs	$4,229,333
Annual O&M Costs	$178,478
Renewal and Replacement Costs	$1,555,555
Salvage Value	($96,686)
Dual-use benefits	($4,410)

To calculate the total cost of the WQM component, all costs and monetized benefits were adjusted to 2007 dollars using the change in the Consumer Price Index (CPI) between 2007 and the year that the cost or benefit was realized. Subsequently, the implementation costs, renewal and replacement costs, and annual O&M costs were combined to determine the total cost over the 20 year life-cycle of the project:

WQM Total Cost: **$8,202,994**

A similar WQM component implementation at another utility should be less expensive when compared to the Cincinnati pilot as it could benefit from lessons learned and would not incur research-related costs.

Dual-use benefits and compliance were evaluated through documentation of qualitative data during drills and exercises, and during forums with the utility including lessons learned workshops. While many dual-use benefits were realized over the course of the evaluation period, only one could be monetized and thus included in Table ES-2: a savings in the cost of chlorine feed solution was realized by allowing utility operators to more accurately adjust the amount of chlorine added at the treatment plants while maintaining the target disinfectant residual in the distribution system.

Compliance was demonstrated through 100% utility participation in drills and exercises which required substantially more effort than routine investigations, but was beneficial to the pilot utility as reported by personnel who indicated that they were able to better understand component response procedures through response to simulated water contamination incidents. Furthermore, compliance was evidenced by a high rate of alert investigations completed by utility personnel: by the end of the pilot evaluation period, compliance with the component response procedures reached an average value of 97%. For more information on this topic, see Section 9.0.

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Section 1.0: Introduction

The purpose of this document is to describe the evaluation of the online water quality monitoring (WQM) component of the Cincinnati pilot, the first such pilot deployed under the U.S. Environmental Protection Agency's (EPA) Water Security Initiative (WSI). This evaluation was implemented by examining the performance of the WQM component relative to the design objectives established for the contamination warning system (CWS).

1.1 CWS 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:

- **Spatial Coverage**. The objective for spatial coverage is to monitor the entire population served by the drinking water utility. It depends on the location and density of monitoring points in the distribution system and the hydraulic connectivity of each monitoring location to downstream regions and populations. Metrics evaluated under this design objective include area coverage and population coverage.
- **Contaminant Coverage**. The objective for contaminant coverage 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 system around a handful of specific contaminants. Contaminant coverage depends on the specific data streams analyzed by each monitoring and surveillance component, as well as the specific attributes of each component. Metrics evaluated under this design objective include contaminant detection potential, contamination scenario coverage, and contaminant detection threshold.
- **Alert Occurrence**. The objective of this aspect of system design is to minimize the rate of invalid alerts (alerts unrelated to contamination or other unusual water quality conditions) while maintaining the ability of the system to detect real incidents. It depends on the quality of the underlying data as well as the event detection systems that continuously analyze that data for anomalies. Metrics evaluated under this design objective include invalid alerts, valid alerts and alert co-occurrence.
- **Timeliness of Detection and Response**. The objective of this aspect of system design is to provide detection of a contamination incident in a timeframe that allows for the implementation of response actions that result in significant consequences reduction. Metrics associated with timeliness of detection and response include time for initial detection and time to investigate an alert. Timeliness of response is not addressed in this report: it is covered under the consequence management and sampling and analysis components.
- **Operational Reliability**. The objective for operational reliability is to achieve a sufficiently high degree of system availability, data completeness, and data accuracy in order to minimize the probability of missing a contamination incident. Metrics evaluated under this design objective include data completeness, data accuracy and availability.
- **Sustainability**. The objective of this aspect of system design is to develop a CWS that provides benefits to the utility and partner organizations while minimizing costs. This can be maximized by leveraging existing systems and resources. Furthermore, a design that results in dual-use applications that benefit the utility in 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 life cycle costs, benefits and acceptability.

The design objectives provide a basis for evaluation of each component - in this case WQM - as well as the entire integrated system. Because the deployment of a drinking water CWS is a new concept, design standards or benchmarks are unavailable. Thus, it was necessary to evaluate the performance of the pilot CWS in Cincinnati against the design objectives relative to the baseline state of the utility prior to CWS deployment.

1.2 Role of WQM in the Cincinnati CWS

Under the WSI, a multi-component design was developed to meet the above design objectives. Specifically, the WSI CWS architecture utilizes four monitoring and surveillance components common to the drinking water industry and public health sector: WQM, enhanced security monitoring (ESM), customer complaint surveillance, and public health surveillance. Information from these four components is integrated under a consequence management plan, which is supported by sampling and analysis activities, to establish the credibility of possible contamination incidents and to inform response actions intended to mitigate consequences.

As one of the four monitoring and surveillance components, WQM is intended to provide early detection of possible contamination incidents through monitoring for typical water quality parameters that have been experimentally shown to change in the presence of harmful contaminants (Hall, et al., 2007). In order to provide effective coverage throughout the distribution system, monitoring stations were installed at strategic locations selected with the aid of the utility's hydraulic model and sensor placement optimization software. Data from these monitoring stations is collected at a central location and analyzed in real-time for anomalies that might be indicative of contamination. If an anomaly is detected, an alert is generated and an investigation ensues to determine whether the alert can be explained by a known, benign cause. If it cannot, contamination is considered Possible and the Cincinnati Pilot Consequence Management Plan is activated to determine the credibility of the incident and respond as appropriate.

1.3 Objectives

The overall objective of this report is to demonstrate how well the WQM component functioned as part of the CWS deployed in Cincinnati (i.e., how effectively the component achieved the design objectives). This evaluation will describe how the deployed WQM component could reliably detect a possible drinking water contamination incident based on the operational strategy established for the Cincinnati pilot. Although no known contamination incidents occurred during the pilot period, data collection during routine operation, drills and exercises and computer simulations yielded sufficient data to evaluate performance of the WQM component against each of the stated design objectives. In summary, this document will discuss the approach for analysis of this information and present the results that characterize the overall operation, performance, and sustainability of the WQM component of the Cincinnati CWS.

1.4 Document Organization

This document contains the following sections:

- **Section 2: Overview of the WQM Component**. This section introduces the WQM component of the Cincinnati CWS and describes each of the major design elements that make up the component. A summary of significant modifications to the component that had a demonstrable impact on performance is presented at the end of this section.

- **Section 3: Methodology**. This section describes the data sources and techniques used to evaluate the WQM component.
- **Sections 4 through 9: Evaluation of WQM Performance against 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 WQM component against that design objective. Each supporting evaluation metric is discussed in a dedicated subsection, including an overview of the analysis methodology employed for that metric and discussion of the results. Each section concludes with a summary of WQM component performance relative to the design objective.
- **Section 10: Summary and Conclusions**. This section provides an overall summary of the WQM component evaluation, discusses limitations of the study, and describes potential additional applications.
- **Section 11: References**. This section lists all sources and documents cited throughout this report.
- **Section 12: Abbreviations**. This section provides a list of acronyms approved for use in the WQM component evaluation.
- **Section 13: Glossary**. This section defines terms used throughout the WQM component evaluation.

Section 2.0: Overview of the WQM Component

The WQM component of the CWS deployed at the Greater Cincinnati Water Works (GCWW) was operational by the end of 2007. A detailed description of the system at this point in the project can be found in *Water Security Initiative: Cincinnati Pilot Post-Implementation System Status* (USEPA, 2008a). During the next phase of the pilot, from January 2008 through June 2010, the system was evaluated and modified in an effort to optimize performance.

The WQM component of the Cincinnati CWS consists of four design elements:

1. WQM Stations: the sensors and ancillary systems that monitor water quality parameters at specific locations throughout the distribution system in real-time.
2. Data Collection System: the communication and data management system that captures the data from each WQM station and transfers it to the event detection system and a centralized data repository for further analysis and archiving. The data collection system also includes a user interface that displays event detection system alerts and real-time data from each monitoring location.
3. Event Detection System: the computer hardware and software that continually analyzes the time-series WQM data for anomalies indicative of possible contamination.
4. Component Response Procedures: the procedures involved in routine operation of the WQM component, including the initial investigation of alerts.

The objectives for each of these WQM design elements are shown in **Table 2-1** and were derived from the overarching design objectives for the CWS presented in Section 1.1.

Table 2-1. WQM Design Objectives

Design Element	Descriptions
1. WQM Stations	Deploy monitoring stations consisting of a suite of water quality sensors that provide broad contaminant coverage at locations in the distribution system that optimize spatial coverage and timeliness of detection. The sensors and equipment used in the design of the WQM stations must function within specifications and consistently produce accurate data. Proper instrument maintenance and routine calibration are essential to meeting this design objective, and the utility must be able to sustain the effort required to maintain the equipment.
2. Data Collection System	Deploy a communication system that transfers data from remote monitoring stations to a user interface for real-time monitoring, the event detection system, and a centralized data repository with minimal delay (i.e., less than five minutes from the time of measurement) and a high degree of reliability.
3. Event Detection System	Deploy an event detection system to continuously analyze the large amount of water quality data produced by the water quality sensors to detect anomalies that may be indicative of contamination. The event detection system should produce a minimal number of invalid alerts without missing significant water quality anomalies, including possible contamination incidents.
4. Component Response Procedures	Deploy procedures, roles, and responsibilities that support routine operation and the systematic review of WQM alerts in an effective and efficient manner that is aligned with normal utility activities to the extent possible.

The WQM design elements have been revised since they were presented in the *Water Security Initiative: Cincinnati Pilot Post-Implementation System Status* report (USEPA, 2008a). The "WQM Stations" and "WQM Network" design elements from the System Status report were combined into the "WQM

Stations" design element. The "Data Management and Communications" design element from the System Status report was renamed "Data Collection System". Lastly, the "Water Quality Event Detection" design element from the System Status report was divided into two design elements. The first, "Event Detection System", includes the hardware and software necessary to analyze time-series data for water quality anomalies. The second, "Component Response Procedures", includes the procedures that guide the investigation of WQM alerts. These changes were made in order to better align the design elements with the performance metrics discussed in this report.

Sections 2.1 through 2.4 provide an overview of each of the four WQM design elements, with an emphasis on changes to the component during the evaluation period. Section 2.5 summarizes all significant modifications to the WQM component that are relevant to the interpretation of the evaluation results presented in this report.

2.1 WQM Stations

The purpose of the WQM stations is to provide broad contaminant coverage by reliably and accurately monitoring select water quality parameters in real-time. WQM stations are located throughout the distribution system with the intent of optimizing spatial coverage and timeliness of detection. The WQM station designs were developed and locations were selected to satisfy these objectives.

2.1.1 WQM Station Design

The design of the WQM sensor stations includes selection of the specific water quality parameters to be monitored, the sensors used to monitor each parameter, and the design of the monitoring station that houses the sensors and ancillary equipment. Based on empirical data from bench and pilot studies demonstrating the response of typical water quality parameters to priority contaminants, the following parameters were selected for the design of the WQM stations: free chlorine residual; total organic carbon (TOC); conductivity and pH. Turbidity and temperature sensors were also incorporated into the monitoring stations even though they are not expected to be reliable indicators of contamination (Hall, et al., 2007). Some monitoring stations were also equipped with sensors for oxidation reduction potential (ORP), which tracked changes in the disinfectant residual and thus were used to corroborate trends observed from the chlorine sensors.

In order to evaluate different types of instruments and sensors, three monitoring station prototypes were installed which incorporated technology from different vendors. The three prototypes are generically referred to as Types-A, B, and C monitoring stations. The Type-A and Type-B stations were installed initially, and experience with these units were used to inform design of the Type-C stations. **Table 2-2** lists the instrumentation included in each of these prototypes. It is important to note that this was a pilot study and thus multiple instruments were chosen to provide information on a range of equipment. Also, the performance of each instrument is particular to the water quality and application in the Cincinnati pilot. Different results may be experienced by other utilities or on different waters.

One each of the Type-A and Type-B systems also included an s::can "carbo::lyser" TOC/turbidity analyzer with "con::stat" transmitter. The carbo::lyser is an optical spectral (visible-ultraviolet (UV) range) instrument, as contrasted with the standard, chemically-based methodology used by the Hach Astro and GE-Sievers TOC instruments. It was included as a redundant TOC analyzer to allow for side-by-side comparison of these two technologies.

Table 2-2. Instrumentation Included in each of the WQM Station Prototypes

Parameter	Type-A	Type-B	Type-C
pH	Hach GLI pHD	US Filter Depolox 3+, YSI 6500 multiparameter probe	Hach pHD sc
Conductivity	Hach GLI 3422	YSI 6500 multiparameter probe	Hach D3422C3
Turbidity	Hach 1720D	YSI 6500 multiparameter probe	Hach 1720E
ORP	Not included	YSI 6500 multiparameter probe	Hach pHD/ORP sc
Temperature	Hach GLI pHD	YSI 6500 multiparameter probe	Hach pHD sc
Chlorine	Hach chlorine-17	US Filter Depolox 3+ (Bare-Electrode Flow Cell was replaced by Membrane-Type Flow Cell in July 2008) YSI 6500 multiparameter probe	Hach chlorine-17
TOC	Hach Astro 1950Plus	GE-Sievers 900	GE-Sievers 900

All three WQM prototypes were designed as free standing systems mounted on casters for easy setup and relocation. They were neither hard-wired to a power source nor hard-piped to a water source or drain. Each system includes an electric cord compatible with a standard 120 VAC power receptacle. Each system is powered by an uninterruptable power supply (UPS) which provides approximately 24 hours of operation of all instruments, a local programmable logic controller (PLC), and communication equipment in the event the main power supply fails.

Each WQM station is equipped with a Normal/Calibrate switch which is used to indicate when a monitoring station is being serviced or calibrated. The state of this switch is transmitted back to a dedicated data collection system where it is used to suppress alerts from the event detection system, as discussed in Section 2.3.

The Type-B prototype WQM stations were equipped with two types of chlorine and pH sensors; one set of sensors was manufactured by U. S. Filter Depolox and the other by YSI. The intent of this design was to provide a preliminary evaluation of the solid-state technology offered by YSI. The YSI chlorine readings spiked and dipped on numerous occasions when compared to the U. S. Filter Depolox chlorine readings, which were relatively constant. Technicians also found that the YSI chlorine calibration process was tedious and overly-sensitive. YSI pH readings were consistently high, and technicians observed during site visits that the Depolox pH readings on the sensor display were accurate. In January 2007, prior to the start of the formal evaluation period, the decision was made to move forward with only the Depolox sensors and to decommission the YSI chlorine and pH sensors. This opened a channel that allowed temperature data to be transmitted to the supervisory control and data acquisition (SCADA) system, consistent with the Type A and C prototypes. Also, an analog signal cable was routed from the Depolox pH output to a spare analog input on the PLC, allowing Depolox pH to be monitored by the SCADA and event detection system systems.

In addition to the modification listed above, several changes were made to the WQM stations during the evaluation period. First, the s::can carbo::lyser TOC sensors deployed at one Type A monitoring station and one Type B monitoring station were producing erratic TOC measurements that deteriorated with time after periodic cleanings of the lamp assembly. The inaccurate readings were due to excessive buildup of aluminum oxide on the lamp assemblies, which was a product of a chlorinated water supply and the relatively high pH of the water. The problem was first observed in September 2007. The impact was reduced with additional cleanings but the issue persisted until May 2008, when the manufacturer agreed to provide two stainless steel carbo::lysers in exchange for the aluminum-based units at no cost to the utility. The new units were installed on May 19, 2008, requiring six hours of effort for installation, setup and calibration.

The Hach temperature sensors deployed on nine Type C stations produced measurements that were consistently 4.5 to 5.5 degrees higher than the values generated by temperature sensors on the Type A and B stations. The inaccurate readings were a result of the measurements being taken from water flowing through the pH probe, which does not maintain a constant head pressure. The problem was first observed in December 2007 and resolved on March 18, 2008 when the temperature inlets for the nine impacted stations were switched from the pH probe to the conductivity probe. No additional parts were needed for this modification which required 6.8 hours of effort.

The U.S. Filter Depolox chlorine and pH sensors deployed on five Type B stations were producing erratic and inaccurate measurements that could not be attributed to calibration or other routine maintenance activities. This problem was first experienced in January 2008. In March 2008, it was identified that the relatively high pH of the distribution system water was incompatible with the upper pH tolerance of the unit. The chlorine measurements were also determined to be inaccurate because chlorine is pH-compensated. The issue was resolved on July 16, 2008 when the US Filter-Depolox bare electrode probes and flow cell assemblies were replaced with US Filter-Depolox membrane probes and flow cell assemblies at all of the impacted stations. The manufacturer provided materials for four of the five upgrades, and the total cost for materials at the remaining monitoring station was $1,700. The replacements required 29.5 hours of effort for installation, setup, and calibration of the new probes.

The Hach Astro TOC units at all three Type A stations were eventually taken offline due to a long history of erratic and inaccurate measurements. The first was taken offline in June 2009. At this time, one of the Type B stations had two TOC units reading accurately (s::can and Sievers 900), so the s::can carbo::lyser was moved to the Type A monitoring station where the Hach TOC was removed. The Hach Astro TOC unit was taken offline at the next station in February 2010 and the last was taken offline in April 2010.

2.1.2 WQM Station Location Selection

For the Cincinnati CWS, the available sensor budget allowed for deployment of 17 WQM stations. Two of these monitoring stations were installed at the two entry points to the distribution system to provide a baseline for water quality in the distribution system. The remaining 15 monitoring stations were located throughout the distribution system using the drinking water utility's distribution system model, updated in 2005, and the Threat Ensemble Vulnerability Assessment and Sensor Placement Optimization Tool (TEVA-SPOT).

TEVA-SPOT uses a utility's distribution system model to simulate tens of thousands of contamination incidents throughout the distribution system and estimate the consequences associated with each. The resulting database of consequences is used to place a pre-defined number of monitoring stations at locations that maximize public health protection across all of the simulated scenarios (USEPA, 2008b). Potential monitoring locations were constrained to approximately 200 sites, including utility-owned facilities (e.g., pump stations), fire department stations, police department stations and a handful of other government-owned buildings to which GCWW had access. From this pool of potential sites, TEVA-SPOT produced candidate locations for the 15 remaining stations. These sites were inspected to verify that the locations met established requirements including site security, 24/7 access for utility staff, sufficient space for the monitoring equipment, an available 20-amp circuit, adequate water flow and pressure and hydraulic residence time of less than one hour in the supply line to the facility. Alternate locations were selected if the original location was practically infeasible. Finally, a regret analysis was performed to verify that the final design provided the desired coverage.

The selected monitoring locations included utility facilities, fire department facilities, and a police department facility. These locations were spread throughout the distribution system and typically served large downstream populations.

Only one change was made to the WQM locations during the evaluation period. In late 2007, one of the monitoring stations located at a utility pumping station began to periodically produce erratic sensor readings. Investigations revealed that the problem was caused by low pressure and intermittent flow to the monitoring location: operation of the pump station had been gradually reduced as more flow was moved through a newer pump station located just a few blocks away. To remedy this situation, the WQM station was moved to the new pump station on March 10, 2009 at a cost of $3,108 and approximately 40 hours of effort.

2.2 Data Collection System

The purpose of the data collection system is to receive and manage the raw data, provide this data to the event detection system, display the data from each WQM station in real-time, and display alerts generated by the event detection system when an unusual water quality condition is detected.

In the Cincinnati pilot, data from the WQM stations is transmitted to a central location using a secure digital cellular network. Two SCADA systems are used: one was pre-existing and handles the water quality and operations data collected outside of the pilot, and the second was implemented specifically for this pilot project to manage and store the data generated by the WQM sensors. In addition, this second SCADA system provides data to and collects results from the CANARY event detection system, described in Section 2.3, which is installed on a separate dedicated workstation.

Users access the data on SCADA workstations located throughout the utility via Human Machine Interface (HMI) software. HMI screens, designed as part of this pilot project, allow users to view a system map detailing the location and status of each monitoring station, as well as real-time values for all data streams collected, instrument faults, and event detection system alerts. Through the HMI, operators can also initiate remote sample collection at any monitoring station.

The data communication network includes many network security devices such as routers, switches, and firewalls to ensure data security and integrity. In addition, servers and user workstations are placed in demilitarized zones (DMZs) in order to protect the utility's critical networks. Protected networks can only communicate out through firewalls to these DMZs. This ensures that outside users do not have direct access to these systems.

In general, the data collection system performed according to specification and met the performance objectives for this design element of the system. Thus there were no significant modifications to this design element.

2.3 Event Detection System

The purpose of a WQM event detection system is to analyze time-series water quality data to search for anomalies indicative of possible contamination in real-time. If an anomaly is detected, an alert is generated and sent to the SCADA HMI implemented as part of the pilot project to notify users, and staff from various divisions in the utility participate in a joint investigation to determine the validity of the alert based on component response procedures.

In the Cincinnati pilot, the CANARY event detection system, developed by the Sandia National Laboratories in cooperation with USEPA's National Homeland Security Research Center, was deployed for real-time monitoring. CANARY contains multiple algorithms (Hart et al., 2007) developed and tested using empirical data relating water quality response to specific contaminants, as well as historic baseline data from large water utilities.

Deployment of the event detection system at the Cincinnati pilot involved training CANARY on historic water quality data from each monitoring station as well as establishing the procedures used to investigate an alert. Initially, three months of water quality data from each of the seventeen monitoring stations was used to train CANARY. The CANARY developers used this data to establish baseline water quality and determine initial algorithm configuration settings for each monitoring station.

The Event Detection Deployment, Integration, and Evaluation System (EDDIES) is an application that was developed to interface with the SCADA system and CANARY. EDDIES supports CANARY by collecting data from the SCADA systems in real-time, providing the data to CANARY and sending the outputs from CANARY back through the SCADA system to be viewed by utility staff.

CANARY and EDDIES underwent several modifications over the course of the evaluation period which are further described in detail in Table 2-5 and Section 6.1. The most effective changes were removing sensor data streams from analysis that had a long history of sensor issues and updating the parameter sensitivity variable in CANARY (described below). Forty-two hours of effort were required for CANARY configuration. Significant additional effort was required for debugging, implementing and testing software updates.

An important configuration setting in CANARY is the parameter sensitivity assigned to each data stream, which should reflect the smallest change that can be discriminated from normal instrument noise. Practically, this represents the smallest true change in the parameter value that could generate an alert. When CANARY was initially implemented in real-time, the CANARY parameter sensitivity settings were set to the manufacturer-specified sensor sensitivity. However, these did not represent actual instrument performance, and invalid alerts occurred due to extremely small changes in water quality parameter values. Parameter sensitivity settings for all parameters were updated to reflect actual instrument performance observed by GCWW staff. For example, the parameter sensitivity setting for chlorine sensors was changed from 0.01 to 0.1 mg/L, as a chlorine change of 0.01 mg/L was well within the range of typical instrument noise. The final parameter sensitivity values for all parameter types are shown in **Table 2-3**.

Table 2-3. Final CANARY Parameter Sensitivity Values

Parameter Type	Final Parameter Sensitivity Value
Chlorine	0.1
Conductivity	5
pH	0.1
ORP	10
TOC	0.1

EDDIES and CANARY also caused significant downtime of the WQM component. The SCADA system implemented as part of the pilot would periodically post files to the input source directory that contained no data, and this caused EDDIES to lock up. Also, there was no prompt verifying that the user indeed wanted to stop EDDIES, and there were several instances when staff accidently hit a button when browsing and EDDIES quit running. Following an EDDIES downtime event, CANARY required two to three days of data collection before producing a valid output. These issues were first discovered in

October 2007 and resolved on February 22, 2010 when new versions of EDDIES and CANARY were installed. 48 hours of effort were required.

After the February 2010 installation of the new version of CANARY, the performance of the event detection system was still not ideal. CANARY often alerted shortly after calibration events and would not alert for significant water quality (WQ) anomalies. As a result, new CANARY configuration files were developed which suppressed alerts shortly after calibration events, which significantly reduced the rate of invalid alerts. The updates to the CANARY configuration files required 80 hours of effort.

One significant issue remains at the time of writing. If the time between the SCADA system and EDDIES workstation is out of sync at all, CANARY output becomes erratic. Despite significant effort, no robust solution to this issue has been found. GCWW has found that the issue is generally resolved if the systems are reset and CANARY is restarted.

2.4 Component Response Procedures

When an event detection system alert indicates unusual conditions at a particular monitoring station, the pilot utility follows procedures that guide the initial investigation into potential causes of the alert (USEPA, 2008c). Component response procedures established a process flow, roles and responsibilities, information flow paths and checklists to provide a systematic process for reviewing relevant information about the possible cause of the alert. Specifically the following checks were performed:

- Treatment plant data is reviewed to determine if the alert was triggered by plant water quality changes.
- Distribution system operations are reviewed to determine whether recent changes in pumping, tank/reservoir operations or other changes in the hydraulic operations of the system caused the water quality change that generated the alert.
- Distribution system maintenance activities are reviewed to determine whether ongoing problems or repairs in the system caused the water quality change that generated the alert.
- Maintenance logs are reviewed for the alerting monitoring station.
- The monitoring station is inspected to determine whether instrument malfunction is responsible for the alert.

Several utility divisions and personnel are involved in the investigation of a WQM alert, and **Table 2-4** describes the role of various utility users. If the initial investigation does not reveal an obvious cause, contamination is considered Possible and the investigation is turned over to the Water Utility Emergency Response Manager, who will take additional steps to determine whether contamination is credible.

While no major changes were made in the component response procedures during the evaluation period, the process underwent several revisions based on the results of drills and exercises and experience with routine operation of the WQM component. Most modifications to the component response procedures involved clarifying roles and responsibilities and streamlining the investigation process.

Table 2-4. Roles and Responsibilities under the WQM Component Response Procedures

Utility User	Role in Routine Operation of WQM
Water Utility Emergency Response Manager	• Assume the lead in the credibility determination process, as outlined in the Cincinnati Pilot Consequence Management Plan, once possible contamination incident has been reported

Utility User	Role in Routine Operation of WQM
Water Quality & Treatment Chemist[1]	• Lead investigation of WQM alerts • Coordinate with System Operators and the Distribution Dispatcher to determine if operations or maintenance activities caused the alert • Review relevant data maintained by Water Quality & Treatment • Assess all information compiled during the investigation to determine if the alert is valid • Notify the Emergency Response Manager of possible contamination incidents
Water Quality & Treatment Technician	• Assist the Water Quality & Treatment Chemist during investigation of WQM alerts • Inspect monitoring stations that have detected unusual water quality, perform field verification of water quality sensor readings, and collect samples from the site
System Operator	• Receive the initial alert and notifies the Water Quality & Treatment Chemist • Support the alert investigation by reviewing operational data and assessing whether system operations might be the cause of the alert
Distribution Dispatcher	• Support alert investigation by reviewing maintenance activities in the distribution system and assessing whether these activities might be the cause of the alert
Treatment Supervisor/ Senior Plant Supervisor	• Support the investigation of alerts by reviewing operational data and assessing whether system operations might be the cause of the alert

[1] During off-hours or if the Water Quality & Treatment Chemist is unavailable, the Water Quality & Treatment Shift Chemist assumes these responsibilities. If neither of these is available, the Plant Supervisor leads an abbreviated investigation.

2.5 Summary of Significant WQM Component Modifications

The modifications discussed in the previous subsections were implemented to improve the performance of the WQM component. The impact of these component modifications on performance can be observed in the metrics used to evaluate the degree to which the component met the design objectives described in Section 1.1. **Table 2-5** summarizes these modifications and will serve as a reference when discussing the results of the evaluation presented in Sections 4.0 through 9.0.

Table 2-5. Sequential Listing of WQM Component Modifications

ID	Design Element	Component Modification		Date
1	Event Detection System	Modification	The CANARY configuration settings were changed for all stations.	May 16, 2008
		Cause	The number of alerts was unacceptable.	
2	Monitoring Stations	Modification	The aluminum housings for the s::can carbo::lysers were switched to stainless steel housings at one Type A and one Type B monitoring station.	May 19, 2008
		Cause	The aluminum housings were producing erratic TOC measurements resulting from a buildup of aluminum oxide on the lamp assemblies, which was caused by the relatively high pH of the chlorinated distributed water.	
3	Monitoring Stations	Modification	US Filter-Depolox bare electrode probes and flow assemblies were decommissioned and replaced with US Filter-Depolox membrane probes and flow assemblies at five Type B WQM Stations.	July 16, 2008
		Cause	The sensors were producing erratic and inaccurate chlorine and pH measurements because of the relatively high pH of the utility's water, which was higher than the upper pH tolerance of the sensor.	

ID	Design Element	Component Modification		Date
4	Event Detection System	Modification	The CANARY sensor settings (parameter sensitivity, max value, and min value) were changed.	October 29, 2008
		Cause	The number of alerts was unacceptable.	
5	Event Detection System	Modification	The TOC data streams were removed from analysis for eight stations	November 13, 2008
		Cause	The number of alerts triggered by the inaccurate TOC data was unacceptable.	
6	Event Detection System	Modification	Removed problematic data streams from two sites and changed configuration settings at two other sites with high false alert rates.	February 23, 2009
		Cause	The number of alerts was unacceptable.	
7	Monitoring Stations	Modification	One of the monitoring stations at a utility pump station was moved to a newer pump station located a few blocks away. Both pump stations serve the same general area of the distribution system.	March 10, 2009
		Cause	Operation of the first pump station had been gradually reduced by the utility as more flow was moved through the newer pump station several blocks away. The sensors at the original pump station location were increasingly producing erratic readings because of low pressure and intermittent flow.	
8	Event Detection System	Modification	The CANARY parameter sensitivity values were returned to previous values.	May 18, 2009
		Cause	The values were accidentally changed during the recent installation of the new version of EDDIES.	
9	Monitoring Stations	Modification	The Hach Astro TOC units were taken offline at three Type A WQM Stations.	June 2, 2009 – April 5, 2010
		Cause	There was a long history of erratic and inaccurate measurements.	
10	Event Detection System	Modification	New versions of EDDIES and CANARY were installed. A series of updates were installed as various bugs were encountered.	February – March 2010
		Cause	Software updates and an unacceptable number of alerts.	

Figure 2-1 presents a summary timeline for deployment of the WQM component, including milestone dates indicating the occurrence of significant component modifications and drills and exercises. The timeline also shows the completion date for design and implementation activities, followed by a transition period during which a few stations at a time were added to active monitoring until June 2009, when the full system was being monitored in real-time.

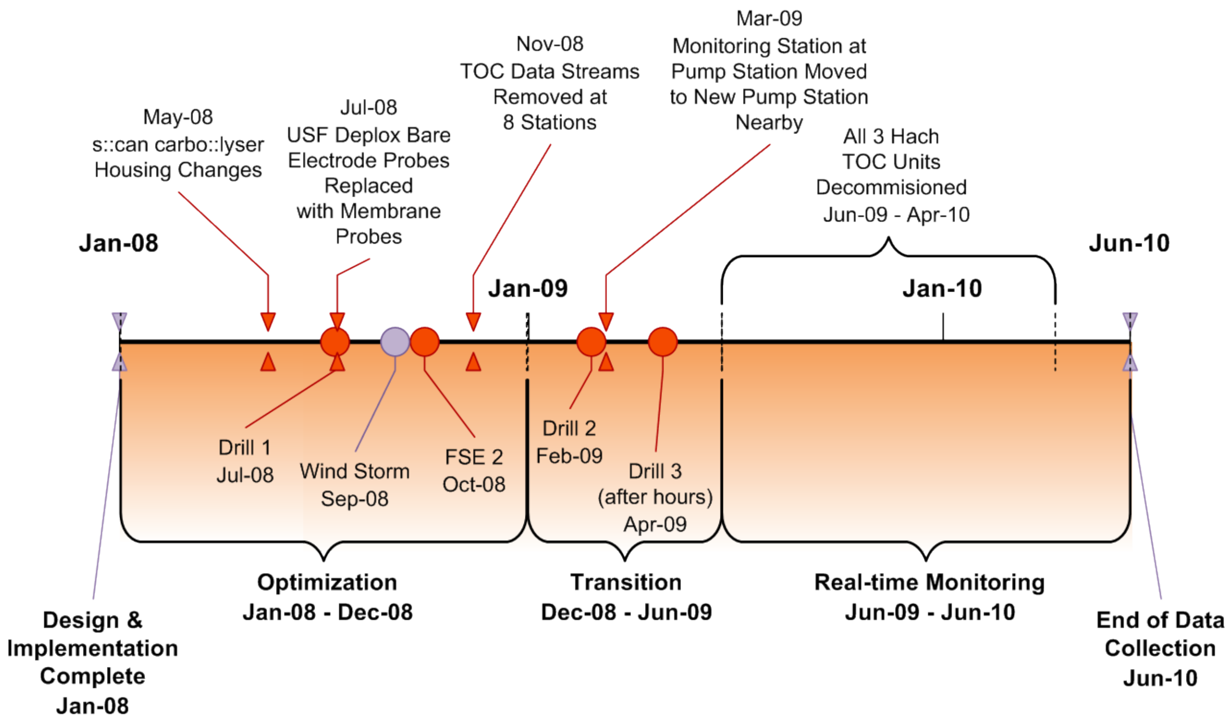


Figure 2-1. Summary Timeline of WQM Component Deployment

Section 3.0: Methodology

The following section describes five evaluation techniques and data sources that were used to fully evaluate the performance of the WQM component against the design objectives described in Section 1.1: empirical data from routine operations, results from drills and exercises, results from bench-scale contaminant studies, results from computer simulations of the Cincinnati CWS and findings from forums such as lessons learned workshops.

3.1 Analysis of Empirical Data from Routine Operations

This evaluation includes data on the performance, operation, and sustainability of the WQM component from January 16, 2008 to June 15, 2010. Metrics presented in a time-series format include data summarized on a month-to-month basis, and illustrate fluctuating trends in data over time. In this evaluation, the term "reporting period" is used to refer to a month of metrics data which spans from the 16th of one month to the 15th of the next month. Thus, the January 2008 reporting period refers to the data collected between January 16th, 2008 and February 15th, 2008. This time-series analysis is used to characterize the effectiveness of refinements made during the evaluation period.

The following design objectives were evaluated using empirical data collected during the evaluation period from the utility: operational reliability, alert occurrence and sustainability. Raw data produced by the water quality sensors and the output of the CANARY event detection system were evaluated. In addition, information about alerts and subsequent investigations was gathered from investigation checklists, which were completed for each WQM alert received by the utility during the evaluation period.

3.2 Drills and Exercises

Drills and Full Scale Exercises served a variety of purposes, both for optimization of the system and for evaluation. Benefits included:

- Providing utility staff with the opportunity to practice alert investigation procedures associated with recognition of and response to WQM alerts.
- Providing an opportunity to identify which portions of the component response procedures required modification to be more representative of preferred investigation and communication procedures.
- Allowing for evaluation of the timeliness of detection and response design objective.

Four drills and exercises were conducted for the purpose of evaluating the WQM design objectives. These are discussed below and include:

- WQM Drill 1 (July 14, 2008)
- CWS Full Scale Exercise (October 1, 2008)
- WQM Drill 2 (February 25, 2009)
- WQM Drill 3 After-Hours (April 29, 2009)

3.2.1 WQM Drill 1 (July 14, 2008)

Description: The scenario for the first WQM drill was an initial alert caused by changes in chlorine and conductivity, followed by an alert triggered by a change in TOC 30 minutes later.

Relevant Participants:
- GCWW WUERM, GCWW Water Quality & Treatment Division
- GCWW Water Quality & Treatment Chemist and Shift Chemist, GCWW Water Quality & Treatment Division
- GCWW Water Quality & Treatment Technician, GCWW Water Quality & Treatment Division
- GCWW System Operator, GCWW Distribution Division
- GCWW Plant Supervisor, GCWW Distribution Division
- GCWW Distribution Dispatcher, GCWW Distribution Division

This drill revealed several opportunities for improvement to the alert investigation process. The post-drill discussion also revealed some aspects of the component response procedures and site characterization sections of the Cincinnati Pilot Consequence Management Plan that should be revised to be consistent with utility procedures. Overall the evaluators observed that participants did a good job implementing the component response procedures given that this was the first drill.

3.2.2 CWS Full Scale Exercise (October 1, 2008)

Description: The purpose of this Full Scale Exercise was to allow GCWW and local response partner agencies to exercise their protocols for detecting and responding to a possible drinking water contamination incident. The exercise incorporated all components of the CWS. Several WQM alerts were simulated at different monitoring stations at different times. The overall impression of the evaluators was that utility personnel successfully followed the component response procedures for investigating and responding to a WQM alert.

Relevant Participants:
- GCWW WUERM, GCWW Water Quality & Treatment Division
- GCWW Water Quality & Treatment Chemist, GCWW Water Quality & Treatment Division
- GCWW Water Quality & Treatment Technician, GCWW Water Quality & Treatment Division
- GCWW System Operator, GCWW Distribution Division
- GCWW Plant Supervisor, GCWW Distribution Division
- GCWW Distribution Dispatcher, GCWW Distribution Division

3.2.3 WQM Drill 2 (February 25, 2009)

Description: The objective of the second WQM drill was to evaluate changes made to the component response procedures based on results from the first WQM drill and the Full Scale Exercise. Multiple WQM alerts were simulated at various times from several utility facilities. While evaluators felt that the System Operator and GCWW WUERM effectively implemented response procedures, training needs were identified for the GCWW Water Quality & Treatment Shift Chemist and the GCWW Water Quality & Treatment Technician. This was expected given that this was the first time that these staff were asked to perform these activities during a simulated contamination incident. This drill served as a training activity for staff with limited prior experience in implementation of the WQM component response procedures.

Relevant Participants:
- GCWW WUERM, GCWW Water Quality & Treatment Division
- GCWW Water Quality & Treatment Shift Chemist, GCWW Water Quality & Treatment Division
- GCWW Water Quality & Treatment Technician, GCWW Water Quality & Treatment Division
- GCWW System Operator, GCWW Distribution Division
- GCWW Plant Supervisor, GCWW Distribution Division
- GCWW Distribution Dispatcher, GCWW Distribution Division

3.2.4 WQM Drill 3 (After Hours) (April 29, 2009)

Description: The WQM After-Hours Drill was conducted to evaluate implementation of the component response procedures during non-business hours. An alert at a WQM station was simulated after normal business hours and actions of the utility personnel responsible for participating in the investigation of the alert were observed. The overall impression of the evaluators was that all utility personnel involved did an excellent job at implementing the procedures in the component response procedures.

Relevant Participants:
- GCWW WUERM, GCWW Water Quality & Treatment Division
- GCWW Water Quality & Treatment Shift Chemist, GCWW Water Quality & Treatment Division
- GCWW Water Quality & Treatment Technician, GCWW Water Quality & Treatment Division
- GCWW System Operator, GCWW Distribution Division
- GCWW Distribution Dispatcher, GCWW Distribution Division

3.3 Bench-scale Contaminant Studies

Bench-scale studies were performed to quantify the response of the water quality parameters monitored by the WQM component to specific contaminants over a range of concentrations. These experiments were performed on finished water from the two treatment plants operated by GCWW: the source for the plant that supplies the majority of the distribution system is surface water, while that for the smaller plant is groundwater. Chlorine is the residual disinfectant for both treatment plants.

Fresh aliquots of finished water from each treatment plant were collected. The water quality parameters were measured, and then the water was incrementally dosed with the contaminant under evaluation. In most experiments, five incremental doses were evaluated, with concentrations ranging from less than 1 mg/L to more than 50 mg/L. Actual concentration ranges were contaminant dependant. After each dose, the aliquot of test water was allowed to mix for two minutes after which the water quality parameters were re-measured.

The change in each water quality parameter was plotted as a function of concentration for each contaminant, and the following equation forms were applied to the data: linear, binomial, exponential and logarithmic. The best equation form was selected to model each correlation, considering both the correlation coefficient as well as the applicability of the model beyond the range of the empirical data. In most cases a linear equation was used to model the correlation between water quality parameter response and contaminant concentration. The results from the bench-scale contaminant studies were used to evaluate the contaminant coverage design objective and to parameterize the CWS simulation study, discussed next.

3.4 Simulation Study

Evaluation of certain design objectives relies on the occurrence of contamination incidents with known and varied characteristics. Because contamination incidents are extremely rare, there is insufficient empirical data available 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 (Allgeier et al., 2009). These incidents varied with respect to the contaminated used, the simulated injection location, the injection time, and the quantity and speed of contaminant injection.

For the WQM component, simulation study data was used to evaluate the following design objectives:

- **Contaminant Coverage:** Analyses conducted for this design objective quantify the ratio of contamination scenarios actually detected by the WQM component versus those that could theoretically be detected.
- **Spatial Coverage:** Spatial coverage was indirectly investigated by considering extent of contamination spread for contamination scenarios.
- **Alert Occurrence:** Analyses conducted for this design objective characterize valid alerts, as well as clusters of alerts involving multiple monitoring stations.
- **Timeliness of Detection:** Analyses conducted to evaluate this design objective quantify the time between the start of contaminant injection and the first WQM alert.

A broad range of contaminant types, producing a range of symptoms, was utilized in the simulation study to characterize the detection capabilities of the monitoring and surveillance components of a CWS. 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 broad categories listed below (the number in parentheses indicates the number of contaminants from that category that were simulated during the study).

- Nuisance Chemicals (2): these chemical contaminants have a relatively low toxicity and thus generally do not pose an immediate threat to public health. However, contamination with these chemicals can make the drinking water supply unusable.
- Toxic Chemicals (8): these chemicals are highly toxic and pose an acute risk to public health at relatively low concentrations.
- Biological Agents (7): these contaminants of biological origin include pathogens and toxins that pose a risk to public health at relatively low concentrations.

Development of a detailed CWS model required extensive data collection and documentation of assumptions regarding component and system operations. Model decision logic and parameter values were developed from data generated through operation of the Cincinnati CWS, as well as input from subject matter experts and available research.

The simulation study used several interrelated models, three of which are relevant to the evaluation of WQM: EPANET, the Health Impacts and Human Behavior (HI/HB) model and the WQM component model. The function of each of these models, and their relevance to the evaluation of WQM, is discussed below.

EPANET

EPANET is a hydraulic and water quality modeling application widely used in the water industry to simulate contaminant transport through a drinking water distribution system. In the simulation study, it was used to produce contaminant concentration profiles at every node in GCWW's distribution system model (which was calibrated for 2005 summer weeks), based on the characteristics of each contamination scenario in the ensemble. The concentration profiles were used to determine the number of miles of pipe contaminated during each scenario, which is one measure of the consequences of that contamination scenario. EPANET was also used by the WQM component model to generate alerts at the monitoring stations.

The HI/HB model used the concentration profiles generated by EPANET to simulate exposure of customers in the utility's service area to contaminated drinking water. Exposures occurred during one showering event in the morning (for the inhalation exposure route) or during five consumption events spread throughout the day (for the ingestion exposure route). The dose received during exposure events was used to predict infections, onset of symptoms, health-seeking behaviors of symptomatic customers and fatalities.

The primary output from the HI/HB model was a case table of affected customers, which captured the time at which each transitioned to mild, moderate, and severe symptom categories. Additionally, the HI/HB model outputted the times at which exposed individuals would pursue various health-seeking behaviors, such as visiting their doctor or calling the poison control center. The case table was used to determine the public health consequences of each scenario, specifically the total number of illnesses and fatalities. Furthermore, EPANET and the HI/HB model were run twice for each scenario; once without the CWS in operation and once with the CWS in operation. The paired results from these runs were used to calculate the reduction in consequences due to CWS operations for each simulated contamination scenario.

WQM Component Model

The WQM component model is based on the component as deployed and operated in the Cincinnati CWS. The WQM model consists of three modules, which are described below: a Contamination Simulator, the CANARY event detection system, and an Alert Validation module. The primary inputs to the WQM component model are the contaminant concentration profiles at each monitoring station for each contamination scenario, baseline water quality data collected from the sensors deployed at each monitoring station over the evaluation period, and contaminant properties.

As described in Section 5.1, bench-scale studies demonstrated that all 17 contaminants evaluated in the simulation study produced a measurable change in a measured water quality parameter at a sufficiently high concentration. Thus, all scenarios in the simulation study were considered theoretically detectable by WQM.

The Contaminant Simulator used the results from these bench-scale studies, along with the contaminant concentration profiles generated by EPANET, to predict the change in water quality that would correspond to the concentration profile for the specific contaminant used in the scenario (Allgeier, et al., 2011). The resulting water quality change profile was superimposed on the baseline water quality data for that monitoring station, as shown in **Figure 3-1**. The simulated dataset shown is identical to the baseline data shown in blue except for the short time period on September 1, 2011 where the chlorine dips down during the simulated contamination event.

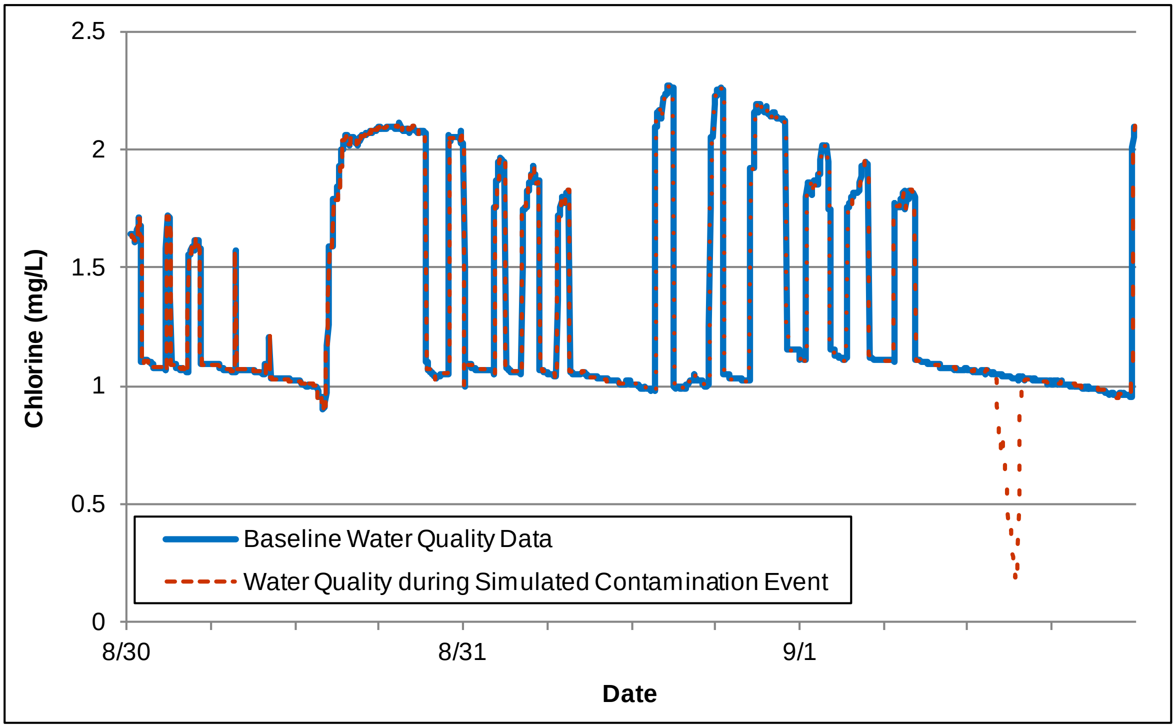


Figure 3-1. Superposition of a Contamination Incident on Baseline Water Quality Data

The following assumptions used in the design of the Contaminant Simulator are important to consider when evaluating the simulation study results presented in this report:

- The period of baseline data selected for use in the simulation study was selected to ensure that no invalid alerts would be generated during the study (though there were a few instances where CANARY produced an invalid alert - an artifact of using external software).

- As described in Section 5.1, for five of the biological agents, it was assumed that a co-contaminant was injected in order to maintain the potency of the biological material, and the co-contaminant produced the water quality response.

The modified water quality profiles generated by the Contaminant Simulator provided the input for CANARY. CANARY analyzed this time series data for each WQM station and each scenario. When CANARY detected an anomaly, it generated an alert along with a list of the water quality parameters that contributed to the alert.

Alerts generated by CANARY were inputted into the WQM Alert Validation module, which is modeled on the procedures used by utility personnel to investigate a WQM alert. Investigators assess the water quality parameters that changed (i.e., TOC or chlorine), check for hydraulic connectivity if more than one alert has occurred, and review distribution system operation work activities. The investigation also involves a site inspection at the monitoring station that generated the alert in order to evaluate whether the equipment is functioning properly. Relevant assumptions used in the WQM Alert Validation module are listed below. Note that these may not precisely reflect GCWW's actions.

- All WQM alerts are found to be valid (not due to a benign cause such as distribution system work activities) and due to changes in the water quality parameters impacted by the particular contaminant used in the scenario.

- All alerts triggered by a change in chlorine or TOC are fully investigated. This assumption is based on the observation that the Cincinnati utility staff place more weight on these two parameters when considering possible contamination because of past experience with these parameters. An alert investigation can be terminated before completion if there is only a single alert and that alert is not due to a change in either chlorine or TOC.
- All sensors are determined to be reading correctly during the site inspection. Shortly after completion of the site inspection, contamination is considered Possible.
- If two or more WQM alerts are generated, the investigator will conclude that they are hydraulically connected (they must be connected based on the study design which is based on the Cincinnati distribution system model). Thus, contamination is considered Possible shortly after receipt of a second alert.

3.5 Forums

Feedback and suggestions from utility personnel on all aspects of the WQM component were captured during the forums listed below. Information gathered through these forums provided insight regarding acceptability of the component to end users, as well as lessons learned from routine operations and recommendations for other utilities interested in implementing a CWS. Results from the forums were used to evaluate sustainability of the system related to the benefits of implementing a CWS.

- **Quarterly WQM Component Meetings**: Quarterly WQM component meetings were held throughout the evaluation period. These meetings were attended by EPA and utility personnel and a team of contractors. Component design, functionality, and modifications were discussed during these meetings, including the component modifications listed in Table 2-5.
- **WQM Lessons Learned Workshop**: A workshop was held on August 31, 2009 to capture lessons learned from the Cincinnati pilot through interactive discussions, 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 systems used in the WQM component (i.e., sensors, TEVA-SPOT, SCADA, CANARY, the component response procedures, etc.) used over the course of the pilot.
- **WQM Exit Interview**: An exit interview was held on August 18, 2010 to discuss the future of the WQM component at the Cincinnati pilot and to capture additional lessons learned since the workshop in August 2009. The utility indicated that they would continue to operate and maintain the WQM component, they discussed the dual-use benefits of the CWS which will be presented in Section 9.0, and they provided advice for new utilities considering CWS deployment.

3.6 Analysis of Costs

A systematic process was used to evaluate the overall cost of the WQM component over the 20-year lifecycle of the Cincinnati CWS. The analysis includes implementation costs, component modification costs, annual operations and maintenance (O&M) costs, renewal and replacement costs and the salvage value of major pieces of equipment at the end of the lifecycle.

Implementation costs include labor and other expenditures (equipment, supplies and purchased services) for installing the WQM component. Implementation costs were summarized in *Water Security Initiative: Cincinnati Pilot Post-Implementation System Status* (USEPA, 2008a), which was used as a primary data source for this analysis. In that report, overarching project management costs incurred during the implementation process were captured as a separate line item. However, in this analysis, the project management costs were equally distributed among the six components of the CWS and are presented as a separate line item for each component.

Component modification costs include all labor and expenditures incurred after the completion of major implementation activities in December 2007 that were not attributable to O&M costs. These modification costs were tracked on a monthly basis, summed at the end of the evaluation period and added to the overall implementation costs.

It should be noted that implementation costs for the Cincinnati CWS may be higher than those for other utilities given that this project was the first comprehensive, large-scale CWS of its kind and had no experience base to draw from. Costs that would not likely apply to future implementers (but which were incurred for the Cincinnati CWS) include overhead for EPA and its contractors, cost associated with deploying alternative designs, and additional data collection and reporting requirements. Other utilities planning for a similar large-scale CWS installation would have the benefit of lessons learned and an experience base developed through implementation of the Cincinnati CWS.

Annual O&M costs include labor and other expenditures (supplies and purchased services) necessary to operate and maintain the component and investigate alerts. O&M costs were obtained from procurement records, maintenance logs, investigation checklists and training logs. Procurement records provided the cost of supplies, repairs, and replacement parts, while maintenance logs tracked the staff time spent maintaining the WQM component. 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 logs 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.

Labor hours for both implementation and O&M were tracked over the entire evaluation period. Labor hours were converted to dollars using estimated local labor rates for the different institutions involved in the implementation or O&M of the WQM component.

The renewal and replacement costs are based on the cost of replacing major pieces of equipment at the end of their useful life. The useful life of WQM equipment 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 lifecycle of the Cincinnati CWS. The salvage value was estimated for all equipment with an initial value greater than ~$1,000. Straight line depreciation was used to estimate the salvage value for all major pieces of equipment based on the lifespan of each item.

All of the cost parameters described above (implementation costs, component modification costs, O&M costs, renewal and replacement costs, and salvage value) were used to calculate the total cost for the WQM component, as presented in Section 9.1.

Section 4.0: Design Objective: Spatial Coverage

It is economically infeasible to install WQM stations at a large percentage of distribution system nodes. Thus, 15 WQM locations were strategically selected in the distribution system through use of TEVA-SPOT to maximize spatial coverage in the distribution system. In order to evaluate how well the WQM component met the design objective for spatial coverage, the following two metrics were evaluated: area coverage and population coverage. Sections 4.1 and 4.2 define each metric, describe how it was evaluated and presents the results. Section 4.3 presents an indirect measure of spatial coverage by considering how many scenarios from the simulation study were monitored by the WQM component.

4.1 Area Coverage

Definition: Area coverage is defined as the percentage of the distribution system area that is covered by the WQM network, which is a superposition of the areas covered by each individual monitoring station. The area covered by each monitoring station is made up of the areas monitored by and protected by the station, as described below:

- **Area Monitored:** A portion of the distribution system is monitored by a WQM station if a contaminant injected in that area would flow past the monitoring station and thus potentially be detected. To determine the area monitored by each WQM location, contaminant injections were simulated using single point source injections at each of the nodes in the distribution system model with a non-zero demand, resulting in a total of 5,799 attack nodes. These modeling results were used to determine the monitoring stations that would receive contaminated water under the model conditions and thus potentially generate an alert, for each attack scenario.

- **Area Protected:** An area is protected by a WQM station if it is downstream of the station. Water flowing into a protected area would flow through the monitoring station first, thus providing an opportunity for detection and response. To determine the area protected by each monitoring station, contaminant injection was simulated at each of the 15 monitoring stations to determine the downstream area of the distribution system that would be impacted if contaminant flowed through that monitoring station.

Analysis Methodology: EPANET and the distribution system model were used to simulate contaminant injections throughout the distribution system. The flow path of each injection was captured to determine the areas covered by each monitoring station.

A standard contamination scenario, using the same contaminant type and total mass of contaminant, was used at all nodes for both analyses. The scenario selected for these analyses was one with the potential to spread widely throughout the distribution system and expose a large number of individuals.

The aggregate area containing nodes monitored by and protected by a WQM station constitutes the area *covered by* that station. The combined area covered by all 15 monitoring stations is the area covered by the entire WQM network. Note that the area covered by the WQM network is not simply the sum of the areas covered by the individual stations: some areas are covered by more than one monitoring station, as described below.

Table 4-1 shows the area and percentage of the distribution system covered by *at least* "**X**" monitoring stations, where "**X**" ranges from one to five stations. The distribution system area (339.2 square miles) was defined as the retail service area in Hamilton County included in the 2005 version of the utility distribution system model.

Table 4-1. Area Covered by At Least "X" Number of WQM Stations

Area	1 Monitoring Station	2 Monitoring Stations	3 Monitoring Stations	4 Monitoring Stations	5 Monitoring Stations
Area Covered By At Least "X" Monitoring Stations (mi^2)	243.8	188.8	137.6	89.7	65.8
% of Distribution System Area Covered By At Least "X" Stations	72%	56%	41%	26%	19%

The table shows that 72% of the distribution system is covered by at least one monitoring station. Also, more than half of the system (56%) is covered by at least two monitoring stations, and almost 20% of the distribution system is covered by five or more monitoring stations. There are areas covered by up to 13 monitoring stations, but these areas are in a small, densely populated region of the distribution system.

Redundancy in protection can prove valuable in detecting unusual water quality as there are more chances for potential detection (as subsequent sections show, missed detections are common). In addition, redundancy is beneficial when attempting to validate an alert: an alert is much more likely to be considered Possible if a water quality change can be seen at (or an alert is received from) multiple hydraulically connected monitoring stations.

4.2 Population Coverage

Definition: Population coverage is defined as the portion of the retail population within the area served by the distribution system that is covered by the WQM network.

Analysis Methodology: The results from the analysis of Area Coverage, presented in Section 4.1, were converted to population estimates using census data from 2000 on population density information. An individual is considered to be covered if they live in an area covered by the WQM network.

Results: Similar to Table 4-1, **Table 4-2** shows the population covered by at least "**X**" WQM stations, where "**X**" ranges from one to five. The total population served by the retail area of the distribution system, according to census data from 2000, is 759,000 people.

Table 4-2. Population Covered by At Least "X" Number of WQM Stations

Population	1 Monitoring Station	2 Monitoring Stations	3 Monitoring Stations	4 Monitoring Stations	5 Monitoring Stations
Population Covered By At Least "X" WQM Stations (individuals)	635,000	481,000	351,000	248,000	152,000
% of Population Covered By At Least "X" Stations	84%	63%	46%	33%	20%

Percentages of the *population* covered by at least one or two monitoring stations (84%, 63%) are substantially larger than the percentages of the distribution system *area* covered by at least one or two monitoring stations (72%, 56%). This resulted from the network design that was optimized to protect the population rather than attempting to maximize the area covered. Geospatial analyses (not presented) show that the regions within the distribution system with the highest population density are generally covered by at least one monitoring station.

4.3 Extent of Contaminant Spread through the WQM Network

Definition: A WQM location is considered to be *impacted* if it receives sufficient concentration to cause a change in at least one water quality parameter greater than or equal to the parameter sensitivity value set in CANARY in Table 2-3. A scenario is considered practically detectable by WQM if at least one monitoring station is impacted.

Analysis Methodology: In the simulation study, contaminant injections were simulated throughout the distribution system and the contaminant concentration was recorded at each timestep for each WQM station, as described in Section 3.4. In this analysis, the number of stations impacted in each simulated contamination scenario was determined through analysis of the contaminant concentration profile at each monitoring location: if the contaminant concentration at any timestep was sufficient to cause a change in at least one water quality parameter greater than or equal to the parameter sensitivity value set in CANARY in Table 2-3, then the monitoring location was considered impacted and added to the count used to quantify contaminant spread for the given scenario.

Note that the results presented in this section cannot be used to make general conclusions about spatial coverage. Contaminant spread is highly dependent on the design of the contamination scenarios selected for this study – particularly the injection locations and times, which determine the flow paths through the system, and the total mass of contaminant which determines its spread throughout the system. In addition, it relies on a specific version and configuration of the distribution system model.

Results: Of the 2,015 simulation study events, 737 scenarios were practically detectable by WQM. This is 36.6% of the simulated contamination scenarios. Within these scenarios, there were a total of 1,959 impacted WQM stations with an average of 2.7 stations impacted per scenario.

Figure 4-1 shows the number of scenarios for which at least "**X**" WQM stations were impacted (in red) and for which exactly "**X**" stations were impacted (blue). No scenarios impacted all 15 monitoring stations, though 8 scenarios impacted 14 stations.

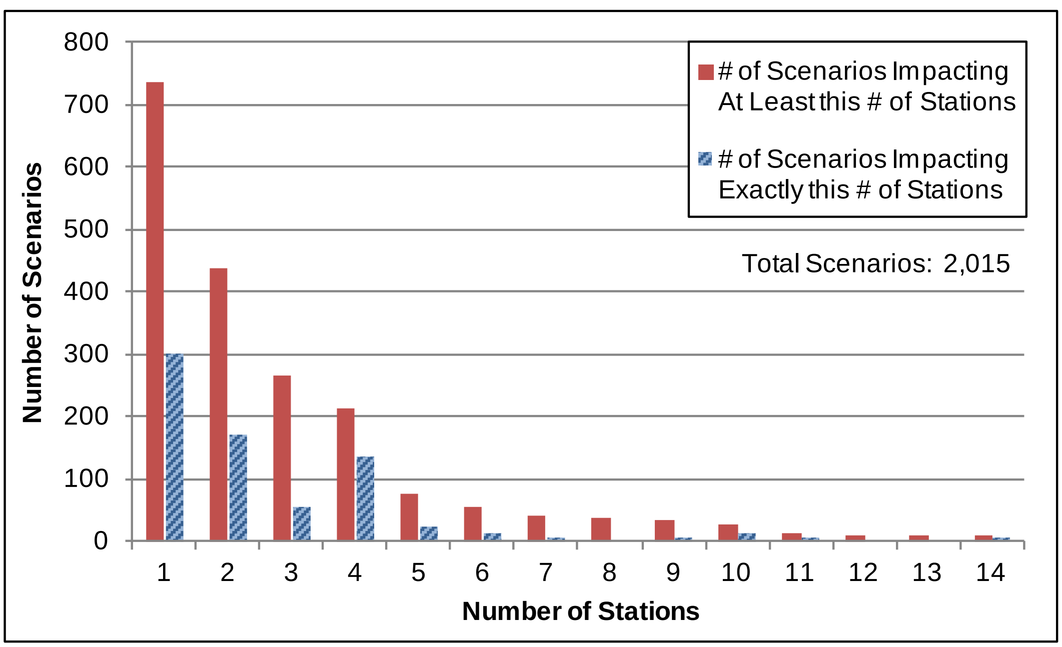


Figure 4-1. Number of Scenarios Impacting "X" WQM Stations

The majority of the 737 practically detectable scenarios (63.9%) impacted one or two monitoring stations, and the number of stations impacted seems to decrease exponentially from there. Looking at the second series, which shows the number of scenarios impacting exactly a given number of stations, it is interesting to note the unexpectedly low number of scenarios impacting exactly three stations compared to the number impacting two and four stations, and the relatively high number of scenarios impacting 10 and 14 stations. This is likely related to network hydraulics: there are large areas of the system where, if contaminant enters, it spreads significantly and impacts multiple monitoring stations.

In addition to the 1,959 impacted monitoring stations noted above, there were 1,664 instances where non-zero contaminant concentration reached a monitoring station, though not at a concentration that produced a sufficient change in a water quality parameter. Per the analysis methodology, these stations were not considered impacted and were thus not sites of potential alerts. A total of 866 of these instances occurred in scenarios that were not practically detectable by WQM, as no monitoring station observed a sufficient concentration during the scenario. There were 278 such scenarios, with a maximum of 14 stations receiving non-zero, though insignificant, concentrations during the scenario. Thus, the contaminant reached a WQM station in 1,015 scenarios (50.4%).

4.4 Summary

Spatial coverage of the WQM component is entirely dependent on the locations of WQM stations. Cincinnati's EPANET model was used to estimate the portion of the distribution system covered by the 15 monitoring stations, both in terms of area and population. The distribution area was well covered by the monitoring network as a whole, with 72% of the area and 84% of the population covered by at least one monitoring station. Almost 20% of the distribution area and population were covered by five or more monitoring stations. Portions of the most densely populated area were covered by up to 13 monitoring stations. The percentage of the population covered by at least one monitoring station was considerably larger than the percentage of the distribution system area covered by at least one monitoring station because the WQM network was designed to optimize the population protected rather than the amount of area covered.

Simulation study results were used to supplement the evaluation of this design objective. The contaminant concentration profiles generated during each of the simulated scenarios were used to identify all WQM stations that were impacted by a practically detectable contaminant concentration. Scenarios in which at least one WQM station received sufficient concentration to cause a change in at least one water quality parameter greater than or equal to the parameter sensitivity value set in CANARY found in Table 2-3 were considered to be practically detectable. Of the 2,015 simulation study scenarios, 737 (36.6%) were practically detectable by WQM, as at least one of the WQM stations was impacted. For detectable scenarios, between one and 14 stations were impacted. Note that these values are entirely dependent on the scenarios selected for this study; however, an effort was made to construct an ensemble of diverse and representative scenarios, as described in Section 3.4.

Section 5.0: Design Objective: 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 WQM component of the Cincinnati CWS was designed to detect a broad range of contaminants. Specifically, sensors were selected to monitor water quality parameters that respond to a broad range of potential contaminants. In order to evaluate how well the WQM component met this design objective, the following three metrics were evaluated: contaminant detection potential, contaminant scenario coverage and contaminant detection threshold. The following subsections define each metric, describe how it was evaluated and present the results. Note that the 17 contaminants being modeled in the simulation study were assigned generic IDs for security purposes.

5.1 Contaminant Detection Potential

Definition: The contaminant detection potential is the capability of the system to detect specific contaminants or contaminant classes. The detection potential is a function of the monitoring station design - specifically the water quality parameters that are monitored. In order for the WQM component to have the potential to detect specific contaminants, at least one of the measured water quality parameters must produce a statistically significant change from the baseline in the presence of the contaminant at a concentration capable of producing significant consequences. These critical concentrations are described below and are shown in **Table 5-7**.

Analysis Methodology: The critical concentrations used in this analysis were based on adverse impacts to the exposed population or utility infrastructure. Each contaminant was grouped into the categories described in Section 3.4, 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 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}).
- Co-contaminant: For contaminants that are sensitive to inactivation by chlorine, it was assumed that the contaminant would be injected with a dechlorinating agent to maintain the viability of the biological agent. The critical concentration was calculated based on this co-contaminant and was based on the concentration of free chlorine that would need to be quenched by the dechlorinating agent (for Cincinnati, the value used was 2 mg/L of free chlorine).

Empirical correlations derived from the bench-scale studies on distributed water, as described in Section 3.3, were used to calculate the change in each water quality parameter for eleven contaminants at the critical concentration. The study considered finished water from both of GCWW's treatment plants.

The calculated values were normalized by the parameter sensitivity values shown in Table 2-3. If the normalized response for a specific parameter was greater than or equal to 1.0, then that parameter has the potential to detect that contaminant. Note that the true capability of the WQM component to detect a contamination incident is strongly dependent upon the performance of the sensor hardware and event detection system. The use of a static threshold in this analysis is intended to serve as a theoretical estimate of the detection capabilities of the WQM component.

Results: The normalized response for each water quality parameter is presented in **Table 5-1** and **Table 5-2** for GCWW's two plants. The response value is shown for parameters significantly impacted by the contaminant, and these cells are green. Fields in the table with a dash indicate that no significant change was observed. Note that the reactions are influenced by the measurement technique and instrument used.

Table 5-1. Normalized Water Quality Response for Water from the Surface Water Plant

Contaminant	TOC	UV	Chlorine	ORP	Conductivity	pH
Nuisance Chemical 1	4.8	-	1.7	-	-	2.2
Toxic Chemical 1	23.5	-	228.4	5.3	13.1	6.9
Toxic Chemical 2	-	-	107.9	329.3	-	-
Toxic Chemical 3	-	175.8	8.8	136.4	3.9	178.5
Toxic Chemical 4	No Data	-	-	-	-	-
Toxic Chemical 5	48.3	33.6	54.0	6.4	-	-
Toxic Chemical 6	354.8	791.3	22.2	-	-	-
Toxic Chemical 8	-	-	-	1.1	-	-
Biological Agent 1	No Data	214.9	29.8	12.3	-	2.9
Co-contaminant 1	No Data	-	8.3	22.6	-	-
Co-contaminant 2	123.8	-	4.4	7.9	3.6	-

Table 5-2. Normalized Water Quality Response for Water from the Groundwater Plant

Contaminant	TOC	UV	Chlorine	ORP	Conductivity	pH
Nuisance Chemical 1	4.9	-	-	-	-	-
Toxic Chemical 1	No Data	No Data	No Data	No Data	No Data	No Data
Toxic Chemical 2	No Data	No Data	No Data	No Data	No Data	No Data
Toxic Chemical 3	-	153.7	-	160.6	13.3	128.8
Toxic Chemical 4	102.6	-	-	-	8.5	-
Toxic Chemical 5	51.5	169.8	49.9	34.2	3.1	-
Toxic Chemical 6	334.8	665.1	38.5	-	-	-
Toxic Chemical 8	-	-	-	2.8	-	-
Biological Agent 1	266.3	152.0	18.9	15.7	-	1.0
Co-contaminant 1	-	-	22.2	26.6	-	-
Co-contaminant 2	16.1	2.3	2.4	4.0	-	-

For the surface water plant, at least one parameter changed for each of the eleven contaminants tested, with the exception of Toxic Chemical 4 for which the TOC sample could not be analyzed. For the groundwater plant water, at least one parameter changed for each of the nine contaminants tested (Toxic Chemical 1 and Toxic Chemical 2 were not tested with this water). In general, the water quality parameter responses were consistent between the two water matrices. The differences in response were generally small and partially attributable to experimental error or uncertainty in the curve fit.

The results from the two waters were averaged to produce the response matrix shown in **Table 5-3**. In cases where results were available for only one of the waters, that value is used.

Table 5-3. Average Normalized Water Quality Response

Contaminant	TOC	UV	Chlorine	ORP	Conductivity	pH
Nuisance Chemical 1	4.9	-	-	-	-	1.1
Toxic Chemical 1	23.5	-	228.4	5.3	13.1	6.9
Toxic Chemical 2	-	-	107.9	329.3	-	-
Toxic Chemical 3	-	164.7	4.4	148.5	8.6	153.7
Toxic Chemical 4	102.6	-	-	-	4.3	-
Toxic Chemical 5	49.9	101.7	51.9	20.3	1.6	-
Toxic Chemical 6	344.8	728.2	30.4	-	-	-
Toxic Chemical 8	-	-	-	2.0	-	-
Biological Agent 1	266.3	183.4	24.4	14.0	-	2.0
Co-contaminant 1	-	-	15.2	24.6	-	-
Co-contaminant 2	70.0	1.2	3.4	6.0	2.0	-

The average results show all contaminants have the potential to be detected through WQM. Also, all contaminants except for Toxic Chemical 8 changed two or more parameters, which would increase the likelihood of detection.

Chlorine and ORP (which generally tracks chlorine) provided the greatest contaminant coverage, responding to eight of the eleven test contaminants. TOC increased in the presence of all organic contaminants to provide detection potential for seven of the test contaminants. UV changed above the parameter sensitivity value for five contaminants, four of which also produced a response in TOC. Five contaminants impacted conductivity, and all five were either salts or compounds that dissociate into ionic species in water. Four contaminants changed pH above the parameter sensitivity value.

The results of these empirical, bench-scale studies were used to establish the detection potential for each of the 17 test contaminants evaluated in the simulation study, which was described in Section 3.4. The results in **Table 5-4** show the water quality parameters that are expected to change significantly for each contaminant present at the critical concentration. The potential response is indicated only by a YES/NO designation. Also, the parameter type(s) which are most significantly impacted are specified by bolded text in Table 5-4. These are the parameter type(s) which reached the required minimum change at the lowest concentration.

In cases where the particular contaminant was not tested during the bench-scale contaminant study, the response was extrapolated from the results of a tested contaminant that exhibits similar chemistry to the subject contaminant. For five of the biological agents, the co-contaminant introduced with these contaminants is responsible for the water quality change detectable by WQM. While the actual biological contaminants would be undetectable at the critical concentration, the concentrations of co-contaminants could cause detectable changes in water quality parameter values.

Table 5-4. Expected Water Quality Response for Contaminants Evaluated in the Simulation Study

Contaminant	TOC	UV	Chlorine	ORP	Conductivity	pH
Nuisance Chemical 1	**YES**	NO	NO	NO	NO	YES
Nuisance Chemical 2	**YES**	NO	NO	NO	NO	NO
Toxic Chemical 1	YES	NO	**YES**	YES	YES	YES
Toxic Chemical 2	NO	NO	YES	**YES**	NO	NO
Toxic Chemical 3	NO	YES	YES	YES	YES	**YES**

Contaminant	TOC	UV	Chlorine	ORP	Conductivity	pH
Toxic Chemical 4	**YES**	NO	NO	NO	YES	NO
Toxic Chemical 5	YES	YES	**YES**	YES	YES	NO
Toxic Chemical 6	**YES**	YES	YES	NO	NO	NO
Toxic Chemical 7	**YES**	NO	YES	NO	NO	NO
Toxic Chemical 8	NO	NO	NO	**YES**	YES	NO
Biological Agent 1	**YES**	YES	YES	YES	NO	YES
Biological Agent 2	**YES**	NO	NO	NO	NO	NO
Biological Agent 3	NO	NO	**YES**	**YES**	NO	NO
Biological Agent 4	NO	NO	**YES**	**YES**	NO	NO
Biological Agent 5	NO	NO	**YES**	**YES**	NO	NO
Biological Agent 6	NO	NO	**YES**	**YES**	NO	NO
Biological Agent 7	NO	NO	**YES**	**YES**	NO	NO

All simulation study contaminants are theoretically detectable through WQM. For every detected contaminant except for Toxic Chemical 3, chlorine or TOC was the most significantly impacted parameter.

Table 5-5 shows the practically detectable concentration for each of the 17 simulation study contaminants, along with the water quality changes that concentration produces. As discussed in Section 4.3, a contaminant concentration is practically detectable if it causes a change in at least one water quality parameter greater than or equal to the value of the parameter sensitivity value as configured in CANARY. Each parameter's sensitivity value (from Table 2-3) is shown in the second row of the table, and the second column shows the practically detectable concentration for each contaminant. The remaining cells show the change in each water quality parameter that would be caused by this detectable concentration. The green shading and asterisk indicate that the water quality change meets the sensitivity value for that parameter.

Table 5-5. Practically Detectable Contaminant Concentrations and Resulting Water Quality Changes

Contaminant	Minimum Practically Detectable Concentration	Parameter Type and Parameter Sensitivity Value				
		TOC (0.1 ppm)	Chlorine (0.1 mg/L)	ORP (10 mV)	Conductivity (5 µS/cm)	pH (0.1)
Nuisance Chemical 1	**2.1 mg/L**	0.1*	-0.03	0	2.91	0.05
Nuisance Chemical 2	**0.30 mg/L**	0.1*	0	0	0	0
Toxic Chemical 1	**0.13 mg/L**	0.01	-0.1*	-6.42	0.29	0.003
Toxic Chemical 2	**0.11 mg/L**	0	-0.03	-10*	0	0
Toxic Chemical 3	**2.0 mg/L**	0	-0.01	8.76	0.42	-0.1*
Toxic Chemical 4	**0.56 mg/L**	0.1*	0	2.94	0.42	0
Toxic Chemical 5	**0.29 mg/L**	0.08	-0.1*	-1.12	0.09	0
Toxic Chemical 6	**0.29 mg/L**	0.1*	-0.01	-0.5	0	0

Contaminant	Minimum Practically Detectable Concentration	Parameter Type and Parameter Sensitivity Value				
		TOC (0.1 ppm)	Chlorine (0.1 mg/L)	ORP (10 mV)	Conductivity (5 µS/cm)	pH (0.1)
Toxic Chemical 7	0.29 mg/L	0.1*	-0.01	-0.5	0	0
Toxic Chemical 8	0.45 mg/L	0	0	10*	0.44	0
Biological Agent 1	0.17 mg/L	0.1*	-0.01	-0.46	0	0.001
Biological Agent 2	0.15 mg/L	0.1*	0	0	0	0
Biological Agent 3	0.00005 mg/L[1]	0	-0.1*	-10*	0.1	0
Biological Agent 4	1,271 organisms/L[1]	0	-0.1*	-10*	0.1	0
Biological Agent 5	127 organisms/L[1]	0	-0.1*	-10*	0.1	0
Biological Agent 6	29,863 organisms/L[1]	0	-0.1*	-10*	0.1	0
Biological Agent 7	2,818,131 organisms/L[1]	0	-0.1*	-10*	0.1	0

[1] For these contaminants, the co-contaminant was used to determine the practically detectable concentrations
* Water quality change meets the sensitivity value for that parameter

5.2 Contaminant Scenario Coverage

Definition: Contaminant scenario coverage is defined as the number or percentage of contamination scenarios detected by the WQM component. A scenario is considered detected if at least one alert is generated during the scenario.

Analysis Methodology: The results from the simulation study were used to characterize contaminant scenario coverage by the WQM component. As discussed in Section 5.1, all contaminants evaluated in the simulation study are theoretically detectable by WQM, but a scenario is only considered practically detectable if one or more WQM station is impacted by sufficient contaminant concentration. At lower concentrations, the contaminant changes monitored parameter(s) but the resulting water quality changes are below the parameter sensitivity value in CANARY, which reflects normal system water quality variability.

Note that the results presented in this section cannot be used to make general conclusions about contaminant scenario coverage outside of the context of the simulation study. Different scenario designs, using different contaminant masses, target in-pipe concentrations, injection rates, and injection locations, could produce drastically different results leading to different conclusions about contaminant scenario coverage.

Results: The analysis presented in Section 4.3 showed that 1,278 scenarios (63%) were not practically detectable because no WQM location witnessed a practically detectable contaminant concentration. Of the 737 practically detectable scenarios, 643 were actually detected, which is 87.2% of practically detectable scenarios and 31.9% of all scenarios. WQM was the only component to detect 178 of the scenarios (9% of all scenarios), and it produced the first alert for 257 scenarios (12.8% of all scenarios).

Table 5-6 summarizes scenario detection by contaminant. The second column lists the number of scenarios that were simulated for each contaminant and the third column shows the number and percentage of simulated scenarios that were practically detectable by WQM. The final column shows the number and percentage of practically detectable scenarios for the contaminant that were detected.

Though the number of events simulated for each contaminant is essentially the same, the number of practically detectable scenarios varies significantly by contaminant, from 1 (1% of simulated events) for Toxic Chemical 8 to 85 (71%) for Biological Agent 5.

Table 5-6. Scenarios Detected by Contaminant

Contaminant	# of Scenarios Simulated	Practically Detectable Scenarios	Practically Detectable Scenarios Detected
Nuisance Chemical 1	119	84 (71%)	79 (94%)
Nuisance Chemical 2	119	83 (70%)	70 (84%)
Toxic Chemical 1	119	45 (38%)	41 (91%)
Toxic Chemical 2	119	18 (15%)	14 (78%)
Toxic Chemical 3	119	23 (19%)	15 (65%)
Toxic Chemical 4	119	45 (38%)	40 (89%)
Toxic Chemical 5	119	31 (26%)	25 (81%)
Toxic Chemical 6	119	72 (61%)	65 (90%)
Toxic Chemical 7	119	7 (6%)	4 (57%)
Toxic Chemical 8	119	1 (1%)	0 (0%)
Biological Agent 1	119	31 (26%)	29 (94%)
Biological Agent 2	119	15 (13%)	10 (67%)
Biological Agent 3	119	84 (71%)	78 (93%)
Biological Agent 4	119	80 (67%)	71 (89%)
Biological Agent 5	119	85 (71%)	80 (94%)
Biological Agent 6	113	28 (25%)	18 (64%)
Biological Agent 7	117	5 (4%)	4 (80%)
OVERALL	**2,015**	**737 (37%)**	**643 (87%)**

This is directly related to the amount of contaminant injected relative to the practically detectable concentration. The three contaminants with the least number of practically detectable scenarios (Toxic Chemicals 2 and 8 and Biological Agent 2) were also the contaminants that had the lowest total mass available for injection into the distribution system. Thus, the contaminant did not spread far from the injection location at practically detectable concentrations, limiting the potential for detection by WQM. At the other end of the spectrum, more than 67% of the simulated scenarios were practically detectable for the two nuisance chemicals and three of the biological agents. The two nuisance chemicals are available in large quantities and are injected at rates that can spread widely throughout the distribution system. Biological Agents 3, 4, and 5 are available in much smaller quantities but are injected with a co-contaminant that is available in large quantities: it is this co-contaminant that is detectable by WQM.

Biological Agent 6 is also injected with a co-contaminant. However, the dose of this contaminant required for infection is much larger than the other biological agents. The scenarios using this contaminant were designed to achieve a limited spread in order to prevent the contaminant from being diluted to harmless concentrations. Thus, practically detectable concentrations often did not reach a monitoring location.

The percentage of practically detectable scenarios that were detected also varied by contaminant, from 0% for Toxic Chemical 8 to 94% for Nuisance Chemical 1, Toxic Chemical 4 and Biological Agent 5.

With the exception of Toxic Chemical 8, at least 57% of practically detectable scenarios were detected. There was a direct relationship between the number of practically detectable scenarios and detection percentage: less than 80% of scenarios were detected for all contaminants with less than 30 practically detectable scenarios, and more than 80% were detected when there were more than 30 practically detectable scenarios.

Comparison of Table 5-4, which shows the water quality parameters impacted by each contaminant, with the detection percentages shown in Table 5-6 shows no obvious correlation. Two contaminants impact only TOC (Toxic Chemical 4 and Biological Agent 2); however, scenarios involving the former were detected at a rate of 94%, while those involving the latter were detected at a rate of only 67%. Scenarios involving Toxic Chemical 7 were detected at the lowest rate other than Toxic Chemical 8, yet this toxic chemical impacts two reliable water quality parameters, TOC and chlorine. What cannot be gleaned from these tables is the actual change in water quality values caused by the contaminants which is further investigated in Section 5.3.

5.3 Contaminant Detection Threshold

Definition: The contaminant detection threshold is the lowest concentration of a specific contaminant that can be detected by the WQM component.

Analysis Methodology: Two sources of information were used to assess the contaminant detection threshold: the bench-scale contaminant studies and the simulation study. The results from the bench-scale contaminant studies, described in Section 3-3, were used to develop empirical relationships between the contaminant concentration and a change in water quality parameters impacted by the contaminant (see Table 5-5). The minimum change in each water quality parameter considered practically detectable (i.e., the parameter sensitivity values used in CANARY, shown in Table 2-3) were used with these empirical relationships to estimate the detection threshold for each of contaminants evaluated in the simulation study.

Additionally, results from the simulation study were used to investigate the minimum contaminant concentrations that triggered WQM alerts during simulated contamination scenarios. Unlike the analysis of the empirical results from the bench-scale studies, which rely on only the water quality change in a beaker, the results from the simulation study incorporate the effects of the sensitivity of the water quality event detection system and the baseline water quality variability of each monitoring location. For this analysis, a simplifying assumption was made that the peak contaminant concentration at a monitoring location that detected the scenario was the concentration that triggered the specific alert (an assumption necessary due to limited concentration data extracted during simulations). In reality, the alert may have been triggered before this peak was reached and thus detected at a lower concentration. This simplifying assumption generally results in an overestimate of the contaminant detection threshold. Again, these results are specific to conditions of the simulation study and the configuration of the WQM component of the Cincinnati CWS and cannot be extrapolated to WQM in general.

Results: Table 5-7 presents estimates of the detection threshold for each contaminant, normalized to the critical concentration, as described in Section 5.1. The second column shows the ratio of the critical concentration to the minimum concentration at which practically detectable water quality changes occur, from Table 5-5. As described previously, this practically detectable concentration is based on the results of bench-scale studies and the precision settings in CANARY. The third column shows ratio of the critical concentration to the smallest peak concentration that generated a WQM alert during the simulation study. The ratios presented in this table are intended to show whether the detection limit, as characterized by these two different techniques, was lower than the critical concentration (i.e., the smallest concentration that could produce significant consequences). A ratio greater than one indicates that the contaminant can be detected at a concentration below the critical concentration. Larger ratios generally imply superior detection capabilities.

Table 5-7. Ratio of Critical Concentration to Detection Threshold by Contaminant

Contaminant	Ratio of Critical Concentration to Contaminant Concentration that is Practically Detectable	Ratio of Critical Concentration to Minimum Peak Concentration Actually Detected in Simulated Contamination Scenarios
Nuisance Chemical 1	4.76	2.7
Nuisance Chemical 2	33.0	16
Toxic Chemical 1	228	122
Toxic Chemical 2	463	227
Toxic Chemical 3	185	99
Toxic Chemical 4	104	66
Toxic Chemical 5	57.6	23
Toxic Chemical 6	352	182
Toxic Chemical 7	1.97	1.1
Toxic Chemical 8	0.0333	-
Biological Agent 1	265	128
Biological Agent 2	1,310	736
Biological Agent 3[1]	2.40	1.03
Biological Agent 4[1]	3.57	3.5
Biological Agent 5[1]	7.87	5.3
Biological Agent 6[1]	9.70	5.3
Biological Agent 7[1]	0.582	0.41

[1] For these contaminants, the co-contaminant was used to determine the practically detectable concentrations

Detection limits characterized using the practically detectable concentration were consistently lower than those determined from the simulation study results, and thus the ratios were larger for the former for all 17 contaminants. This is expected given that the simulation study results incorporated the variability in the water quality baseline at each monitoring location as well as the performance limitations of CANARY. However, both methods used to assess the detection limit show that WQM can detect the contaminants at concentrations lower than the critical concentration, with the exception of Toxic Chemical 8 and Biological Agent 7. The ratios for Biological Agent 7 were 0.58 and 0.41 according to the two methods, indicating that the detection limit is about twice the critical concentration. Toxic Chemical 8 was not detected during the simulation study and has an extremely low ratio using the practically detectable concentration due to the extremely low critical concentration established for this contaminant.

Each monitoring location has different baseline water quality patterns, as discussed in Section 6.1, and these differences dramatically impact the monitoring location's contaminant detection threshold. Simulation study results were used to evaluate the impact of water quality variability on the detection threshold. For each monitoring station, the minimum peak concentration that was detected was captured for each contaminant. Location J had detection thresholds that were significantly greater than those observed at the other WQM locations over all contaminants. This was not due to water quality variability at location J, but instead was an artifact of the simulated contamination scenarios used in this study which resulted in this monitoring location witnessing only extremely high contaminant concentrations and thus not having the opportunity to detect lower concentrations. In order to obtain a representative range of detection thresholds for each contaminant, location J was excluded from the following analysis.

The range of detection thresholds across the remaining 14 monitoring locations is presented in **Table 5-8**: specifically, the minimum, maximum and median detection thresholds are shown for each contaminant, normalized by each contaminant's practically detectable concentration. For the minimum and maximum thresholds, the monitoring location at which that threshold occurred is shown in parentheses. For example, the lowest peak concentration of Nuisance Chemical 1 that was detected was 1.8 times (less than twice) the practically detectable concentration, and that detection occurred at location F. However, this same contaminant was not detected at concentrations less than 14.8 times the practically detectable concentration at location I.

Table 5-8. Detection Threshold Across 14 WQM Locations (Station J Excluded)

Contaminant	Ratio of Minimum Detection Threshold To Practically Detectable Concentration Across Monitoring Locations	Ratio of Median Detection Threshold To Practically Detectable Concentration Across Monitoring Locations	Ratio of Maximum Detection Threshold To Practically Detectable Concentration Across Monitoring Locations
Nuisance Chemical 1	1.8 (F)	3.9	14.8 (I)
Nuisance Chemical 2	2.1 (F)	5.4	131.5 (H)
Toxic Chemical 1	1.9 (C)	14.7	102.5 (H)
Toxic Chemical 2	2.1 (O)	4.6	12.7 (I)
Toxic Chemical 3	1.9 (C)	13.3	178.9 (O)
Toxic Chemical 4	1.6 (C)	14.4	37.2 (H)
Toxic Chemical 5	2.6 (N)	5.3	18.4 (K)
Toxic Chemical 6	1.9 (L)	9.5	130.5 (O)
Toxic Chemical 7	1.8 (F)	10.6	35.9 (O)
Toxic Chemical 8	N/A	N/A	N/A
Biological Agent 1	2.1 (F)	15.5	253.5 (I)
Biological Agent 2	1.8 (M)	4.5	9.7 (K)
Biological Agent 3	2.1 (A)	12	53.8 (O)
Biological Agent 4	0.3 (F)	1.2	7.9 (I)
Biological Agent 5	0.2 (F)	1	2.8 (L)
Biological Agent 6	0.2 (O)	0.3	2.5 (B)
Biological Agent 7	2.4 (C)	8.6	128.8 (B)

The impact of the monitoring location on the contaminant detection threshold is apparent from the results presented in this table. For most contaminants, the highest detection threshold across monitoring locations is orders of magnitude larger than the lowest. Even the median thresholds shown in the table are generally much higher than the minimum threshold. On average, the median detection threshold across the monitoring locations was 4.5 times the minimum.

In general, the trend in detection capability by monitoring location was fairly consistent across contaminants. For example, the lowest concentrations were able to be detected at locations C and F for 10 of the 17 contaminants. Conversely, locations H, I and O had the highest detection thresholds for the most contaminants. These trends are influenced by the simulation study design, but are also largely influenced by the water quality variability at each monitoring location, which is discussed in greater detail in Section 6.

5.4 Summary

For WQM, contaminant coverage is determined by the water quality parameters that are monitored. Specifically, a contaminant is covered by WQM if the contaminant impacts at least one monitored parameter. The analyses in this section focused on the 17 contaminants used in the simulation study.

Laboratory testing was performed to determine the impact of each of the 17 contaminants on the water quality parameters monitored in the Cincinnati CWS: free chlorine, conductivity, pH, ORP and TOC. As shown in Table 5-5, all contaminants impacted at least one of these parameters and were thus theoretically detectable by WQM.

Simulation study scenarios using each contaminant were analyzed to estimate the true "detectability" of each contaminant: the percent of practically detectable scenarios using the contaminant that were detected was captured, as well as the minimum concentration at which it was detected. **Table 5-9** summarizes detection of the 17 simulation study contaminants.

The second and third columns show the number of practically detectable scenarios using each contaminant and the percentage of these that were indeed detected. All contaminants were detected except for Toxic Chemical 8, though only one scenario with that contaminant was practically detectable. As Section 5.2 discusses, this percentage is closely related to the number of practically detectable scenarios for each contaminant, and thus these values are heavily dependent on the simulation study scenarios used.

The final column shows the practically detectable concentration for each contaminant, which represents a theoretical lower bound on the detection threshold for each contaminant for the water quality parameters monitored by the Cincinnati CWS. With the exception of Toxic Chemical 8 and Biological Agent 7, the practically detectable concentration is below the concentration that would cause infrastructure or public health consequences.

Table 5-9. Contaminant Coverage for the WQM Component

Contaminant	# of Practically Detectable Scenarios Using this Contaminant	% of Practically Detected Scenarios Detected	Practically Detectable Concentration
Nuisance Chemical 1	84	94%	2.1 mg/L
Nuisance Chemical 2	83	84%	0.30 mg/L
Toxic Chemical 1	45	91%	0.13 mg/L
Toxic Chemical 2	18	78%	0.11 mg/L
Toxic Chemical 3	23	65%	2.0 mg/L
Toxic Chemical 4	45	89%	0.56 mg/L
Toxic Chemical 5	31	81%	0.29 mg/L
Toxic Chemical 6	72	90%	0.29 mg/L
Toxic Chemical 7	7	57%	0.29 mg/L
Toxic Chemical 8	1	0%	0.45 mg/L
Biological Agent 1	31	94%	0.17 mg/L
Biological Agent 2	15	67%	0.15 mg/L
Biological Agent 3	84	93%	0.00005 mg/L
Biological Agent 4	80	89%	1,271 organisms/L
Biological Agent 5	85	94%	127 organisms/L

Contaminant	# of Practically Detectable Scenarios Using this Contaminant	% of Practically Detected Scenarios Detected	Practically Detectable Concentration
Biological Agent 6	28	64%	29,863 organisms/L
Biological Agent 7	5	80%	2,818,131 organisms/L
Overall	737	87%	

Section 6.0: Design Objective: Alert Occurrence

An important capability of a CWS is its ability to generate an alert when indicators of a contamination incident have been detected. In the case of WQM, this requires differentiating between normal variations in water quality and unusual deviations that could be indicative of contamination. For water quality anomalies to be reliably detected, the monitoring stations, data collection and event detection system design elements must be functioning properly. Additionally, in an effective system, the majority of alerts produced are caused by water quality anomalies.

Minimizing the occurrence of invalid alerts is important because an excessive occurrence of invalid alerts may cause utility staff to lose confidence in the system and stop investigating alerts. But it is just as critical to maintain the ability of the system to detect unusual water quality. The effectiveness of WQM alert generation was evaluated by analyzing the following metrics: alert occurrence during routine operations, alert occurrence for simulated contamination incidents and alert co-occurrence.

6.1 Alert Occurrence During Routine Operations

Definition: An alert is an indication from an event detection system that unusual water quality characteristics have been detected. In the case of the Cincinnati CWS, the event detection system in use is CANARY, and both visual and audible notifications are generated for each alert produced. Alerts are considered either valid or invalid, as defined below.

- **Valid Alert:** An alert resulting from a verified water quality anomaly. Several potential sources of water quality anomalies that may lead to valid alerts, including contamination, are discussed below in the analysis methodology.
- **Invalid Alert:** An alert that is not caused by a verified water quality anomaly. Again, several causes of invalid alerts are discussed under analysis methodology.

Analysis Methodology: During the evaluation period, the water quality data generated by the sensors at each monitoring location was collected. This data was analyzed by the CANARY event detection system in real-time to monitor for water quality anomalies. When an anomaly was detected, CANARY generated an alert for a specific monitoring location and time and outputted the water quality parameters whose changes triggered the alert (referred to as *trigger parameters*). Utility staff investigated these alerts as they were generated and documented their conclusion regarding the alert cause in an investigation checklist. If an alert was not investigated or a cause not recorded on the investigation checklist, the water quality and system data were analyzed in an attempt to categorize the cause of the alert. Alerts were first categorized as valid or invalid per the definitions above and then categorized by cause.

V**alid alerts** were grouped into the following causes:

- **Contamination Incident:** Confirmed presence of a contaminant in the distribution system.
- **Main Break:** A confirmed break in a water distribution system pipe.
- **Distribution System Work:** A planned activity in the distribution system such as flushing mains, pipe repair or replacement and opening or closing valves.
- **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 confirmed by the utility such as a change in system pumping or valving, resulting in unusual water quality patterns.
- **Other:** A verified change in water quality that could not be definitively attributed to one of the above causes.

Invalid alerts are grouped into five major categories according to the cause of the alert:

- **Background Variability:** Changes in water quality parameter values that fall within the range of typical water quality patterns. The most common cause of background variability is normal system operations. Changes in pumping and valving can result in a WQM location receiving water from different sources within a short span of time, often causing rapid changes in the monitored water quality. Background variability also includes shifts in the baseline due to seasonal operation and changing source water quality. Figure 3-1 shows an example of highly variable baseline data.
- **Equipment Problem: Monitoring Station Hardware:** The following monitoring station hardware equipment problems caused incomplete or inaccurate data, as discussed in Section 8.0, to be provided to CANARY, which often caused alerts.
    - *Monitoring Station Power Loss:* A loss of power to a monitoring station causes a failure of data generation and transmission. CANARY alerts often occurred when the monitoring station came back online following restoration of power, as the new values represent a large, sustained change from the values provided to CANARY while the power was lost (generally a default invalid value of “0” or a flat-line of the last value received).
    - *Monitoring Station Flow Loss:* An interruption in the flow of pressurized water to a WQM station can impact all of the monitoring station’s data streams. Sensor faults can occur, as well as actual water quality changes such as depletion of chlorine in the stagnant water. These changes, though real, are not considered valid alerts because they are due to an equipment problem and not representative of water quality in the distribution system.
    - *Sensor Malfunction:* Hardware malfunctions can result in inaccurate or erratic data. While the water quality is normal, the sensor readings and thus the values provided to CANARY, are not.
- **Equipment Problem: Communication System:** Data collection failure often causes incomplete data, as discussed in Section 8.0. As with monitoring station power loss, CANARY often generates an alert when data communications are restored. Communication system problems are further broken down into the following sub-causes:
    - *Monitoring Station Data Collection Failure:* Communication failure at a specific WQM station, causing flat-lined or missing data from all data streams from that monitoring station.
    - *System-Wide Outage:* A system-wide network malfunction resulting in flatlined or missing data from all monitoring stations.
- **Equipment Problem: Event Detection System:** A number of invalid alerts were caused by bugs in CANARY’s internal alert generation processes and configuration settings. For alert classification, these were broken into two sub-causes.
    - *Identified CANARY Bug:* A defect within the CANARY software that caused invalid alerts.
    - *Incorrect Parameter Sensitivity Settings in CANARY:* Incorrect settings due to non-optimal software configuration, not a software problem.

- **Procedural Error:** Failure to follow procedures during instrument maintenance can produce erratic or inaccurate data that generates CANARY alerts. Alerts due to procedural errors were grouped into the following sub-causes:
  - *Calibration Selector Switch Not Used Correctly:* The selector switch is supposed to be placed to the "Calibration" position when a monitoring station is being serviced so that all data streams are flagged as unusable and thus not analyzed by CANARY. In some cases this was not done, and the calibration signal that would cause CANARY to ignore the erratic data often produced during maintenance activities was not transmitted.
  - *Sensor Maintenance Error:* In some cases, a maintenance activity resulted in degradation in sensor performance. For example, there were instances where improper maintenance trapped air in the internal plumbing of a sensor, yielding erratic data that generated CANARY alerts.

Section 2.3 notes that improvements were made to the CANARY software and configuration settings in an effort to reduce the rate of invalid alerts and improve its ability to detect true water quality anomalies. Changes which reduced avoidable, clearly invalid alerts included:

- **Update parameter sensitivity values**: As described in Section 2.3, the parameter sensitivity value in CANARY represents the smallest change in the parameter value that could generate an alert. When CANARY was initially implemented in real-time, the sensitivity settings did not represent actual instrument performance and invalid alerts occurred due to extremely small changes in water quality parameter values. These were updated based on the experience of GCWW staff to reflect the smallest change in water quality that could be reliably detected by the deployed sensors.
- **Suppress alerts after calibration**: As described above, CANARY uses the calibration signal from each monitoring station and does not analyze the data, or produce alerts, during monitoring station maintenance. However, many invalid alerts were received immediately following calibration due to the large change in water quality parameter values that can occur following sensor calibration or other maintenance. CANARY configurations were updated to suppress alerts just after calibration.
- **Fix software bugs**: A variety of bugs were identified and corrected during and after the evaluation period. Most bugs resulted from the fact that the EDDIES software was used to deploy CANARY. The Cincinnati CWS is currently the only utility where EDDIES is used with CANARY in real-time, and thus testing of the interface between these software applications was limited. As an example, a substantial bug was encountered when a CANARY update was installed that caused CANARY to enter "alert loops." With each initial alert, CANARY would begin producing one alert after another until analysis for the monitoring location was restarted.
- **Remove sensors from analysis**: Sensor issues can cause inaccurate and widely varying water quality values. There were several instances of significant sensor hardware problems that persisted for months which caused CANARY to produce invalid alerts. By removing these data streams from analysis until the sensor issue was resolved, additional alerts were avoided.
- **Definition of acceptable range**: Knowledge about valid values from specific sensors was used to screen out inaccurate data that might otherwise generate an invalid alert. For example, for one model of TOC instrument, a value of 10 indicated a sensor fault. As a result, CANARY was adjusted to ignore any TOC parameter value larger than 9.9, thus eliminating invalid alerts that might result from this instrument malfunction.

During the evaluation period, understanding of the CANARY analysis methodology and configuration variables improved significantly, as did familiarity with local water quality patterns at each WQM location. This was used to reconfigure CANARY (separate from the above fixes) and improve performance, increasing the ability of CANARY to detect unusual water quality while decreasing the number of invalid alerts.

- Periodic changes were made to the configuration settings for individual WQM locations to reflect changes in the baseline water quality. At some WQM locations, real-time data from pumps, tanks and valves was used to create CANARY "cluster files" which helped suppress invalid alerts caused by changes in operations.
- In late 2010, a rigorous re-analysis of CANARY configurations was performed in which multiple configurations were compared for each monitoring location using 104 days of data and 12 simulated contamination incidents. For several stations, significant improvements were seen under new configurations. The new configuration at one monitoring location produced half the number of invalid alerts while increasing the number of incidents detected from zero to four.

Several of these modifications to CANARY were made during the evaluation period, while others were implemented later as additional issues were encountered: modifications were made well into 2011. To assess CANARY's performance under this optimized condition, the data collected over the entire evaluation period was reprocessed through the latest version of CANARY in off-line, batch mode. The results of this reprocessing were a new set of alerts that better represent performance for the conditions under which the Cincinnati CWS is currently operating.

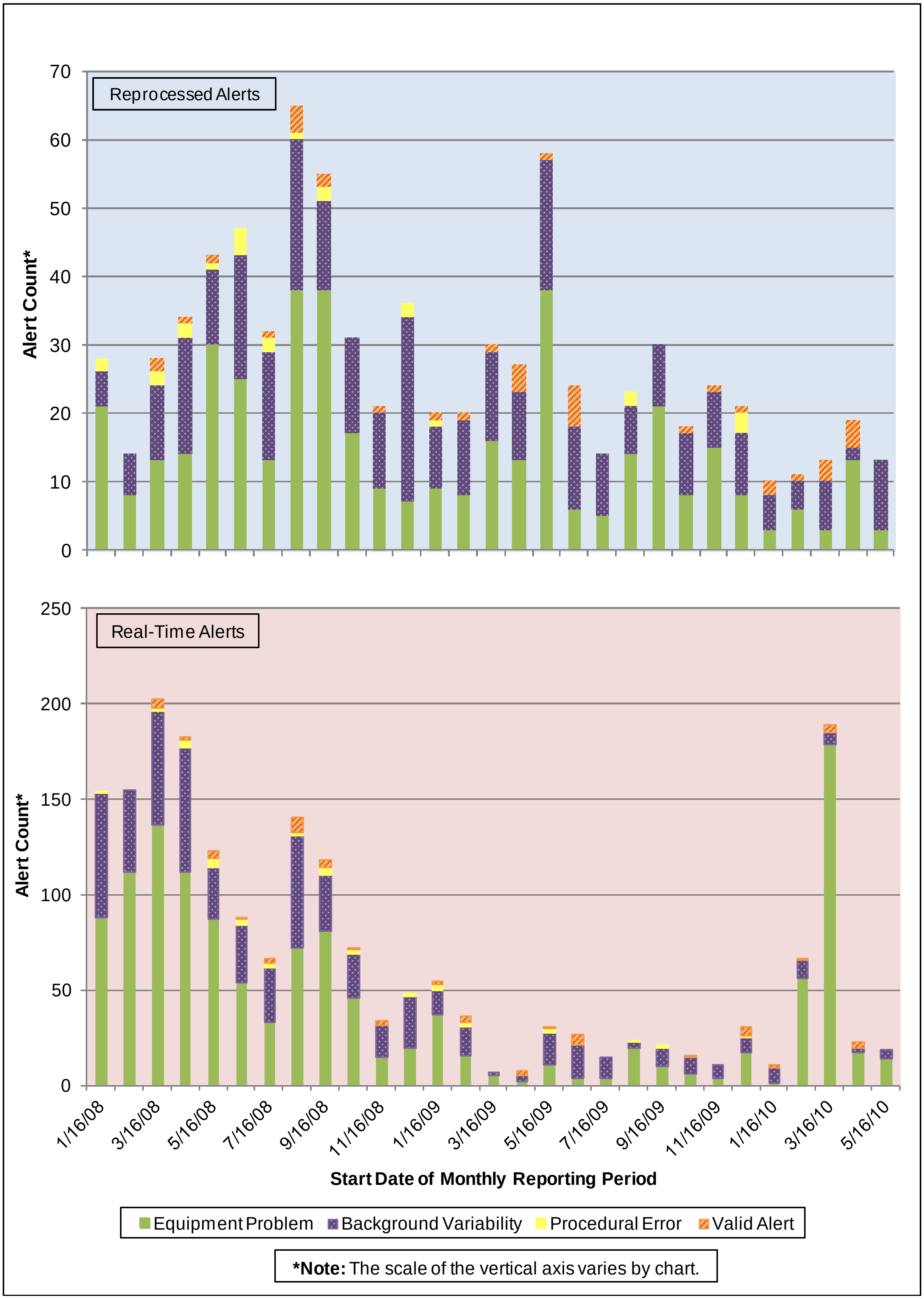
Both sets of alert data will be presented in this section:

- *Real-time monitoring alerts* that were collected during real-time operation.
- *Reprocessed alerts* that were generated by the latest version and configurations of CANARY in an off-line batch analysis.

Results: This section summarizes the alerts produced during the evaluation period, which were analyzed by reporting period, alert cause, location and trigger parameter. Both real-time monitoring and reprocessed alerts are included in all figures. Those showing reprocessed alerts are always shown first and have a blue background. Real-time monitoring alert summaries follow and have a pink background.

Figure 6-1 shows the number of alerts for each reporting period for the real-time monitoring and reprocessed results. Alerts are shown by cause, with the three categories related to equipment problems (Event Detection System, Monitoring Station Hardware and Communication System) combined into one overall Equipment Problem category.

Overall, the number of observed alerts during real-time monitoring ranged from 7 to 203 per reporting period with an average of 68 per reporting period. There was a downward trend in alert occurrence during real-time monitoring, which was driven by improved sensor performance and CANARY upgrades. The benefit of the CANARY configuration updates in May 2008 and October 2008, described in Table 2-5, can clearly be seen, as alert numbers drop significantly after these periods. The exception to this downward trend is seen as an increase in alert occurrence from February through March 2010. This was largely due to problems when a new, faulty version of CANARY was installed. More information on specific changes that were implemented during the evaluation period can be found in Table 2-5.



*Note that the y-axis scales are different due to the markedly different number of alerts generated

Figure 6-1. Cause of Reprocessed and Real-Time Alerts by Reporting Period

With the reprocessed analysis, between 10 and 65 alerts were generated per reporting period, averaging 28 over the evaluation period; 59% fewer alerts than the average number generated during real-time monitoring. There were fewer invalid alerts in the reprocessed results compared to real-time monitoring for most reporting periods with the following exceptions: March through May 2009, and September through November 2009. During these periods, CANARY was unavailable in real-time due to software updates, as discussed in Section 8.3. For much of this downtime, complete and accurate data was still being generated and stored, but CANARY was not analyzing it and thus not generating any alerts. This resulted in an artificially low number of real-time monitoring alerts – in some cases zero alerts over an entire reporting period. However, during reprocessing, the entire dataset was processed by CANARY, even during these periods in which CANARY was not operating in real-time. Thus, more alerts were generated during reprocessing than were observed during real-time monitoring. This issue is seen very clearly during the noted reporting periods, and is likely present to a smaller degree in other periods as well.

Figure 6-2 looks more closely at alert causes, showing the causes and sub-causes for the alerts generated during real-time monitoring and reprocessed analysis. A description of the causes and sub-causes is provided above, under analysis methodology. Note that the total number of alerts, shown in the upper-left corner of each figure, is different for the reprocessed and real-time monitoring alerts.

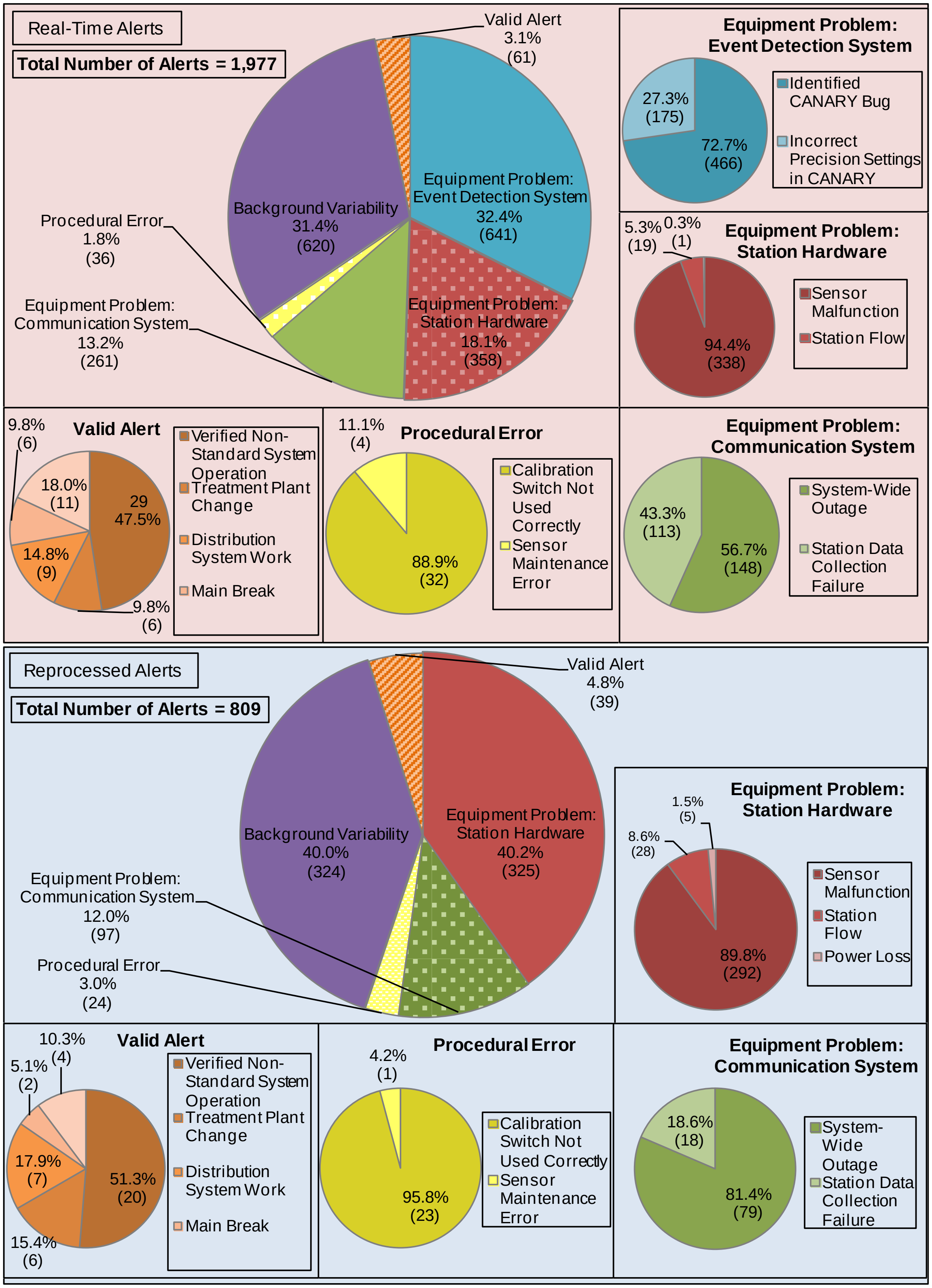


Figure 6-2. Cause and Sub-cause of Reprocessed and Real-Time Alerts

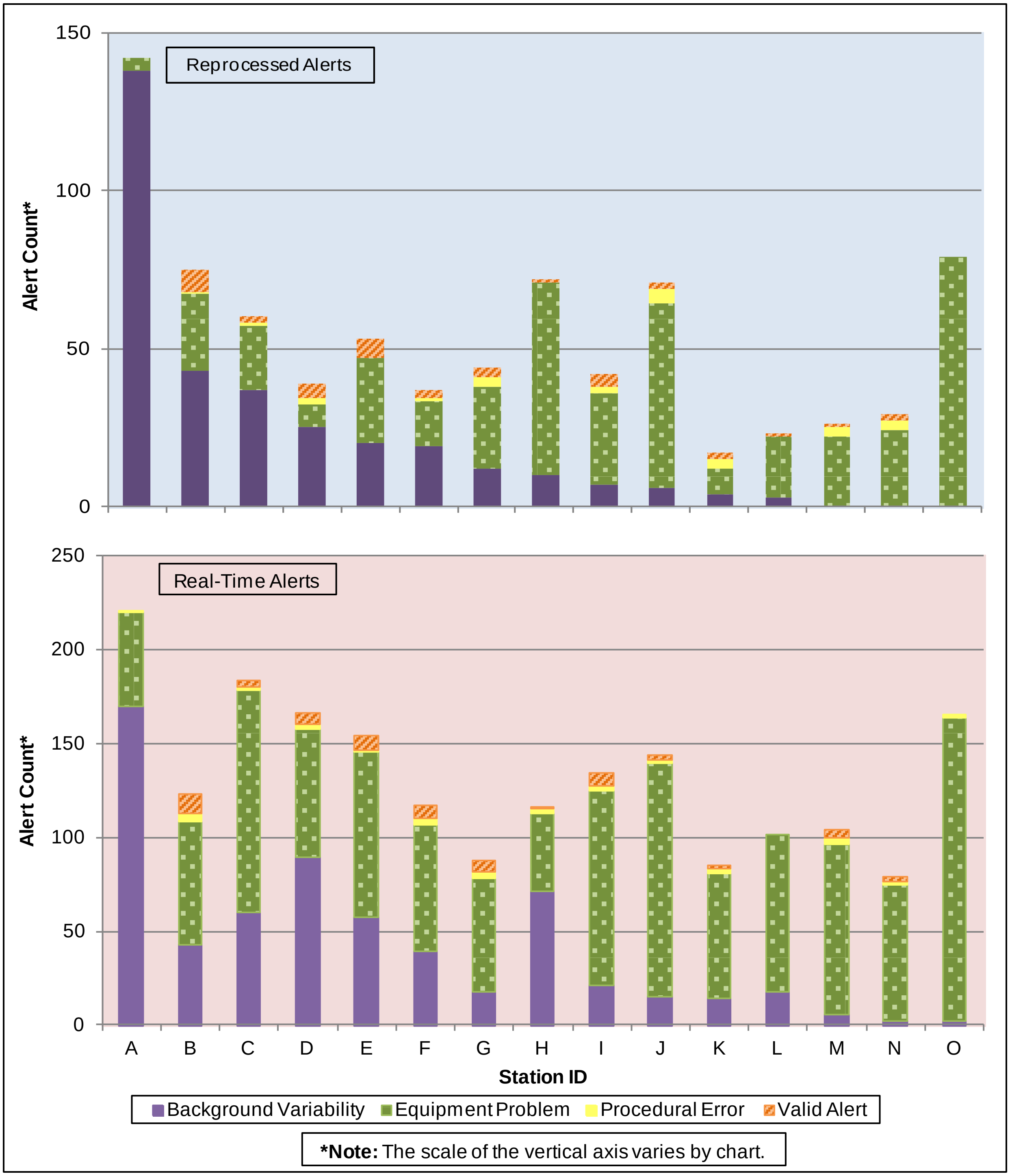
The following discussion provides additional analysis of, and comparison between, the number of alerts observed in real-time and reprocessed alert sets for each category of alert cause.

- **Invalid Alerts:** The reprocessed analysis generated fewer invalid alerts for each cause when compared to the alerts generated in real-time, as discussed below in order of significance.
    - **Equipment Problem: Event Detection System:** CANARY issues were the most significant cause of invalid alerts in real-time (32.4%), mostly due to identified CANARY bugs. The version of CANARY that generated the reprocessed alerts, which incorporated all of the improvements discussed under the analysis methodology, completely eliminated invalid alerts due to this cause.
    - **Background Variability:** Excluding the problems with CANARY discussed above, background variability produced the most invalid alerts in both real-time monitoring and reprocessed analyses. However, refinement of CANARY configuration settings reduced the number of invalid alerts caused by background variability in the reprocessed analysis by 47% when compared to the real-time results.
    - **Equipment Problem: Monitoring Station Hardware:** Excluding the event detection system problems, this category was the second most prevalent cause of invalid alerts in both real-time monitoring and the reprocessed analysis. This type of invalid alert was not significantly impacted by the CANARY upgrades. The best way to reduce invalid alerts due to this cause is to improve data quality through improved maintenance. For the Cincinnati pilot, the number of alerts due to monitoring station hardware was also reduced when instruments with chronic problems were removed from analysis, as discussed in Section 8.1. While this led to fewer alerts during reprocessing, because the poor quality data that CANARY analyzed before the sensors were taken offline in real-time mode was no longer considered, loss of data for a water quality parameter may impact other aspects of performance, such as contaminant coverage.
    - **Equipment Problem: Communication System:** Excluding event detection system problems, this was the third most significant alert cause in both real-time monitoring and the reprocessed analysis. The system-wide and monitoring station outage sub-causes were both significant contributors to this invalid alert type. CANARY configuration updates reflected in the reprocessed analysis reduced the number of invalid alerts due to this cause by 62% when compared to the invalid alerts that occurred in real-time.
    - **Procedural Errors:** This cause was not a significant source of invalid alerts for either the reprocessed or real-time analyses.
- **Valid Alerts:** The CANARY configurations used in the reprocessed analysis generated 41 valid alerts compared to 61valid alerts generated during real-time monitoring. Thus, while the CANARY updates and new configurations were effective at reducing the occurrence of invalid alerts, the decrease in detection of valid alerts in the reprocessed analysis demonstrates the challenge associated with balancing the detection of true anomalies against minimizing the occurrence of invalid alerts.

Table 6-1 and **Figure 6-3** show the alerts for each WQM station that were generated in real-time and during reprocessed analysis. The stations are ordered in decreasing order of reprocessed alerts produced.

Table 6-1. Alerts By Monitoring Station

Station ID	Reprocessed		Real-Time		Monitoring Station Water Quality Variability
	# Valid Alerts	# Invalid Alerts	# Valid Alerts	# Invalid Alerts	
A	0	142	0	220	This monitoring location is at a pump station co-located with multiple ground storage tanks and receives water from both plants. Thus, it can get water from either of the storage tanks, water from either of the treatment plants via the mains, or a mixture of these sources. Thus, water quality here is highly variable and unpredictable.
B	7	68	11	112	This monitoring location is in the seasonal interface zone between the two plants and thus experiences large variations in water quality.
C	2	58	3	180	This monitoring location can receive water pumped directly from the plant or nearby reservoir, and can thus experience slight water quality variability depending on system operations.
D	5	34	6	160	Depending on pumping, this monitoring location can receive water through one of two upstream pump stations or from a co-located reservoir. Water quality is highly variable at this site.
E	6	47	8	146	This monitoring location can receive water pumped directly from the plant or nearby reservoir, and thus can experience slight water quality variability depending on operations.
F	3	34	7	110	This monitoring location primarily receives water pumped from the treatment plant, but can also receive water from the co-located reservoir. Thus, it experiences water quality variability depending on operations.
G	3	41	6	81	This monitoring location can receive water pumped directly from the plant or nearby reservoir, and thus can experience slight water quality variability depending on operations.
H	1	71	1	115	This monitoring location primarily receives water directly from the plant, but occasionally receives water from the co-located reservoir. Thus, there is some water quality variability depending on operations. As noted in Table 2-5, this monitoring location was moved in March 2009 due to low pressure and intermittent flow.
I	4	38	7	127	This monitoring location receives water pumped from the plant through a major pump station. There is little variability in water quality at this location.
J	2	69	2	141	This monitoring location is located just downstream of the groundwater plant: there is little water quality variability.
K	2	15	2	83	This monitoring location is at a pump station and can experience water quality variability due to pump operations.
L	1	22	0	101	This monitoring location receives water pumped from the plant through major pump stations. There is little variability in water quality at this monitoring location.
M	1	25	5	99	This monitoring location receives water pumped from the plant through a major pump station. However, it can also receive water from nearby tanks and reservoirs. Thus there is some water quality variability at this location.
N	2	27	3	76	This monitoring location receives water that is pumped from the plant through a major pump station. There is little variability in water quality at this monitoring location.
O	0	79	0	165	This monitoring location receives water that is pumped from the plant through a major pump station. There is little variability in water quality at this monitoring location.
Total:	39	770	61	1,916	



* Note that the y-axis scales are different due to the markedly different number of alerts generated

Figure 6-3. Cause of Reprocessed and Real-Time Alerts by Location

The CANARY improvements previously discussed led to fewer total alerts and fewer invalid alerts in the reprocessed analysis for all stations, with percentage decreases in invalid alerts ranging from 35% at Station A to 82% at Station K and an average percentage decrease of 61%. The number of valid alerts also decreased for most stations, illustrating that modifications to an event detection system to decrease the occurrence of invalid alerts can also decrease the sensitivity of the event detection system. The percentage reduction in valid alerts ranged from 0% at stations A, H, J and K to 80% at station M with an average percentage decrease of 33%. Examples of stations where performance was dramatically improved by CANARY modification include:

- **Stations L and O:** Both of these stations detected one true anomaly (i.e., generated a valid alert) during reprocessing that was not detected in real-time. Furthermore, the number of invalid alerts decreased by 82% and 65% respectively, resulting in a total of 166 fewer invalid alerts that would be received by the utility.
- **Stations H, J, and K:** The new CANARY configuration did not impact the number of valid alerts generated at these stations, but the number of invalid alerts decreased by 51%, 70%, and 51%, respectively (resulting in a total of 184 fewer invalid alerts received by the utility).
- **Stations D and E:** While the number of valid alerts generated decreased by 17% and 25%, respectively, in the reprocessed analysis, the occurrence of invalid alerts decreased by 68% and 78%, respectively (while three valid alerts were lost, the updated CANARY configuration produced a total of 224 fewer invalid alerts).

Table 6-1 and Figure 6-3 also clearly show the variations among the monitoring stations in terms of alert occurrence and cause, especially for equipment problems and background variability. Notable causes of differences in alert levels among the stations are discussed below:

- **Background Variability at Monitoring Station A:** Table 6-1 describes the water quality variability of each monitoring location, and it is evident from this table that stations with a greater degree of water quality variability generally have a greater occurrence of invalid alerts. In both the real-time monitoring and reprocessed analysis, Station A had the highest number of invalid alerts caused by background variability due to the complex and largely unpredictable water quality. **Figure 6-4** shows typical water quality at this location. Frequent changes in water sources can be clearly seen, and pH may be the most effective way to distinguish between the sources. The surface water source typically has a pH near 8.5, the groundwater source has a pH above 9, and a third source typically has a pH near 8.75 and is most likely from a tank with a mixture of the surface and groundwater sources.

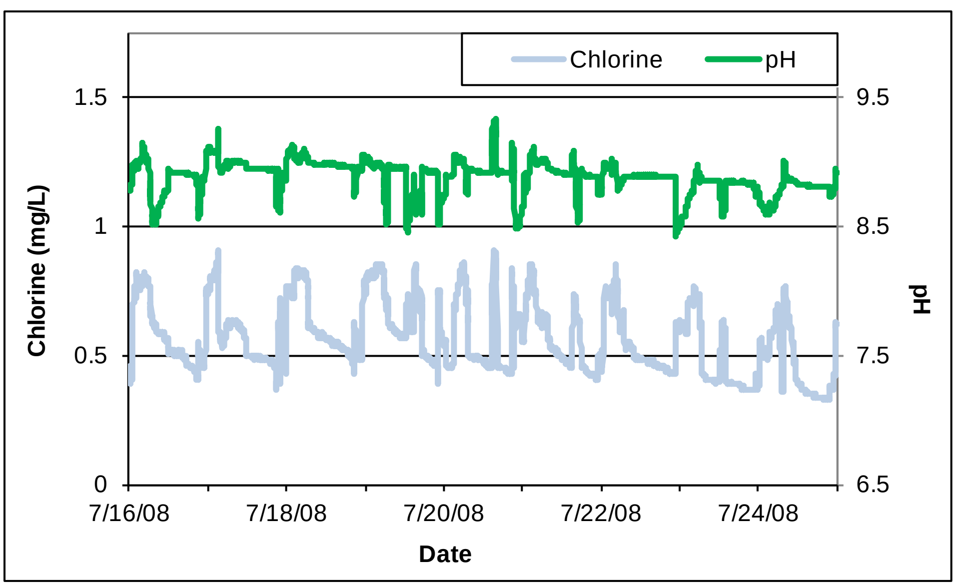


Figure 6-4. Example of Normal Water Quality Variability at Monitoring Station A

- **Equipment Problems at Station O:** In both the real-time monitoring and reprocessed alert sets, station O had the highest number of invalid alerts due to equipment problems caused by chronic issues with the chlorine sensor and occasional problems with the TOC sensor at this station.
- **Differences in Alert Causes:** In many instances, the distribution of alerts among the various causes was significantly different for the reprocessed alerts. These often non-intuitive changes were due to updates in the CANARY configuration settings implemented after the evaluation period that resulted in very different alerting patterns. Station H is one example of this; equipment problems were resoundingly the greatest cause of invalid alerts in the reprocessed results, whereas background variability was the dominant cause during real-time monitoring. Some of these invalid alerts were missed during real-time monitoring because CANARY was unavailable at the time of the equipment problem.

Table 6-2 and **Figure 6-5** analyze the trigger parameters outputted by CANARY for both the reprocessed and real-time monitoring results. The percentages are calculated relative to the total number of alerts in each category, as shown in the final row of this table. For example, in real-time TOC was listed in 48.6% of all alerts received. In some cases, alerts were triggered by more than one parameter so the percentages of alerts across all parameters for a given analysis sum to more than 100%.

Table 6-2. Alerts by Water Quality Parameter

Parameter	Reprocessed						Real-Time					
	Valid Alerts for which Trigger Parameter was Listed		Invalid Alerts for which Trigger Parameter was Listed		Total Alerts for which Trigger Parameter was Listed		Valid Alerts for which Trigger Parameter was Listed		Invalid Alerts for which Trigger Parameter was Listed		Total Alerts for which Trigger Parameter was Listed	
	#	%	#	%	#	%	#	%	#	%	#	%
TOC	4	10.3%	113	14.7%	117	14.5%	20	32.8%	940	49.1%	960	48.6%
Chlorine	26	66.7%	298	38.7%	324	40.0%	34	55.7%	876	45.7%	910	46.0%
ORP	13	33.3%	83	10.8%	96	11.9%	9	14.8%	508	26.5%	517	26.2%
pH	11	28.2%	266	34.5%	277	34.2%	18	29.5%	613	32.0%	631	31.9%
Conductivity	10	25.6%	280	36.4%	290	35.8%	18	29.5%	773	40.3%	791	40.0%
TOTAL:	39	N/A	770	N/A	809	N/A	61	N/A	1,916	N/A	1,977	N/A

NOTE: Totals indicate total number of alerts, not total number of trigger parameters

During real-time monitoring, TOC was the parameter listed as a trigger with the most alerts (48.6%), and ORP the least (26.2%). For the reprocessed analysis, chlorine (40.1%) and ORP (11.9%) were the most and least frequent, respectively.

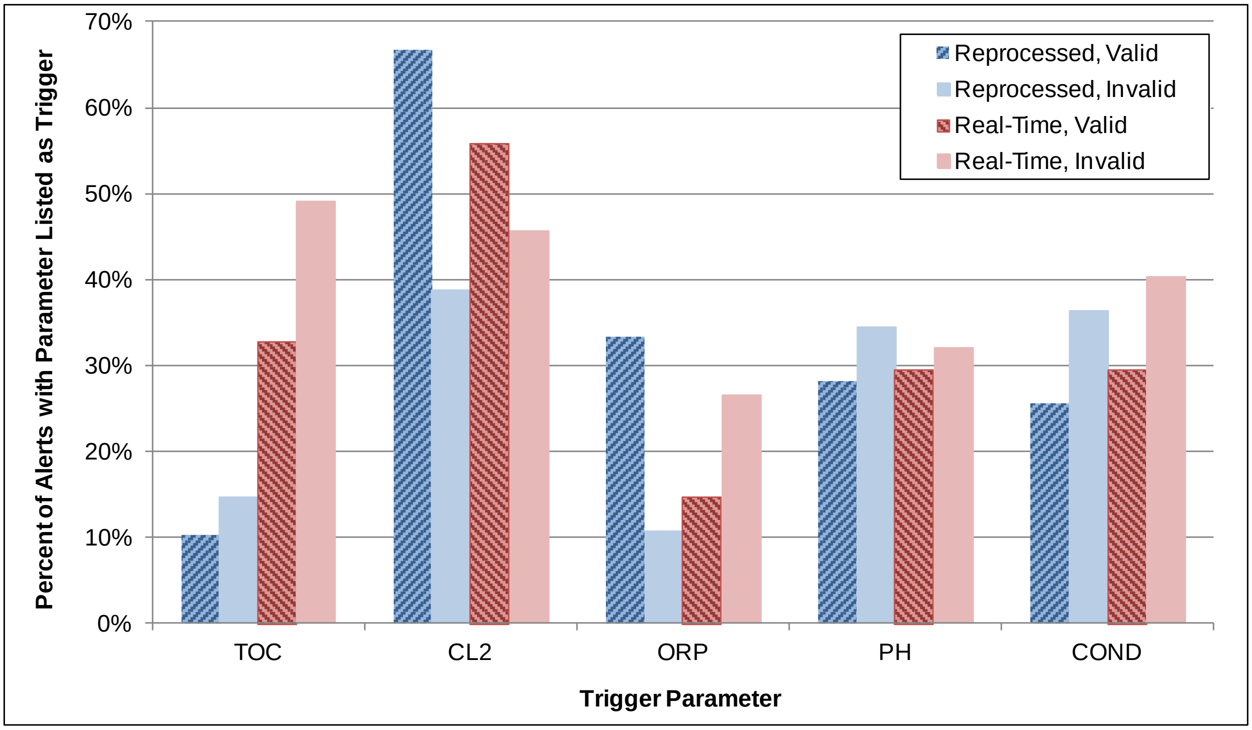


Figure 6-5. Percentage of Alerts with each Parameter Listed as a Trigger

Below is further discussion regarding the attribution of individual parameters to alert occurrence.

- **TOC:** Recurring TOC sensor issues throughout the evaluation period resulted in TOC being the most frequent contributor to invalid alerts. As discussed previously, CANARY configurations were updated to address this specific issue. These changes resulted in an 88% decrease in the number of invalid alerts triggered by TOC, with only 14.4% of reprocessed alerts attributable to TOC.

- **Chlorine:** In both the real-time monitoring and reprocessed alert sets, chlorine was the most frequent contributor to valid alerts. However, it was also the second highest and highest contributor to invalid alerts for the real-time monitoring and reprocessed results, respectively. Thus, while chlorine was a relatively sensitive measure of anomalous water quality conditions, this highly variable parameter also produced a large number of invalid alerts.

- **ORP:** In both the real-time monitoring and reprocessed alert sets, ORP was the least frequent contributor to invalid alerts. However, in the reprocessed analysis ORP was the second largest contributor to valid alerts. In fact, 14% of the reprocessed alerts attributed to ORP were valid, which is the highest for any parameter type. This seems to indicate that ORP was a relatively sensitive and reliable measure of unusual water quality. While it likely won't replace chlorine, it could be used to verify or rule out a possible anomaly indicated by a chlorine-triggered alert.

6.2 Valid Alerts

This section evaluates the ability of the WQM component to produce alerts when unusual water quality is present in the distribution system. Section 6.2.1 considers valid alerts generated for simulated contamination incidents generated as part of the simulation study. Section 6.2.2 examines valid alerts produced at the Cincinnati pilot over the evaluation period.

6.2.1 Valid Alerts from Simulated Contamination Incidents

Definition: A valid alert is a WQM alert generated in response to a simulated contamination incident. Each impacted monitoring location is a site of potential alert. There is at most one valid alert per impacted location; and only the first instance of an alert from each WQM location was recorded during the simulation study. Because these alerts are generated in response to a known, simulated contamination incident, they are considered to be valid.

Analysis Methodology: Section 5.2 summarized detection of simulated contamination scenarios, each of which may contain multiple valid alerts. This section analyzes the simulation study results at a deeper level, considering potential and valid alerts for each of the 737 simulated contamination scenarios practically detectable by Cincinnati's WQM component. Overall alerting rates are presented, as well as the occurrence of valid alerts by monitoring location and by contaminant.
Section 6.3.1 investigates occurrence of multiple alerts produced within a scenario.

Results: Of the 737 scenarios practically detectable by WQM, there were 1,959 potential alerts (i.e., impacted monitoring stations). A total of 1,373 alerts were produced, yielding an overall alerting percentage of 70%.

Table 6-3 summarizes alerting by monitoring location. The number of potential alerts for each monitoring location is given, which is the number of scenarios in which the monitoring location was impacted. The third and fourth columns show the number of alerts that were in fact produced, and the percentage relative to the number of potential alerts.

Table 6-3. Alerts by Monitoring Location

Monitoring Location ID	# of Potential Alerts	# of Potential Alerts Produced	% of Potential Alerts Produced
A[1, 2]	250	39	15.6%
B	267	164	61.4%
C	150	137	91.3%
D[1]	25	8	32.0%
E	51	50	98.0%
F	219	198	90.4%
G[1]	59	38	64.4%
H	50	45	90.0%
I	68	45	66.2%
J	15	14	93.3%
K	194	176	90.7%
L	255	197	77.3%
M	215	163	75.8%
N	100	72	72.0%
O	41	34	82.9%

[1] This monitoring station did not have an ORP instrument
[2] This monitoring station did not have a TOC instrument

The number of potential alerts by monitoring location ranged from 15 to 267. This is largely dependent on the study design, though the stations with very few potential alerts were generally close to a treatment plant, such that scenarios with an injection location at a downstream node would not impact the monitoring location. Station J is in the area served by the smaller treatment plant, and contaminant injections outside this area did not reach this location.

Alerting percentages by monitoring location varied widely, ranging from 16% to 98%. Stations A and D had by far the lowest alerting percentages. As noted in Table 6-1, these stations have complex water quality, getting water from multiple sources and having frequent, large changes in water quality. Thus, it may be more difficult to distinguish water quality changes caused by contamination from the normal variability. Figure 6-5 shows an example of the highly variable water quality at station A.

However, an even stronger influence on alerting percentage was the water quality parameters monitored. Three stations (A, D, and G) did not have the full suite of water quality parameters, and these had three of the four lowest alerting percentages. These stations are Type A (described in Section 2.1.1) and do not have ORP instruments. Thus, other stations had additional information to facilitate detection of contaminants impacting this parameter (all contaminants except Nuisance Chemical 1, Toxic Chemical 1 and Biological Agent 2).

In addition, station A, which had the lowest alerting percentage overall, does not have an operational TOC sensor. As shown in Table 5-5, 7 of the 17 contaminants change TOC. Thus the lack of a TOC sensor at this station hindered detection of scenarios involving these contaminants. Furthermore, Nuisance Chemicals 1 and 2, Toxic Chemical 4, and Biological Agent 2 impact only TOC: no scenarios using these contaminants could be detected at this monitoring location.

These results show monitoring the full suite of water quality parameters provides better detection capabilities. Also, the impact of baseline water quality variability is a factor in detection.

6.2.2 Valid Alerts from Observed Water Quality Anomalies

Definition: *Observed water quality anomalies* are real water quality anomalies observed in the drinking water distribution system. These were identified by reviewers as described below. Alerts triggered by observed water quality anomalies are considered valid. Each water quality anomaly is a discrete incident that may pass through multiple monitoring stations and thus may trigger multiple alerts. Each monitoring location where unusual water quality was observed by the sensors is considered a *site of potential alert.*

Analysis Methodology: All water quality data from the evaluation period was analyzed, and knowledge of routine operations and normal water quality variability at each WQM location was used to identify significant observed water quality anomalies. **Figure 6-6** shows an observed water quality anomaly caused by a change in chlorine dose at the main treatment plant. Reviewers were able to clearly identify this unusual water quality at five monitoring stations: data from two of these sites of potential alert are shown in this figure.

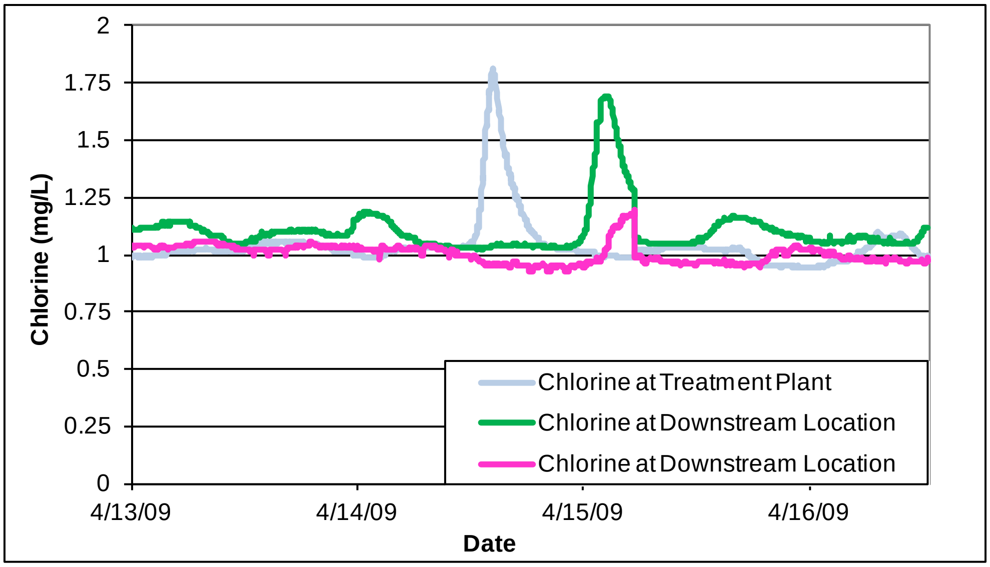


Figure 6-6. Chlorine Data from an Observed Water Quality Anomaly

Unlike the simulation study, there is no way to know with certainty when unusual water is at a monitoring location. Incidents whose water quality changes were not significant when compared to normal variability were likely missed by both data reviewers and the CANARY software.

For example, **Figure 6-7** shows data from another monitoring location during the water quality anomaly shown in Figure 6-6. This location is downstream of the plant and thus should have received the water with elevated chlorine levels, but this change does not show clearly in the data. The black arrow shows a chlorine increase that could be related to the observed anomaly, but it is not sufficiently different from the monitoring location's normal water quality to be certain. Thus this location was *not* considered a site of potential alert.

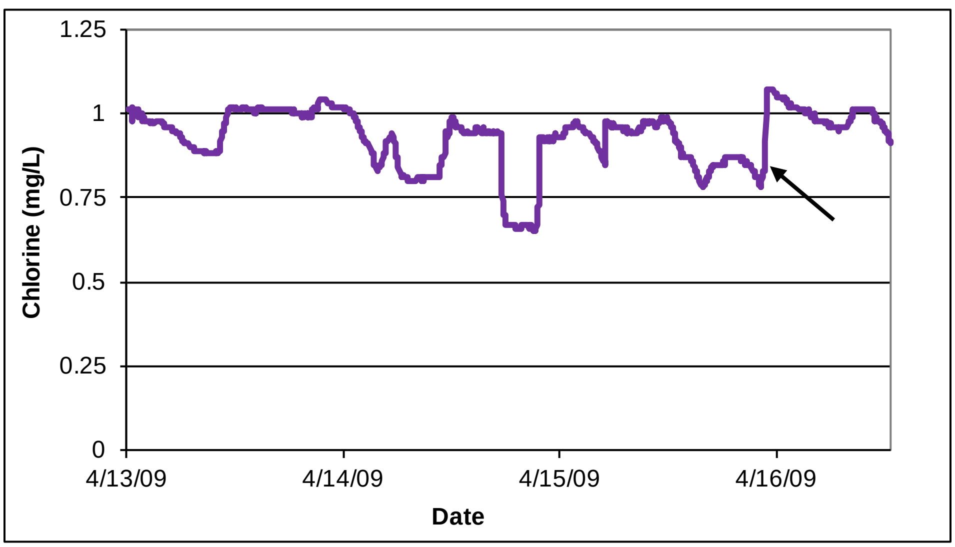


Figure 6-7. Chlorine Data from an Additional Site During the Anomaly shown in Figure 6-6

While the evaluators could have used knowledge of network hydraulics to rigorously attempt to identify all stations that likely observed each incident of anomalous water quality, this was not done in this evaluation. If it had, the hydraulic analysis would be imprecise; flow paths change depending on system operations and demand, and there was no way to retrospectively obtain detailed data on system conditions at that time. Also, there is no way to know how long the slug of water with unusual quality remained intact and significant.

Results: This section summarizes detection of observed water quality anomalies that occurred during the evaluation period. Forty-nine real incidents were identified by reviewers and CANARY detected 69% of them.

Table 6-4 summarizes the number of incidents of each type and the detection percentage for each. A description of these causes of unusual water quality can be found in Section 6.1.

Table 6-4. Observed water quality Anomaly Causes and Detections

Observed Water Quality Anomaly Cause	# of Real Incidents with this Known Cause	% of These Incidents Detected
Contamination Incident	0	N/A
Main Break	2	100.0%
Distribution System Work	4	100.0%
Treatment Plant Change	7	71.4%
Verified Non-Standard System Operation	23	65.2%
Other	13	61.5%
TOTAL:	49	69.4%

Anomalies caused by main breaks and distribution work were all detected: these generally cause quick, significant changes in multiple water quality parameters. The other incident types had similar detection rates.

Table 6-5 shows incident detection percentages by the number of sites of potential alert. Reviewers identified between one and nine impacted monitoring stations for the incidents. The number of sites of potential alert does not seem to have a significant impact on the probability of an observed water quality anomaly being detected, though these results are certainly skewed because for the majority of incidents, water quality changes were identified at only one monitoring location. For this table, an incident is considered detected if an alert was produced for at least one of the sites impacted.

Table 6-5. Incident Detection Percentages by Number of Sites of Potential Alerts

Number of Sites of Potential Alert	# of Real Incidents with this Number[1]	% of These Incidents Detected
1	39	66.7%
2	1	100.0%
3	1	100.0%
4	1	100.0%
5	0	-
6	3	33.3%
7	1	100.0%
8	0	-
9	3	100.0%

[1] It is likely that the number of sites of potential alert is underestimated for many incidents.

6.3 Alert Co-occurrence

The use of multiple WQM stations presents the potential for co-occurrence of alerts within a defined time period, which would constitute an alert cluster. If valid alerts are received from hydraulically connected monitoring stations, the cluster provides compelling evidence that a true water quality anomaly is occurring in the distribution system. In fact, according to the Cincinnati Pilot Operational Strategy, a cluster containing two or more valid, hydraulically connected alerts results in the immediate determination that contamination is Possible.

However, clusters consisting of unrelated or invalid alerts also occur, and such invalid alert clusters may take more time to investigate and rule out compared with an isolated invalid alert.

Alert clusters are considered either valid or invalid, as defined below.

- **Valid Cluster:** A cluster containing co-occurring valid alerts from at least two hydraulically related monitoring stations resulting from a single verified water quality anomaly.
- **Invalid Cluster:** A cluster that does not contain co-occurring valid alerts resulting from a single verified water quality anomaly.

Often more than one alert was received from the same monitoring location. For example, it is likely that CANARY would produce an alert for each monitoring location shown in Figure 6-7 as the chlorine suddenly jumped up, and then another as it abruptly dropped back up to its original level. Only the first alert from each monitoring location is considered in this analysis.

This section presents an analysis of alert co-occurrence using 1) alerts generated during the simulation study, and 2) reprocessed alerts generated by the optimized version of CANARY, as described in Section 6.1. The same version and configuration of CANARY was used in both of these analyses.

6.3.1 Co-occurrence of Alerts for Simulated Contamination Incidents

Definition: For the simulation study, a cluster is formed when alerts are received from two or more monitoring stations for the same simulated contamination incident. The nature of the simulation study guarantees that all clusters generated are valid clusters.

Analysis Methodology: For each scenario, the number of impacted stations was captured, as well as the number of alerts generated. As presented in Section 4.3, there were a maximum of 14 impacted stations in a scenario, and thus a maximum of 14 potential alerts in a single scenario.

Results: In total, clusters were formed for 347 scenarios, which is 47% of those detected. The clusters ranged in size from 2 to 13 alerts, as shown in **Figure 6-8**. The number of alerts of the given size is shown above each bar. Note that no bar is shown for 296 scenarios in which only one alert occurred, as by definition those are not clusters.

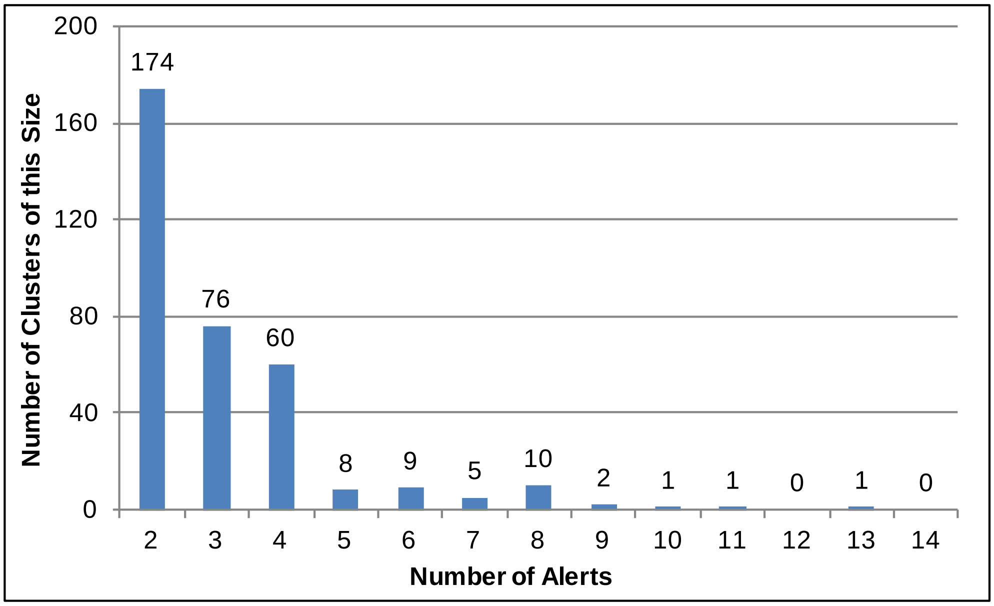


Figure 6-8. Cluster Sizes for Simulated Contamination Incidents

There were two alerts in 50.1% of clusters formed, and the cluster sizes generally decrease exponentially from there. Five or more alerts were generated for 37 scenarios, which is 10.7% of those for which clusters were formed and 5.8% of all scenarios detected.

The box-and-whisker plots shown in **Figure 6-9** shows the number of alerts produced for detected contaminants, broken down by contaminant. All detected scenarios are included here – including those for which only one alert was produced and thus no cluster was formed.

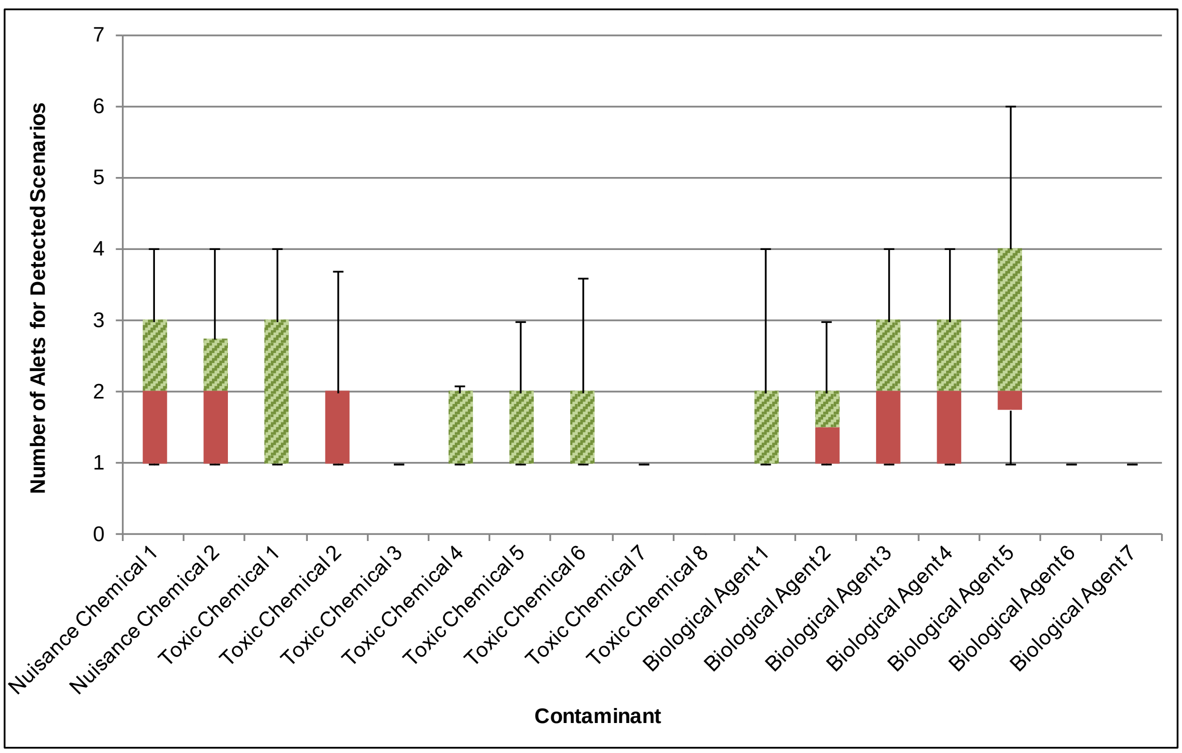


Figure 6-9. Number of Alerts Generated for Detected Incidents by Contaminant

Section 5.2 discussed contaminant spread, which is largely based on the volume of contaminant available to inject. In general, contaminants that had a larger spread (including the Nuisance Chemicals, Biological Agent 3 -5) tended to produce clusters more often; the median number of alerts for these contaminants was two, compared with other contaminants in which the median was one. Conversely, contaminants with limited spread (including Toxic Chemicals 3 and 7 and Biological Agents 6 and 7) produced alert clusters less frequently. Note that on the plot, these simply have a line at one alert, as all detected scenarios for these contaminants had one alert produced. As shown in Table 5-6, no scenarios involving Toxic Chemical 8 were detected.

6.3.2 Co-occurrence of Alerts on Utility Data

Definition: For CANARY output on the utility data, a cluster is formed when alerts are received from two or more monitoring stations within a 24-hour period.

Analysis Methodology: A 24-hour moving window was applied to the reprocessed CANARY alerts (described in Section 6.1) to identify alert clusters. Twenty-four hours was chosen as the basis for defining a cluster because it encompasses the longest travel time between two WQM stations that are hydraulically connected, but is still short enough such that the earliest and latest alerts should still be active or in the recent alert history. This is consistent with the timing seen in the simulation study results discussed in Section 6.3.1. For 95% of the clusters produced, the time between the first and second alerts was less than 24 hours. Clusters that were entirely subsets of another cluster were removed to avoid redundancy.

Alert clusters were first categorized as valid or invalid per the definitions in the introduction to this section, and then categorized by cause.

To be a valid cluster, two or more valid alerts due to the same observed water quality anomaly were required. The same categories used to classify valid single alerts were used for valid clusters: Contamination Incident, Main Break, Distribution System Work, Treatment Plant Change, Verified Non-Standard System Operation and Other. See Section 6.1 for details on these categories.
Invalid clusters were grouped into the following categories.

- **System-wide issue**: System-wide communications and power outages often resulted in invalid alert clusters when restored to service. Due to the nature of these outages, the utility was typically aware of the issue before the alerts occurred, and thus able to determine that the alert cluster was invalid without difficulty.

- **No hydraulic connectivity***:* Each cluster was analyzed to see if any of the cluster's alerts were hydraulically connected. Alerts were considered hydraulically connected if the monitoring location of the later alert is downstream of an earlier alert's monitoring location. The hydraulic travel time was not considered because the data needed to compute the actual travel time were not available. If no hydraulic connectivity exists, the utility would easily discount the cluster.

- **Coincidental station-specific issues**: The remaining clusters were caused by coincidental, unrelated issues at the individual WQM stations. Causes of these unrelated issues include monitoring station hardware problems, procedural errors and normal background variability.

Results: 63.2% of the reprocessed alerts fell into a cluster. A total of 214 clusters were formed. **Figure 6-10** summarizes the number of clusters that fell into each cluster category.

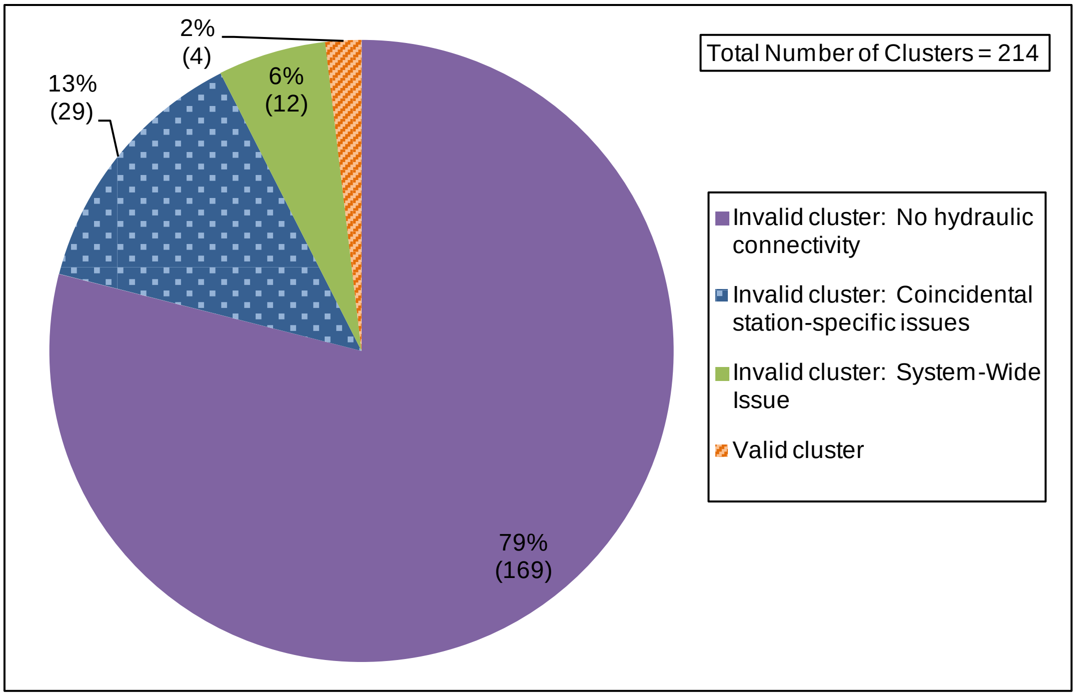


Figure 6-10. Alert Cluster Causes

The majority of clusters (85%) could be easily discounted by the utility because the alerting stations were not hydraulically connected or because they were attributable to a system-wide issue of which utility staff were aware. An additional 3% of clusters, included in coincidental monitoring station-specific issues, were comprised entirely of alerts due to monitoring station equipment issues (such as a malfunctioning TOC sensor), and could also have been easily discounted.

All four valid clusters each contained two alerts. The time between the valid alerts within these clusters ranged from 7.1 to 8.9 hours. Three of these valid clusters were caused by a treatment plant change, and the fourth was caused by verified non-standard system operation. The other valid alert causes such as main breaks and distribution system work generally only impacted one or two stations and thus did not produce alert clusters.

6.4 Summary

The occurrence of valid and invalid alerts has a significant impact on the benefit and sustainability of a WQM system. Benefits of WQM 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 staff from other duties and may ultimately be perceived as an unsustainable system.

As described in Section 6.1, the CANARY software and software configurations were updated during the evaluation period to improve performance and address bugs. Thus, two analyses were performed on the utility data from the evaluation period: the CANARY alerts that were actually produced during real-time deployment were captured, and then the data was reprocessed using the final CANARY configurations to evaluate what performance would have been if these settings had been in place all along. The cause of each alert was identified. Some of the alerts were determined to be valid, as they were triggered by actual unusual conditions in the distribution system.

Using the final CANARY configurations (i.e., reprocessed), 809 alerts were produced, 39 (5%) of which were valid. Alert occurrence varied significantly across the 15 stations, ranging from 15 to 142 invalid alerts and 0 to 7 valid alerts. The majority of invalid alerts were caused by background water quality variability (40%) and equipment issues (40.2%), and the frequency of invalid alerts decreased significantly over the evaluation period as system issues were resolved and sensor performance improved.

There were also 49 incidents of unusual water quality in the utility data, and 69.4% of them were detected. Most were attributed to verified non-standard system operations. These incidents impacted between one and nine monitoring stations. Clusters were formed for four of the detected incidents, each containing two alerts.

Two hundred and ten invalid alert clusters were produced on the utility data. 88% were easily discounted as the alerts were not related hydraulically or did not have similar water quality changes. Utility staff determined that the alerts making up the remaining alert clusters were also unrelated. Thus, while the occurrence of invalid alert clusters was substantially greater than that for valid clusters, the characteristics of the valid clusters were distinct from those of invalid clusters, and thus easy to identify.

Results from the simulation study showed there were 1,959 potential alerts (i.e., impacted monitoring stations) over the 737 practically detectable scenarios. A total of 1,373 alerts were produced, all of which were considered valid under the conditions of the simulation study, yielding an overall alerting percentage of 70%. Alert rates were highly dependent on the monitoring location, with the percentage of potential alerts generated varying from 16% to 98%. WQM stations that lacked ORP had lower detection rates relative to the other stations, and the one monitoring station that lacked both ORP and TOC had the lowest detection rate of all. Baseline water quality variability also had an impact on alert rates, with locations with greater background variability generally having lower detection rates. Clusters were formed for 347 (47%) of the detected scenarios and included between 2 and 13 valid alerts.

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. The timeliness of detection is a function of many aspects of WQM component design, including sensor network design, data transmission rates, data processing speeds, and alert investigation procedures. In order to evaluate how well the Cincinnati WQM component met this design objective, the time for initial detection and the time to investigate a WQM alert will be evaluated.

7.1 Time for Initial Detection

Section 6 summarized valid alerts generated for both simulated contamination incidents and real periods of unusual water quality observed during the Cincinnati pilot. This section discusses timeliness of detection for both types of alerts.

Definition: The time for initial detection is the time between the presence of unusual water quality in the distribution system and the start time of the first alert. The time for initial detection is comprised of two elements. First, since water quality is monitored only at distinct locations in the distribution system, there is a hydraulic travel time before the unusual water reaches a WQM location. Second, there is a delay between the time that unusual water reaches a monitoring location and the time the event detection system generates an alert. The CANARY event detection system used in Cincinnati is designed such that it must witness several consecutive timesteps of abnormal data before generating an alert, which eliminates invalid alerts that would otherwise occur due to a single excursion in the data, as might occur with a brief interruption in data communications.

The following delays also contribute to the time for detection, though they are negligible. Together, they contribute less than eight minutes to the detection timeline.

- Time to analyze water by water quality probes: Hach CL-17 analyzes water quality every 2.5 minutes and GE Sievers TOC analyzes every 4 minutes.
- Time to communicate data from the monitoring stations: GCWW uses a 2-minute polling interval, so this is the maximum time that lapses between data generation and transmittal.
- Time to transmit data to the event detection system: all observed times were less than 30 seconds.
- Time for event detection system analysis: all observed times were less than 30 seconds.
- Time to transmit event detection system output to control system: all observed times were less than 30 seconds.

7.1.1 Timeliness of Detection for Valid Alerts from Simulated Contamination Incidents

Analysis Methodology: For simulated contamination incidents, timeliness of detection is calculated from the scenario's injection time, as this is the time that contaminant is introduced to the distribution system. The two main elements of detection time can be precisely calculated for simulated contamination events. The hydraulic travel delay is the difference between the scenario's contaminant injection time and the first time that non-zero concentration is present at a monitoring location. The event detection system alert delay is the difference between the alert start time and this time of non-zero contaminant concentration.

Results: Of the 737 simulated contamination scenarios for which WQM location(s) were impacted, 1,959 monitoring stations were impacted. Overall, the hydraulic travel time between the contaminant injection location and impacted monitoring locations ranged from 0.25 hours to 56.8 hours, with a median of 10.8 hours. The median time for water to reach a monitoring location for a scenario was 5.8 hours (this uses the earliest time water arrived across the impacted stations for each scenario).

The remainder of this section considers only stations for which an alert was received. The overall time to detect the simulated contamination incidents ranged from 26 minutes to 79.8 hours with an average of 9.2 hours.

Figure 7-1 shows the statistical distribution of times to detect for the simulation study. The first three plots show the detection timeline of all 1,373 alerts generated during the simulation study. The two main elements of detection time (hydraulic travel time and event detection alert delay) are shown, followed by the overall times to alert. The final plot shows the range of total detection times for the 643 detected scenarios. The times in this final plot are shorter than those in the previous because only the first alert for each scenario is included.

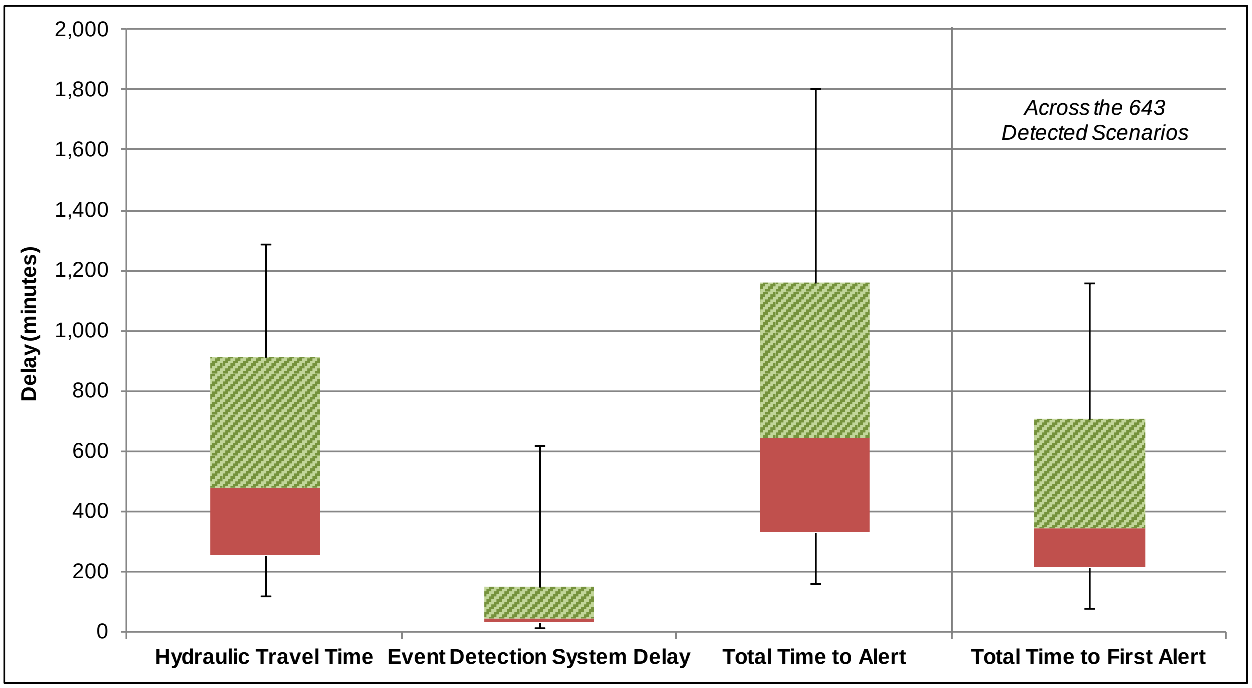


Figure 7-1. Timeliness of Detection for Simulation Study Scenarios

The hydraulic travel time ranged from 15 minutes to 41.8 hours, with a median of 8 hours. Event detection system delays ranged from nine minutes to 120 hours, with a median of 46 minutes. The longer event detection system delays were generally caused when there was a very small initial contaminant concentration at the monitoring location; many hours could go by before a detectable concentration was present.

Overall, times to detect for all alerts were between 26 minutes and 154 hours, with a median of 10.8 hours. When only considering the first alert from each scenario, the times to detect were between 26 minutes and 80 hours, with a median of 5.8 hours. The timing of the first alert is critical as it initiates the investigation process. If the alert is found to be valid, activation of the Cincinnati Pilot Consequence Management Plan and implementation of response actions can begin.

The Cincinnati pilot's threat level is automatically elevated to Possible when two valid alerts that are hydraulically connected and have the same trigger parameters occur within a time period consistent with the hydraulic travel time between the alerting stations. For the 347 scenarios discussed in Section 6.3.1 in which a cluster was formed, the time the second alert was received ranged from 3.1 to 93.6 hours, with a median of 13.2 hours. The time between the first and second alerts ranged from 1 minute to 74.5 hours, with a median of 10.2 hours. Note that a second alert requires that contaminated water has flowed to at least two stations; this metric is highly dependent on hydraulic travel times.

The total time to alert is strongly dependent on the monitoring location at which the alert is generated. **Figure 7-2** investigates the total time to alert for each of the 15 monitoring stations.

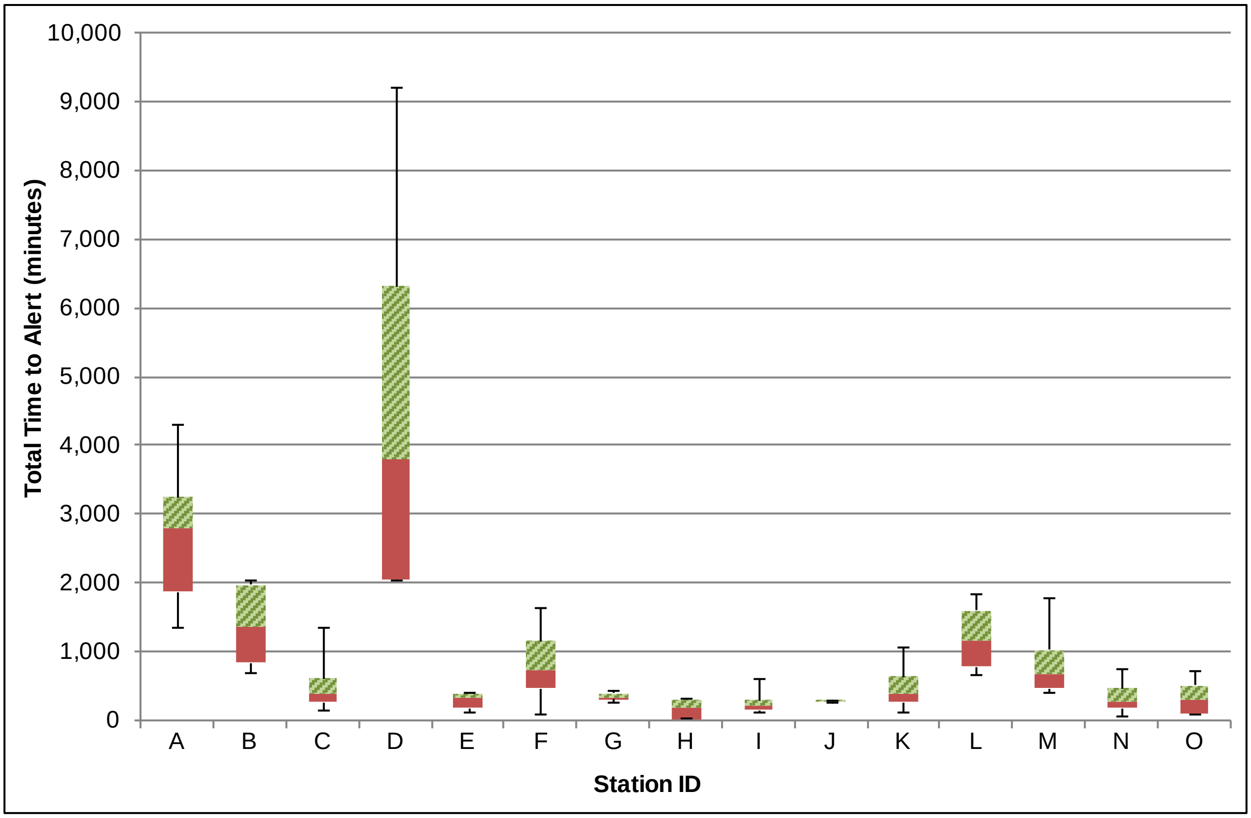


Figure 7-2. Timeliness of Detection by Monitoring Location

The median total time to alert ranged from 3.3 hours (station H) to 63.3 hours (station D). The three stations with the longest alert delays (stations A, B, and D) were also the stations with the lowest percentage of alerts produced, as shown in Figure 6-1. Since these stations experience high water quality variability that can mask water quality anomalies, CANARY was configured to require a longer period of unusual water quality before an alert is produced. 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.

The variability in alert time across monitoring stations is further investigated in **Figure 7-3**, which shows the two components of the total alert time: hydraulic travel time and event detection system delay.

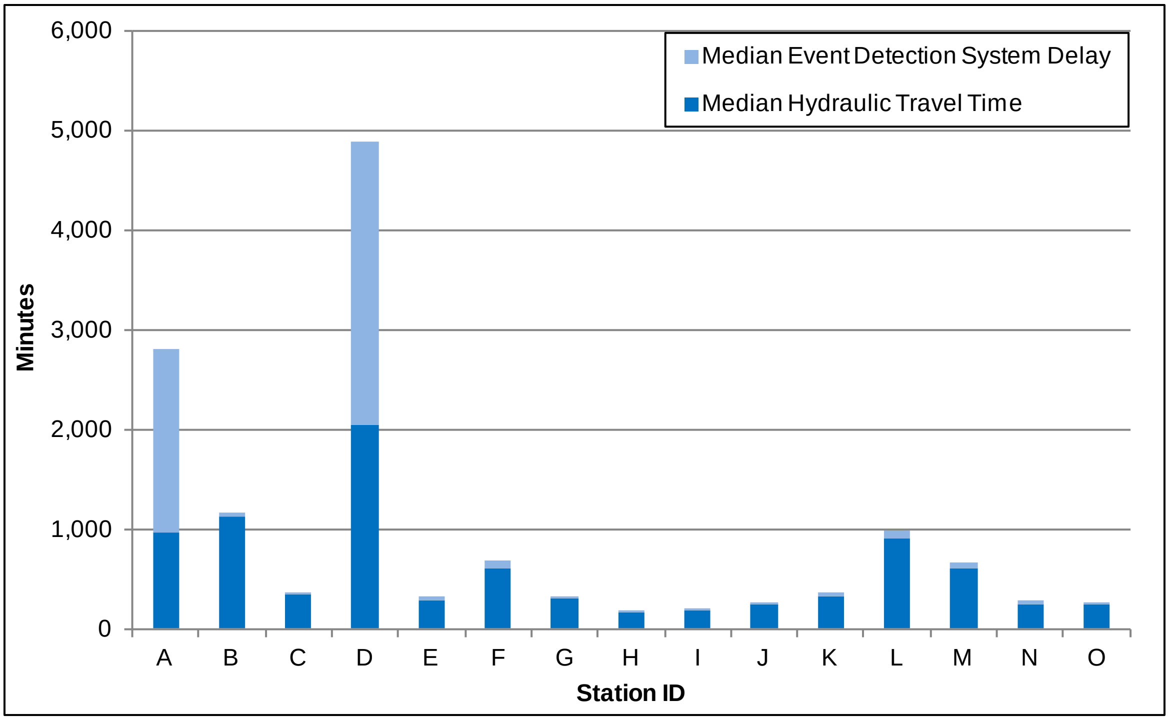


Figure 7-3. Components of Time to Detect by Monitoring Location

Across the stations, the median hydraulic travel time ranged from 2.75 sStation H) to 34 hours (station D). This was fairly consistent across stations, with a median of 5.5 hours (330 minutes).

The median event detection system delays ranged from 26 minutes (stations C and O) to 47.6 hours (station D). As noted above, stations A and D were configured to delay alerting until more unusual data was seen. Excluding these two stations, the median event detection delays ranged from 26 to 75 minutes, and eight stations had a median delay of less than 35 minutes.

Figure 7-4 presents the range of total alert times by contaminant. Note that no scenarios using Toxic Chemical 8 were detected, and thus no times to alert are shown on this plot.

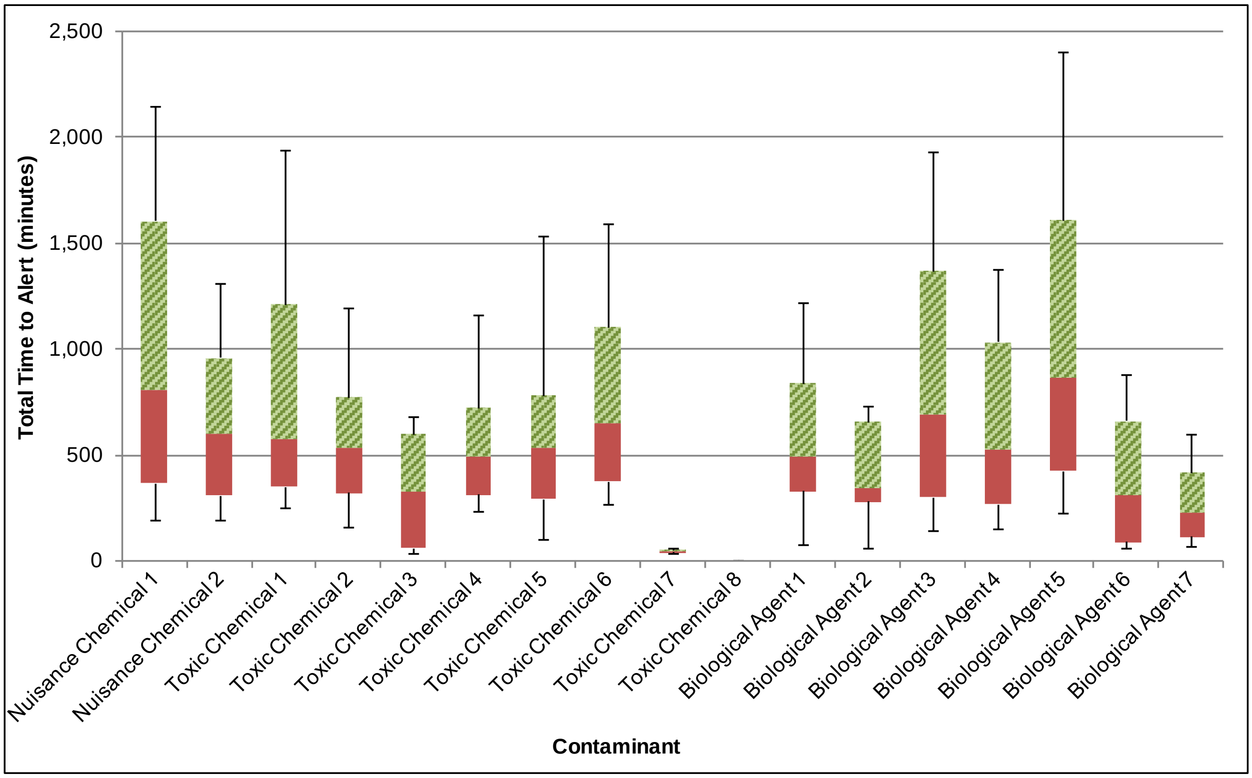


Figure 7-4. Timeliness of Detection by Contaminant

Excluding Toxic Chemical 7, for which only four valid alerts were produced, the median times to alert are fairly similar across the contaminants, ranging from 3.9 (Biological Agent 7) to 14.5 hours (Biological Agent 5). This may be due to the fact that injections were simulated throughout the distribution system for all contaminants. Hydraulic travel time, which is strongly influenced by injection location, is the dominant element of the delay between the start of contaminant injection and the generation of a WQM alert.

7.1.2 Timeliness of Detection for Valid Alerts from Observed Water Quality Anomalies

Analysis Methodology: Unlike the simulation study, there is no definitive "injection time" from which to calculate the timeliness of detection for observed water quality anomalies. In most cases, the point and time at which unusual water enters the system is unknown.

However, the "start times" of the treatment plant changes can be reasonably estimated, as there is monitoring equipment at the effluent of both treatment plants. The data from these plant monitoring stations was mined to determine when the treatment change occurred – and thus when the atypical water quality entered the distribution system.

However, the start time for the other observed water quality anomaly types (described in Section 6.2.2) cannot be determined. For example, there is no record of precisely when the main break events occurred, only when the break was first reported. This uncertainty makes it impossible to calculate a timeliness of detection with any degree of confidence. As a result, only treatment plant changes were considered when quantifying timeliness of detection for observed water quality anomalies.

Results: During the evaluation period, six observed water quality anomalies originated from the treatment plant. One more plant event was detected but is not considered here, as the time anomalous water quality entered the system could not be determined because of a communication failure. Across these, a total of 42 stations were determined to be impacted using the analysis methodology described in Section 6.2.2. Overall, the hydraulic travel time between the treatment plant and impacted monitoring stations ranged from 6.3 hours to 41.4 hours, with a median of 11.3 hours. The median time for water to reach any monitoring location across these events was 7.1 hours (this uses the earliest time water arrived across the impacted stations for the six events).

Four of the treatment plant events were detected – each with one alert received. Considering only the stations from which an alert was received, the hydraulic travel time was between 7.3 and 13.1 hours, with a median delay of 10.5 hours. The median time it took CANARY to alert at a monitoring location once unusual water had reached it was 1.6 hours. Overall, the time to detect for these treatment plant events ranged from 7.6 to 17.4 hours, with a median of 13.1 hours. Note that an alert was not always generated at the first monitoring location reached.

7.2 Time to Fully Investigate a WQM Alert

Definition: The time to fully investigate a WQM alert is the time necessary to complete all steps in the alert investigation process and conclude whether contamination is possible. Generally, this is the time between the start of the alert and the time that the Water Quality & Treatment Technician reports results from the monitoring station inspection to the Water Quality & Treatment Chemist.

Analysis Methodology: The results from four drills and exercises conducted during the evaluation period, described in Section 3.2, were used to estimate the time to fully investigate a WQM alert. In addition, the time to complete major steps of the alert investigation process (e.g., review water quality trends, review operations and work orders, inspect the monitoring station, etc.) were analyzed. The time at which contamination was determined to be Possible is also presented; however, note that the details of the contamination scenario driving each drill or exercise. In several cases, information from other monitoring and surveillance components was available before the WQM alert was fully investigated, which resulted in a time to establish possible contamination that is shorter than the time to fully investigate the WQM alert.

Alert investigation times from routine operations were not included in this analysis. Section 9.1 presents the level of effort required for the routine investigation of alerts. 95% of the WQM alerts generated during routine operations were found to be invalid via an abbreviated investigation process; no real-time investigations required an on-site inspection of the monitoring station that produced the alert.

Results: WQM Drill 1 was conducted on July 14, 2008. The alert from the CANARY event detection software was received at 9:00 am and the GCWW Water Quality & Treatment Chemist began the investigation within three minutes. The investigation concluded after 119 minutes (approximately 2 hours) as the GCWW Water Quality & Treatment Technician reported the results of his station inspection back to the GCWW Water Quality & Treatment Chemist at 10:59 am. **Figure 7-5** shows the timeline progression of the key activities completed during the WQM alert investigation for WQM Drill 1. The timeline was normalized so the alert start time occurs at time 0.

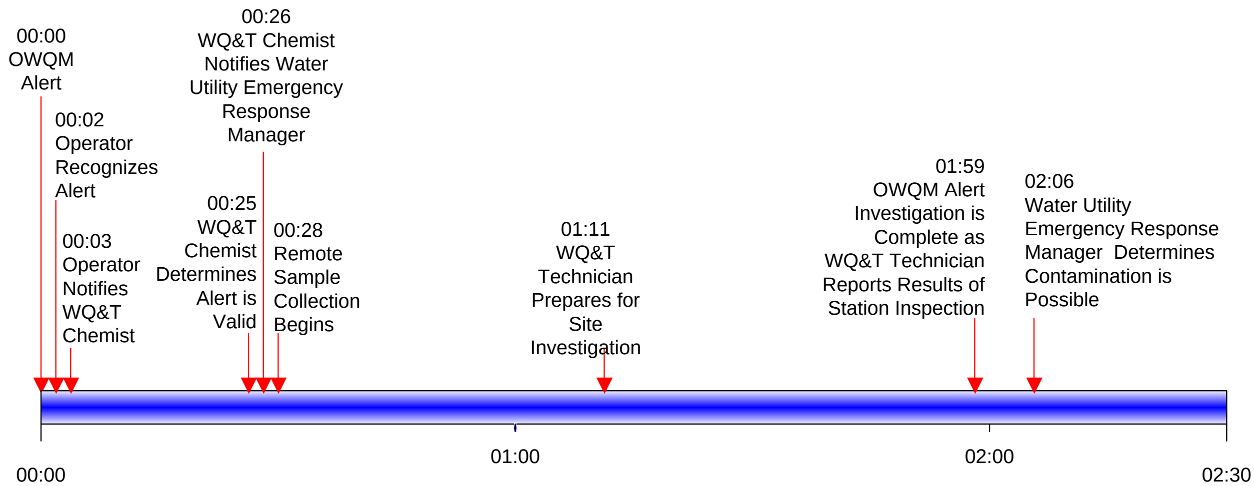


Figure 7-5. Timeline Progression of the WQM Alert Investigation during WQM Drill 1

For WQM Drill 1, the GCWW WUERM made the determination that contamination was Possible following completion of the WQM alert investigation, 126 minutes after the WQM alert was received. This drill was based on a single WQM alert, and no information was available from other components to accelerate the process of establishing possible contamination.

A Full Scale Exercise was performed on October 1, 2008. For the WQM component, the first alert was received at 7:30 am. The investigation of this alert was completed at 10:30 am as the GCWW Water Quality & Treatment Technician reported results from the WQM station inspection. The time to investigate the WQM alert was 180 minutes (3 hours). **Figure 7-6** shows the timeline progression of the key activities completed during the initial WQM alert investigation for the Full Scale Exercise.

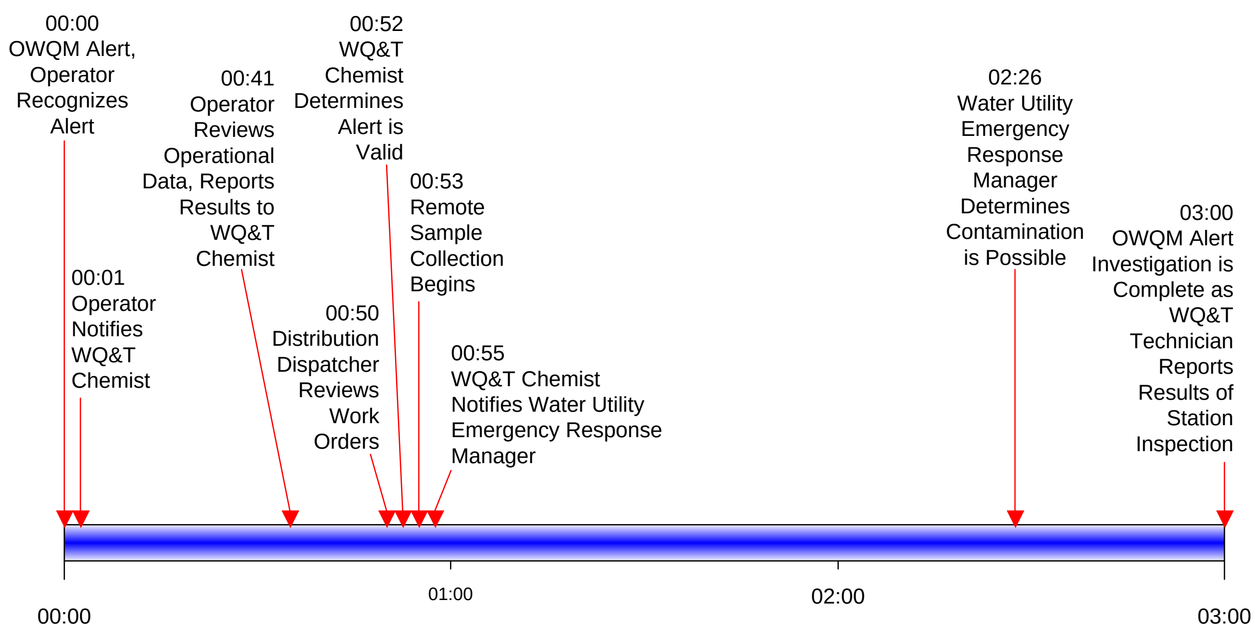


Figure 7-6. Timeline Progression of WQM Alert Investigation During Full Scale Exercise

For this exercise the WUERM determined that contamination was possible at 9:56 am, 146 minutes after the first WQM alert was received. Note that this determination was made prior to completion of the initial WQM alert investigation. This was a result of additional alerts being received; alerts were received from two additional WQM stations at 9:40 am (02:10 on Figure 7-6).

WQM Drill 2 occurred on February 25, 2009. The initial WQM alert was received at 8:22 am. The GCWW Water Quality & Treatment Technician inspected the alerting monitoring station and reported the results back to the Chemist at 11:33 am. For this drill, the time to investigate the alert was 191 minutes (3.2 hours). **Figure 7-7** shows the timeline of key activities completed during the initial alert investigation.

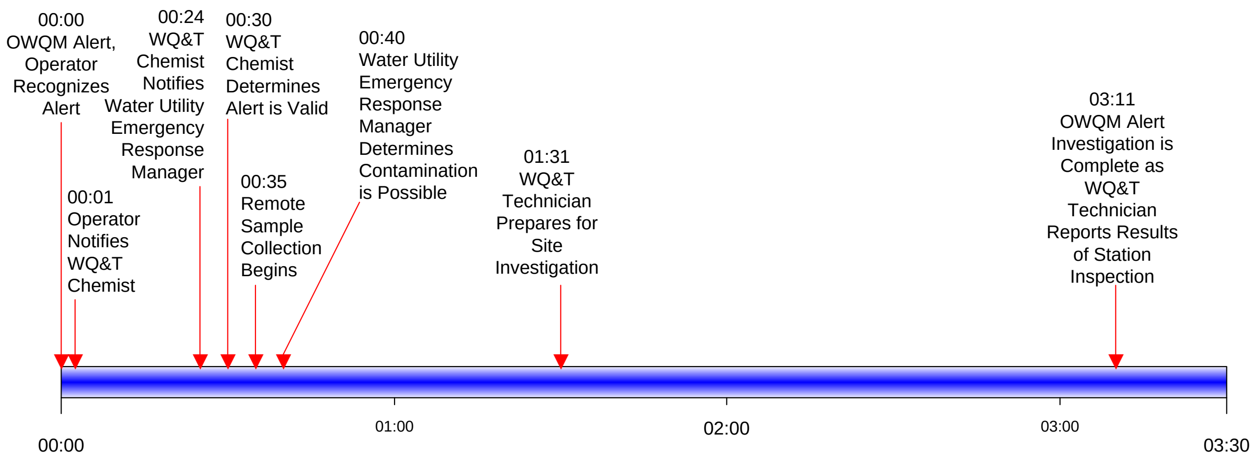


Figure 7-7. Timeline Progression of the WQM Alert Investigation During WQM Drill 2

During WQM Drill 2 the WUERM made the determination that contamination was possible at 9:02 am, 40 minutes after the first WQM alert was received. This decision was made prior to completion of the initial WQM alert investigation because an additional WQM alert had been received with similar parameters and hydraulic connectivity to the first WQM alert and it was verified that operational activities had not caused either alert.

The WQM After-Hours Drill, intended to target staff with less experience investigating alerts, began on April 29, 2009. The WQM alert was received at 9:30 pm. The GCWW Water Quality & Treatment Technician inspected the monitoring station and reported results back to the GCWW Water Quality & Treatment Shift Chemist at 12:12 am (April 30, 2009). For this drill, the time to investigate the alert was 162 minutes (2.7 hours). **Figure 7-8** shows the progression of the key activities completed during the WQM alert investigation.

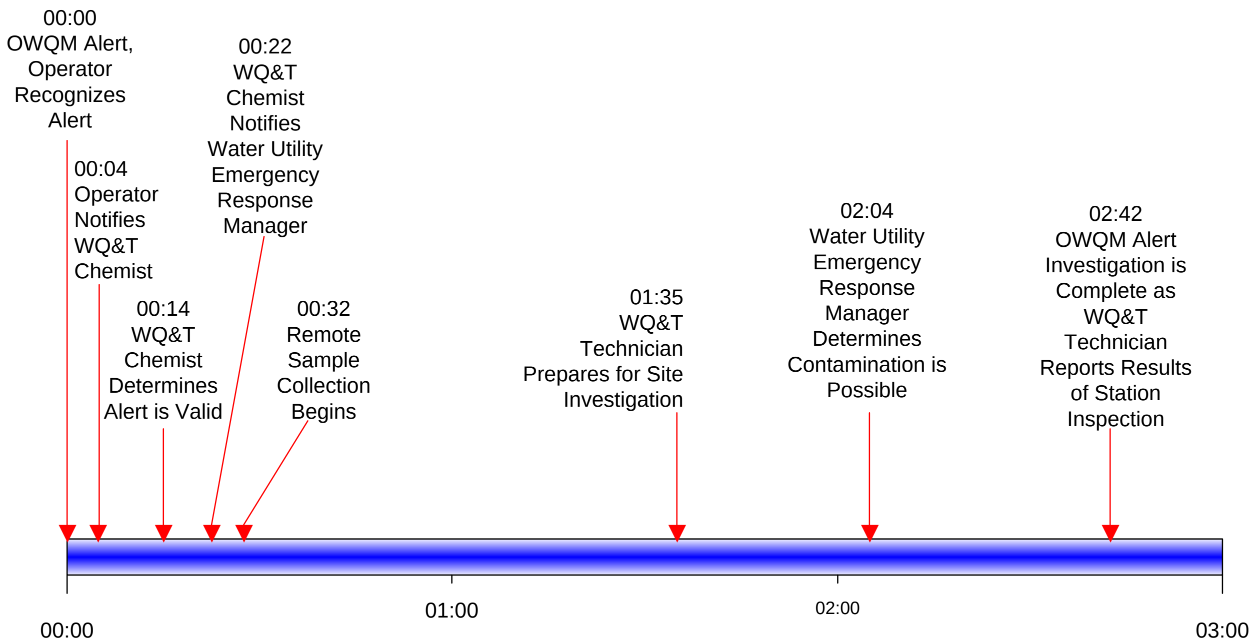


Figure 7-8. Timeline Progression of the WQM Alert Investigation During WQM After-Hours Drill

During the WQM After-Hours Drill the WUERM made the determination that contamination was Possible 124 minutes after the initial WQM alert was received. This decision was made prior to completion of the WQM alert investigation because an alert was received from a second, nearby WQM station. After review of the two alerts and verification that the alerts were related and not caused by operational activities, contamination was deemed Possible.

Table 7-1 provides a summary of the average and range time spent on each activity. The average time to investigate a WQM alert was 165 minutes (2.8 hours) with a range of 119 to 191 minutes.

Table 7-1. Time to Implement Key Activities During Drill and Exercise WQM Alert Investigations

Activity	Average (minutes)	MIN to MAX (minutes)
Time to Investigate WQM Alert	**165**	**119 to 191**
Time elapsed between start of WQM alert and operator recognition of alert	1	1 to 2
Time for operator to notify Water Quality & Treatment Chemist	1	1 to 1
Time for operator to review operational data and report results to Water Quality & Treatment Chemist	7	7 to 7
Time for Distribution Dispatcher to review work orders	2	2 to 2
Time for Chemist to determine WQM alert is valid	28	10 to 51
Time for Chemist to notify Emergency Response Manager	4	1 to 8
Time to initiate remote sample collection	8	1 to 17
Time for Water Quality & Treatment Technician to prepare for site investigation	41	31 to 52
Time for Water Quality & Treatment Technician to inspect WQM station and report results to Water Quality & Treatment Chemist	42	19 to 58

7.3 Summary

The time for initial detection by the WQM component is comprised of two main elements: the time necessary for contaminated water to flow from the contamination site to a WQM station, and the time necessary for the event detection system to produce an alert.

Table 7-2 summarizes these delays for both simulated events and observed water quality anomalies. The range of values observed is shown, followed by the median value in parentheses. The second column shows the hydraulic travel times from the source of unusual water to impacted station(s). The third column captures the same times, but only for stations at which an alert was produced. The fourth column shows the event detection system delays for all alerts produced, and the final column summarizes the overall times to detect.

Table 7-2. Summary of Delays in Time to Detect

Event Type	Hydraulic Travel Time for All Impacted Stations	Hydraulic Travel Time for Alerting Stations	Event Detection System Delay	Total Time to Alert
Simulated Contamination Events	0.25 – 56.8 hours (10.8 hours)	0.25 – 41.8 hours (8 hours)	0.15 – 120 hours (0.8 hours)	0.4 – 154 hours (10.8 hours)
Observed Water Quality Anomalies	6.3 - 41.4 hours (11.3 hours)	6.3 – 11.3 hours (7.6 hours)	0.3 – 6.4 hours (1.6 hours)	7.6 – 17.4 hours (13.1 hours)

Clearly the hydraulic travel time was responsible for the majority of the delay between the start of an incident and alert generation. This emphasizes the importance of sensor network design, as the monitoring locations determine how long it takes for unusual water to reach a location at which it could potentially be detected.

While the range was much larger for the simulated contamination incidents, which originated from many different distribution system locations, the median value for the total time to alert was remarkably similar for the simulated and observed water quality incidents.

Drills and exercises showed that full investigation of a valid alert takes between two and three hours. This timeline is greatly accelerated when additional alerts are received – either from WQM or another CWS component. The additional information can curtail the need for a site inspection of a monitoring station. However, for the 348 simulated scenarios for which multiple alerts were produced, the median time between the first and second alerts was 10.2 hours, indicating that the second alert may not always arrive in sufficient time to avoid the site inspection.

Section 8.0: Design Objective: Operational Reliability

For a CWS to consistently detect incidents of unusual water quality, it must achieve a high degree of operational reliability. Specifically, the four WQM design elements: monitoring stations, data collection, event detection system and component response procedures must all be consistently available and producing quality data. In order to evaluate how well the WQM component met this design objective, the following three metrics were evaluated: data completeness, data accuracy and availability. The following subsections define each metric, describe how it was evaluated and present the results.

8.1 Data Completeness

Definition: Data is considered incomplete if it is missing or unusable. A sensor's data is considered missing if it is not delivered to the SCADA system, as data is expected from every sensor monitored by the WQM component every two minutes. If the data is delivered to the SCADA system but has been flagged to indicate suspect quality, it is considered unusable. Incomplete data is problematic because it represents an opportunity for a missed event.

Data completeness was evaluated for the WQM component to characterize the amount of data that was delivered to, and considered usable by, CANARY. Thus, it characterizes performance of the monitoring station and data collection design elements. Because performance issues with individual sensors were a primary cause of lost data, completeness was also characterized in detail for each sensor. The component and sensor analyses are presented in Sections 8.1.1 and 8.1.2, respectively.

8.1.1 Data Completeness for the WQM Component

Analysis Methodology: All data generated during the evaluation period was analyzed to characterize data completeness for the WQM component. This analysis measured the amount of data delivered to the SCADA system free of flags and thus considered usable by the event detection system. The time, monitoring station and cause of each instance of missing or unusable data were documented.

The following definitions applied to the analysis of component data completeness:

- **Data Stream:** The output signal for a single instrument (e.g. Hach chlorine sensor at a specific monitoring station). There are 84 WQM data streams for the Cincinnati pilot.
- **Potential Data Hours for the Component:** The total number of hours in the evaluation period multiplied by the total number of data streams.
- **Complete Data Hours for the Component:** The potential data hours for the component minus the total hours of incomplete data for all data streams.
- **Percentage Data Completeness:** The complete data hours divided by the potential data hours.

When analyzing data completeness for the WQM component, missing or unusable data was attributed to one of the following causes:

- **Sensor Issue:** Data from an individual sensor is incomplete if no data is being produced by the sensor or if a sensor fault is indicated. A detailed analysis of sensor issues is presented in Section 8.1.2.
- **Data Collection Failure**: Two patterns indicate a data collection failure: 1) the responses from all sensors at a monitoring station are concurrently flat-lined, or 2) the data from all sensors at a monitoring station are missing for a period of time. Data collection failures are grouped into two sub-categories:

  - *System-Wide Outage*: This type of failure is characterized by flatlined or missing data for all WQM data streams, which can result from a system-wide network outage or failure of the SCADA system.
  - *Monitoring station Data Collection Failure*: This type of failure is characterized by flatlined or missing data for all data streams from a single monitoring station which may result from loss of communication service to the monitoring station or PLC failure.
- **Monitoring Station Issue**: Data may be considered incomplete because of a problem with the monitoring station including:
  - *Loss of Flow to Monitoring Station*: A hydraulic problem, such as a main break or clogged pressure regulator, can interrupt the flow of pressurized water to a monitoring station. Some sensors generate a fault in this condition, making those data streams unusable for event detection.
  - *Loss of Power to Monitoring Station*: All sensors used at the utility require power to generate and transmit data. While all stations were equipped with a UPS, there were instances where the primary power supply was lost and the UPS charge expired before the power supply was restored. All sensors stopped producing data when this occurred.
- **Calibration**: Each monitoring station has a "Normal/Calibration" selector switch. A technician places the selector switch to the "Calibration" position when servicing the monitoring station. All data streams from a monitoring station during calibration periods are flagged as unusable and thus not analyzed by the event detection system.
- **Monitoring Station Maintenance Error**: Some data was unusable because of technician error. The most common maintenance error occurred when a technician forgot to take a monitoring station out of calibration mode, often resulting in days of flagged, and thus incomplete data.

Results: Figure 8-1 provides the percentage of data completeness for the WQM component for each reporting period. Over the course of the evaluation period, monthly data completeness ranged from 81.7% to 98.6%, with an average of 93.1%.

Between the January 2008 and February 2009 reporting periods, data completeness gradually increased from 89.2% to 98.6%. This improvement can be attributed to improved O&M of the various sensors over the evaluation period and to modifications that were made during the evaluation period after observing and correcting equipment issues, as shown in Table 2-5. The exception to the upward trend during this period was the September 2008 reporting period during which data completeness was only 83.2% due to widespread and prolonged power and communications outages during the Hurricane Ike windstorm.

Between the February 2009 and May 2010 reporting periods, data completeness for the WQM component ranged between 81.7% and 96.8%, with downtime attributed to recurring maintenance issues and sensors being taken offline due to prolonged equipment malfunction. The decline in data completeness following the transition to real-time monitoring in June 2009 demonstrates the challenge of keeping the complex equipment used in the WQM component in proper working order, even after the initial start-up issues have been worked out.

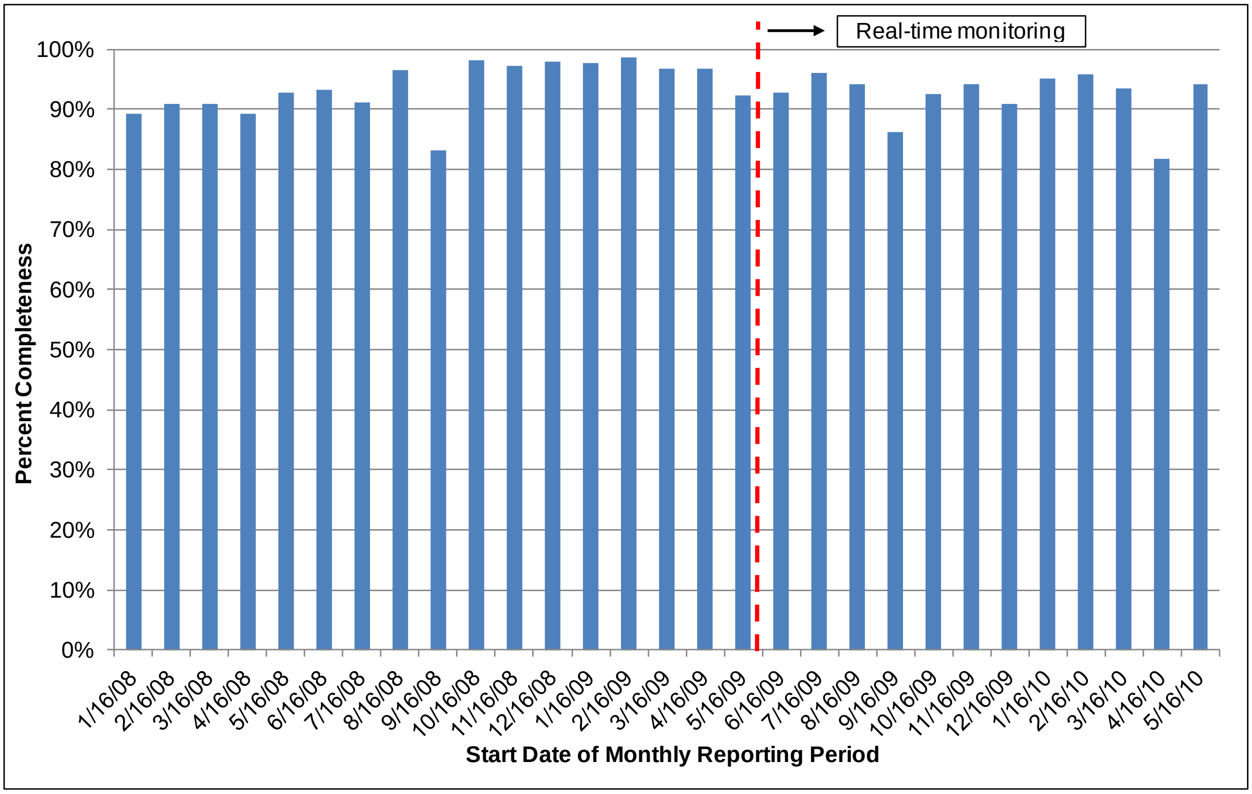


Figure 8-1. Data Completeness for the WQM Component over the Evaluation Period

Figure 8-2 shows the percentage of incomplete data hours by cause and sub-cause for the entire evaluation period. The total hours of incomplete data for each cause or sub-cause are shown in parentheses. The total number of incidents in each category is shown in brackets.

This figure clearly shows that the leading cause of incomplete data hours was sensor issues, which is covered in greater detail in Section 8.1.2. Though there were fewer incidents of sensor issues (318) than data collection incidents (666), the sensor issues lasted much longer. Many of the data collection incidents lasted less than three hours, whereas sensors taken off-line resulted in weeks of incomplete data.

Data collection failure was the second most significant cause of incomplete data hours and had the most incidents of failure. Most of the data loss attributable to system wide communication outages. This sub-cause was responsible for a significant amount of incomplete data because a system wide communication outage results in loss of all 84 WQM data streams. The longest system-wide outage occurred during the Hurricane Ike windstorm in September 2008. There were also system-wide outages when maintenance or updates were being performed on the SCADA system.

The next two largest causes of incomplete data were monitoring station maintenance errors and calibration, which were responsible for 6% and 4% of incomplete data, respectively. Incomplete data due to calibration is unavoidable as it represents the time that instruments are taken off-line for maintenance activities. The most common maintenance error leading to incomplete data occurred when a technician left a monitoring station in calibration mode.

Monitoring station issues accounted for only 2% of incomplete data, with most of the data losses resulting from loss of power. The Hurricane Ike windstorm in September 2008 resulted in data loss because many monitoring stations experienced prolonged power outages that extended beyond the capacity of the UPS.

Beyond that incident, most instances of power loss were associated with two monitoring stations. One experienced numerous power outages due to non-CWS equipment on the same circuit overloading and tripping the circuit breaker. Another, located at a Cincinnati Fire Department facility, occasionally experienced power outages when overspray from vehicle wash-down tripped the ground fault circuit interrupter receptacle that the WQM station was plugged into.

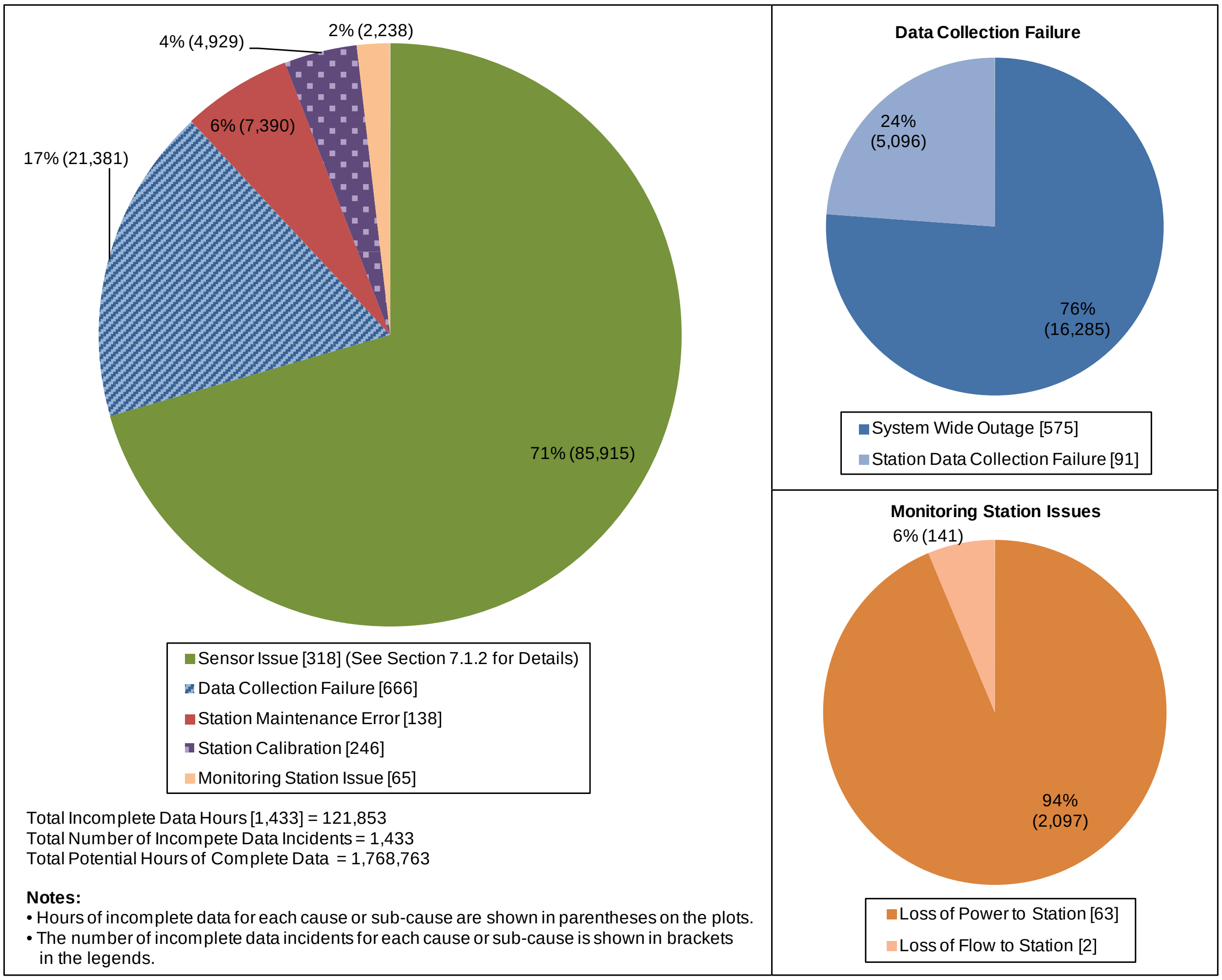


Figure 8-2. Cause and Sub-cause of Incomplete Data for the WQM Component

8.1.2 Data Completeness for Individual Water Quality Sensors

Definition: Data completeness was calculated for each individual sensor during the evaluation period. This analysis measured the amount of data delivered by each sensor to the SCADA system free of flags, and thus considered usable by the event detection system.

Analysis Methodology: When analyzing completeness for an individual sensor, the number of potential data hours excluded the incomplete data hours attributable to causes other than sensor issues. Thus, the number of hours of incomplete data attributable to data collection failure, monitoring station issues, calibration of other sensors and monitoring station maintenance errors as described above were subtracted from the total number of potential data hours in the evaluation period for each sensor.

The definitions for data stream and percentage data completeness from Section 8.1.1 also apply to Section 8.1.2. The following definitions apply to the analysis of data completeness for individual sensors:

- **Potential Data Hours for a Sensor:** The total hours that data is expected to be collected from an individual sensor during the evaluation period.
- **Complete Data Hours for a Sensor:** The potential data hours for the sensor minus the total hours of incomplete data for the sensor.

When analyzing data completeness for individual sensors, missing or unusable data was attributed to one of the following causes:

- **Sensor Offline**: A sensor is considered "offline" when it has been turned off by the utility. Many instruments were taken offline temporarily for maintenance, and a few were taken offline permanently due to persistent issues.
- **Sensor Fault**: Data is flagged as unusable when the sensor diagnostics detect an internal fault which can be due to a hardware malfunction or a software error.
- **Flat-line Response**: Flat-line data from an individual sensor indicates that new values are not being produced, which can result from a loose cable connection or an error with hardware, firmware or software. If all sensors from a particular monitoring station were flat-lined, those hours of incompleteness were attributed to data collection failure and not included in the potential data hours for the station's individual sensors.
- **Improper Sensor Maintenance**: This cause was used when a sensor fault was triggered by work performed by a technician during a sensor maintenance activity.

Results: The sensor completeness is summarized in **Table 8-1** below. See Table 2-5 for detailed descriptions of the WQM modifications, many of which significantly impacted data completeness.

Table 8-1. Average Annual Percentage Data Completeness for WQM Sensors

Sensor*	Percentage Completeness		
	2008	2009	2010
Hach Astro TOC	85.9%	55.7%	30.1%
Hach Chlorine	98.5%	99.8%	100%
Hach conductivity	99.0%	100%	100%
Hach ORP	98.7%	100%	100%
Hach pH	98.9%	98.1%	100%
s::can carbo::lyser	43.2%	91.4%	100%
Sievers 900	93.0%	90.8%	86.3%
US Filter Chlorine – Bare Electrode Flow Cell	53.7%	-	-
US Filter Chlorine – Membrane Flow Cell	78.6%	95.2%	100%
US Filter pH	98.8%	99.5%	100%
YSI conductivity	97.2%	100%	100%
YSI ORP	98.1%	100%	100%

* See Table 2-2 for a list of the sensor models

As discussed in Section 2.1.1, the utility switched from U. S. Filter bare electrode chlorine probes to membrane probes and flow assemblies in July 2008 because the relatively high pH of the distributed water was incompatible with the upper pH tolerance of the sensor. The difference in data completeness is dramatic and emphasizes the importance of selecting sensors that are compatible with a utility's specific water quality.

The percentage completeness for most sensors increased from 2008 to 2009 as modifications and improvements were performed. The s::can carbo::lyser had the most significant improvement. The s::can carbo::lysers experienced relatively low data completeness during 2008; these units produce sensor faults when there are hardware issues, causing CANARY to ignore the data. Section 2.5 describes that original aluminum housings were replaced with stainless steel housings to remedy the build-up of aluminum oxide on the lamp assemblies, significantly increasing data completeness in 2009. Technicians continued to identify and address s::can issues in 2009, such as backwards flow through the flow cell and fouled windows, resulting in 100% data completeness in 2010.

However, the data completeness for the Hach Astro TOC and Sievers TOC decreased from 2008 to 2009. The decrease in data completeness for the Sievers TOC was due to multiple defects and issues, including faulty inorganic carbon removers, leaky syringes, and clogged or loose tubing. In the case of the Hach Astro TOC, the decrease in data completeness resulted from the sensors being decommissioned starting the latter half of 2009 due to recurring equipment problems that caused inaccurate and erratic data. The two types of TOC instruments continued to experience recurring equipment malfunctions into 2010, resulting in substantial downtime. The utility began decommissioning the Hach Astro TOC instruments in 2009, and all three Hach Astro TOC sensors were offline for nearly all of 2010.

In 2010, the data completeness for all sensors, except the Hach Astro and Sievers TOC instruments, increased to 100%. The 2010 sensor data completeness indicates that a high level of performance can be expected from most instruments after initial startup issues have been addressed.

Figure 8-3 shows the sub-causes of sensor issues over the evaluation period. The percentage and total hours (in parentheses) of incomplete data for each sub-cause are shown.

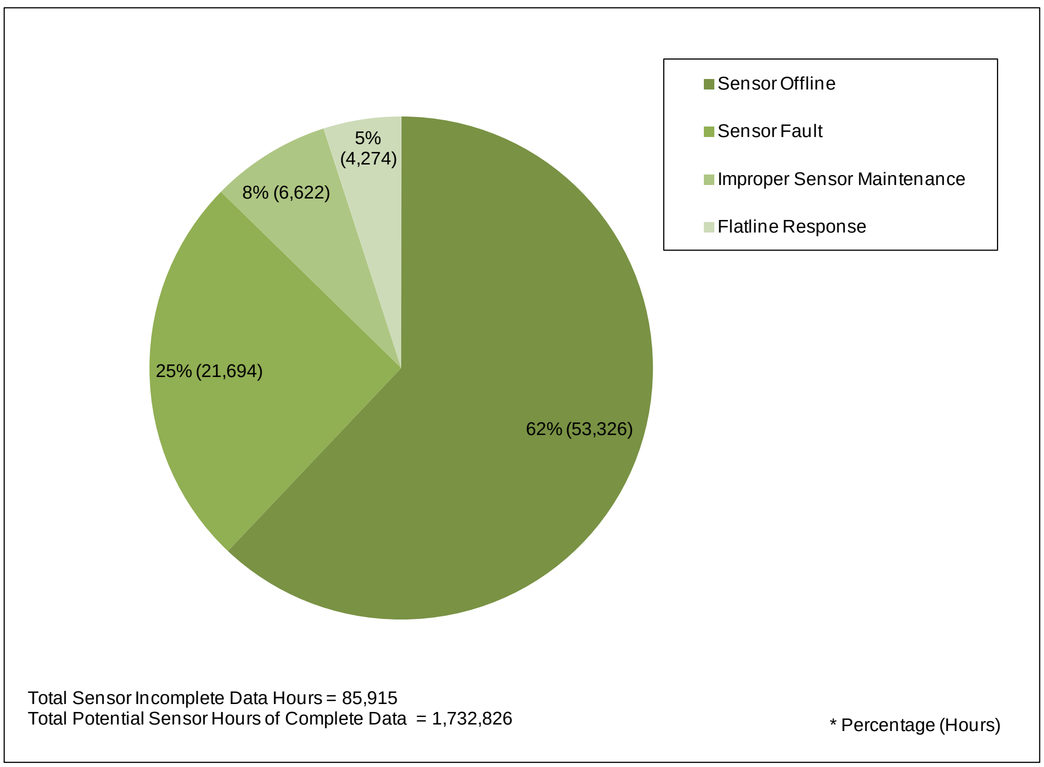


Figure 8-3. Incomplete Sensor Data by Sub-cause

The most significant sub-cause of incomplete data hours attributable to sensor issues was intentionally taking the sensors offline. Offline sensors accounted for 62% of all component incomplete data hours, the most by far of any sensor or component cause or sub-cause.

Sensor faults were second largest cause of incomplete data. The US Filter bare electrode chlorine sensor had the most incomplete data hours attributable to sensor faults because of the incompatibility with GCWW's high pH water. Numerous prolonged faults occurred until the bare electrode probes were replaced as described previously. The Sievers TOC had a slightly inflated number of sensor faults early in the evaluation period because sensor outputs were considered faults which were instead purely informational. The sensor fault output was reconfigured to initiate "fault" conditions only for tags which did in fact indicate that the sensor output was unusable. Note that sensor faults were not received from the YSI sensors and US Filter pH sensors. The YSI sensors did not have the capability of producing a sensor fault, and faults that were produced by the US Filter pH sensor were not transmitted to the SCADA system due to communications bandwidth limitations.

Improper sensor maintenance was the third leading cause of incomplete data, with the Sievers TOC sensor losing the most data to improper sensor maintenance. The complex, compact, and sensitive nature of the Sievers TOC sensor led to multiple occasions where data from these instruments was missing or flagged as unusable soon after a technician had serviced the device

Finally, flat-line response was the sub-cause that contributed least to incomplete data. The Hach Astro TOC had the most incomplete data hours caused by flat-line responses due to recurring sensor issues.

8.2 Data Accuracy

Definition: In addition to being complete, as defined in Section 8.1, data must also be accurate to ensure that the event detection system is analyzing information that reflects actual real-time water quality conditions in the distribution system. Inaccurate data is problematic because it can generate invalid alerts, as seen in Section 6.0, and mask true water quality anomalies.

Data is considered accurate if the measured value is within an acceptable range of the true value obtained through an independent method. The acceptable range for accurate data is defined for each water quality parameter in **Table 8-2**. The true value for each water quality parameter at any given time was approximated using historic data and variability for the monitoring location and by considering the quality of the water leaving the treatment plant.

Table 8-2. Water Quality Parameter Accuracy Ranges

Parameter	Accuracy Range
TOC	± 50%
Chlorine	± 50%
pH	± 10%
ORP	± 30%
Conductivity	± 30%

Accuracy was evaluated for the entire WQM component and for each sensor, as presented in Sections 8.2.1 and 8.2.2, respectively. The component analysis measured the amount of complete and accurate data that was suitable for event detection. The sensor analysis illustrates how malfunction in each sensor type contributed to inaccurate data.

8.2.1 Data Accuracy for the WQM Component

Analysis Methodology: Empirical data that were considered complete during the evaluation period were analyzed to quantify data accuracy at the component level. The time, monitoring station, and cause of each instance of inaccurate data were documented.

The following definitions applied to the analysis of component data accuracy. The definitions for data stream and complete data hours for the component from Section 8.1.1 also apply to Section 8.2.1.

- **Accurate Data Hours for the Component:** The number of complete data hours for the component minus the total hours of inaccurate data for all data streams.
- **Percentage Accuracy:** The accurate data hours divided by the potential data hours.

When analyzing data accuracy for the WQM component, inaccurate data was attributed to one of the following causes:

- **Sensor malfunction:** Sensor malfunctions that caused inaccurate data include sensor hardware or firmware errors, internal flow blockage, defective equipment, and breakage.
- **Improper maintenance:** Examples of improper maintenance that caused inaccurate data included incorrect calibration and failure to replenish reagents before they ran out.
- **Monitoring station flow loss:** In Section 8.1.1, monitoring station flow loss was listed as a cause of incomplete data when the monitoring station's sensors produced sensor faults. However, for sensors which did not produce a fault, the erratic data resulting from a flow loss was considered complete but inaccurate.

Results: In order for data to be considered *usable* for event detection or most other applications, it must be both complete and accurate. **Figure 8-4** shows the total percentage of potential data hours for the component that were unusable, broken down into the hours that were incomplete, as discussed in Section 8.1, and the hours that were complete but inaccurate. Over the evaluation period, the average percentage of data hours that were unusable per reporting period was 10.4%, ranging from 4.98% to 21.9%. Over the same period, the average percentage of complete but inaccurate data hours was 3.46%, with a range from 0.23% to 7.90% per reporting period. These results demonstrate that incomplete data was more common than inaccurate data. This is largely a result of the utility taking sensors with persistent issues off-line – either permanently or until they were fixed.

Figure 8-4 can be evaluated with respect to the two phases of the evaluation period; the optimization phase from January 2008 through May 2009, and the real-time monitoring phase from June 2009 through May 2010. During the optimization phase, data completeness and accuracy for the component fluctuated as issues with different sensors were encountered, causes diagnosed and modifications implemented throughout the optimization period. After the transition to real-time monitoring, data accuracy increased due to a combination of improved maintenance, resolution of equipment malfunctions and decommissioning of instruments with chronic performance issues. An exception to this trend occurred during the December 2009 reporting period, during which a Hach Astro TOC sensor malfunctioned for multiple days. Another month with a high percentage of unusable data was April 2010. In this case, the server providing data to CANARY went down and thus all data streams were incomplete.

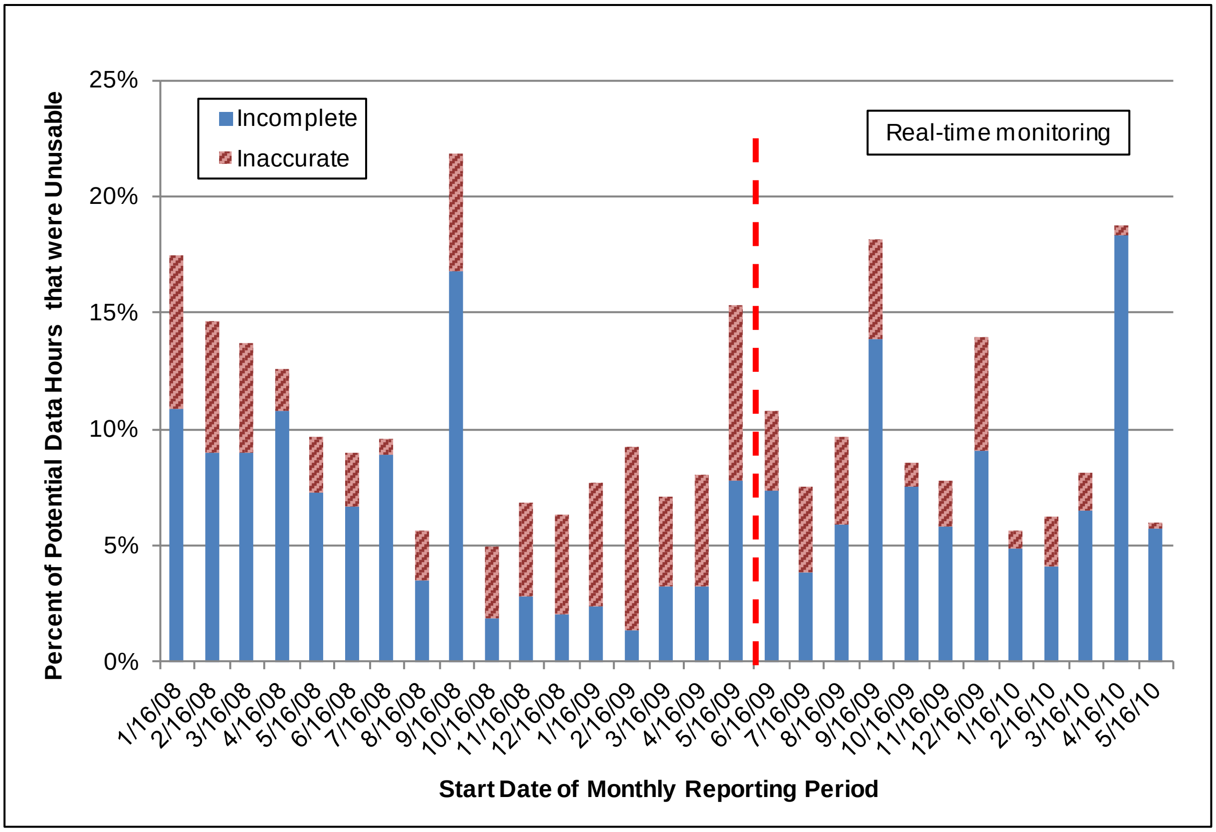


Figure 8-4. Percentage of Potential Data Hours That Were Unusable for the WQM Component

Figure 8-5 shows the breakdown of causes of inaccurate data during the evaluation period. The percentage and total hours (in parentheses) of incomplete data for each sub-cause are shown.

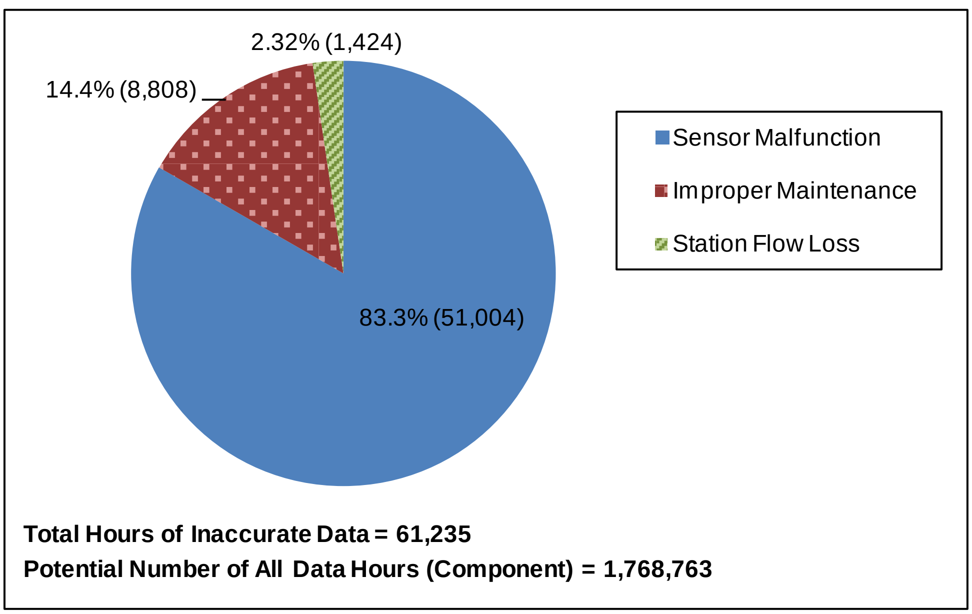


Figure 8-5. Percentage of Component Potential Data Hours that were Inaccurate by Cause

Sensor malfunction was by far the largest cause of inaccurate data, mostly due to issues with the Hach Astro TOC sensors, as discussed in Section 8.2.2. The second largest cause of inaccurate data was improper maintenance, and a major contributor to this was sensors running out of reagents. Station flow loss was the least significant cause of inaccurate data because most sensors generated a fault when there was a loss of flow and thus those data hours were considered incomplete instead of inaccurate.

8.2.2 Data Accuracy for Individual Water Quality Sensors

Analysis Methodology: The empirical data collected from the pilot to evaluate the component accuracy were further characterized to assess the accuracy of the data produced by individual sensors. As monitoring station flow loss and improper maintenance do not reflect sensor performance, inaccurate data hours with those causes are not included in the analyses in this section.

The following definitions applied to the analysis of sensor accuracy:

- **Potential Number of Accurate Data Hours for a Sensor:** The total number of complete data for the sensor minus the inaccurate data hours caused by monitoring station flow loss and improper maintenance.
- **Accurate Data Hours for a Sensor:** The potential number of accurate data hours for a sensor minus the total hours of inaccurate data for a sensor.

Results: **Table 8-3** shows the average annual percentage accuracy for each sensor type over the evaluation period. Overall, most issues that reduced sensor accuracy during 2008 and 2009 resulted in modifications that improved accuracy in 2010. Trends in the data accuracy for a few specific sensors are discussed below.

Table 8-3. Average Percentage Accuracy for Sensors

Sensor ID	Percentage Accuracy		
	2008	2009	2010
Hach Astro TOC	79.0%	75.1%	58.9%
Hach Chlorine	97.7%	99.2%	99.3%
Hach conductivity	99.7%	100.0%	100.0%
Hach ORP	99.2%	100.0%	100.0%
Hach pH	98.7%	94.7%	98.4%
s::can carbo::lyser	81.1%	83.8%	100.0%
Sievers 900	96.4%	96.7%	95.7%
US Filter Chlorine US Filter Chlorine	95.4%	-	-
US Filter Chlorine – Membrane Flow Cell	99.9%	84.2%	100.0%
US Filter pH	97.0%	86.2%	99.6%
YSI conductivity	96.9%	99.3%	100.0%
YSI ORP	96.6%	95.3%	100.0%

In 2008 and 2009, the s::can carbo::lyser exhibited the second lowest percentage of data accuracy. Section 8.1.2 discussed many issues with this instrument that resulted in incomplete data due to sensor faults. However, there were occasions when sensor faults were not produced when these issues were present, and this data was classified as inaccurate. The resolution of these issues resulted in 100% accuracy in 2010.

Likewise, much of the inaccurate data from the US Filter instruments were also caused by instrument malfunctions for which a sensor fault was not produced. In addition, problems with multiple U. S. Filter signal converters caused data accuracy to decrease in 2009.

The YSI conductivity sensor had a lower accuracy of 96.9% in 2008 due to sensor malfunctions and the output signal being inadvertently set to the non-temperature compensated reading at one of the stations. These issues were addressed and accuracy improved to greater than 99% in 2009 and 2010.

In 2009, the Hach pH and YSI ORP sensors had an accuracy of 94.7% and 95.3%, respectively. The cause was determined to be faulty probes, which were replaced resulting in improved accuracies of 98.4% and 100% in 2010.

While efforts were made to optimize the operation of all sensors over the evaluation period, an increasing trend in accuracy was not observed for all sensors. The Hach Astro TOC and, to a much lesser degree the Sievers TOC sensors, experienced recurring equipment malfunctions that were never fully resolved, reducing the accuracy of these sensors throughout the evaluation period.

8.3 Availability

Definition: The WQM component is considered to be available for the detection of possible contamination incidents if the four design elements (monitoring stations, data collection, event detection and component response procedures) are functioning properly.

Analysis Methodology: Empirical data collected from the pilot during the evaluation period were analyzed to quantify the availability of the WQM component. All instances during which the WQM component was unavailable for longer than 1 hour were categorized according to the design element that was down. The total number of hours that the WQM component was unavailable during each reporting period was tabulated. The criteria for each design element to be considered available are as follows:

- **Monitoring Stations**: The monitoring station design element was considered available if at least 12 of the 15 stations in the distribution system were producing complete and accurate TOC or chlorine data. The threshold of 75% of data stream availability for component availability was used for all components with multiple data streams. Chlorine and TOC were chosen because these two parameters have been shown to be most effective for contaminant detection.
- **Data Collection**: The data collection design element is considered available if usable data is successfully transmitted to the SCADA system for at least 12 of the 15 monitoring stations.
- **Event Detection**: The event detection system design element is considered available if the CANARY output is 0 (no alert) or 1 (alert) and that output is transmitted to the SCADA server for at least 12 of the 15 monitoring stations. Though there were rare occasions when utility staff removed one or more monitoring stations from CANARY due to a monitoring station maintenance issue, most instances in which CANARY was unavailable impacted all stations.
- **Component response procedures**: The component response procedures design element is considered available if the WQM alert investigations procedures are in place and trained staff are available to execute those procedures. The Cincinnati pilot has personnel trained to investigate WQM alerts according to the component response procedures working 24/7. Thus there was no unavailability attributable to this design element.

The following definitions applied to the analysis of component availability. The definition for potential data hours for the component from Section 8.1.1 also applies to Section 8.3.

- **Available Data Hours for the Component:** The potential number of data hours for the component minus the total hours of unavailability. If multiple design elements were simultaneously unavailable, the hours associated with concurrent design element unavailability were only counted once. For example, if both the data collection and event detection systems were concurrently unavailable for 8 hours, the WQM component was considered unavailable for 8 hours, not 16.

- **Percentage Availability:** The available data hours divided by the potential data hours.

Results: The average availability of the WQM component was 81.7% over the evaluation period. The event detection, data collection and WQM station design elements were not available for 3,795; 110; and 28.2 hours, respectively, including 69.2 hours where multiple design elements were unavailable. This amounted to 3,864 hours of component unavailability out of 21,168 potential hours, or 81.7% component availability.

Figure 8-6 shows the unavailability of the WQM component over the evaluation period. The bars show the number hours each design element was unavailable. The overall component availability for each reporting period is also shown.

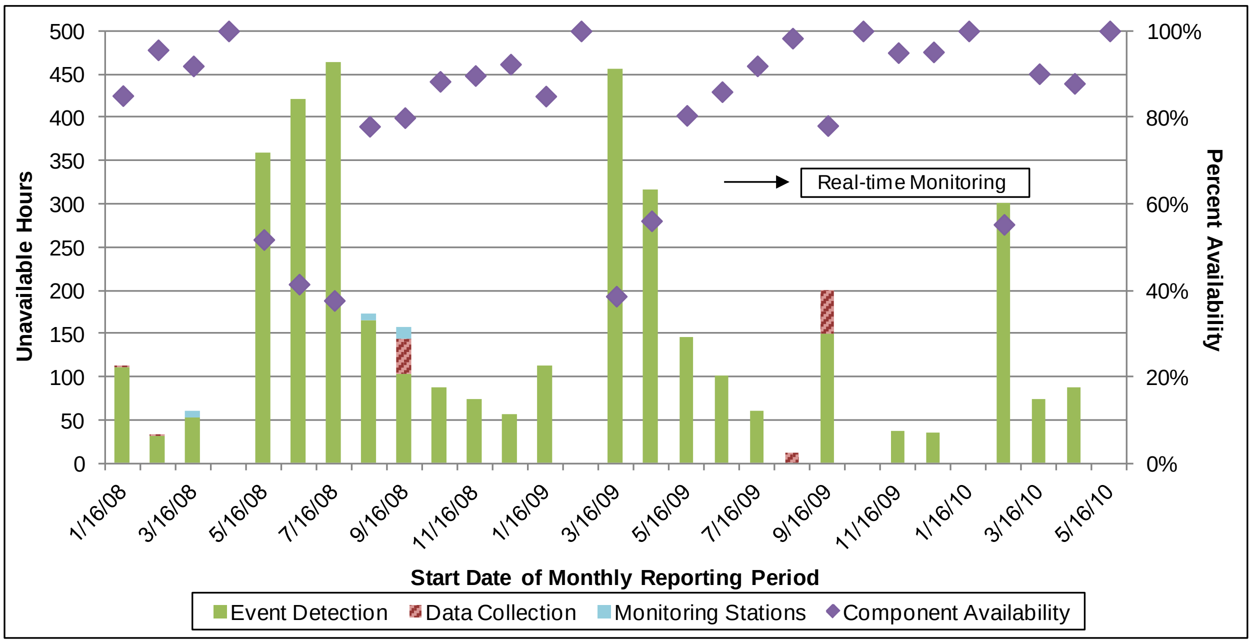


Figure 8-6. WQM Component Unavailability and Unavailable Hours by Design Element

Clearly, periods of unavailability were primarily due to issues with the event detection system. This element was unavailable if either the EDDIES or CANARY applications were not running properly. In addition to minor restarts and maintenance, there were three significant incidents where the event detection design element was unavailable for an extended duration:

- **May 2008 through July 2008 reporting periods:** Updated versions of both CANARY and EDDIES software were loaded onto the workstation to reduce the number of invalid alerts. However, there were bugs in the software updates that resulted in 1,243 hours of unavailability while these issues were addressed.

- **March 2009 through April 2009 reporting periods:** Software updates were installed during the March 2009 reporting period to address minor software bugs. However, this resulted in frequent occurrences of CANARY freezing and failing to produce output until it was restarted. Several software updates and system restarts were needed to resolve this issue resulting in 772 hours of event detection unavailability.

- **February 2010 reporting period:** A bug in a new version of CANARY caused the software to enter loops where dozens of alerts were generated in rapid succession following an initial alert. These nuisance alerts eventually resulted in the decision to shut down the event detection system during the March 2010 reporting period while a solution was developed, resulting in 300 hours of event detection system unavailability.

Interruption in the power supply was also responsible for some periods of event detection system unavailability. Although the CANARY workstation was equipped with a backup battery supply, there were two instances where the backup supply expired following a prolonged loss of line power. Power outages occurred during the August 2008 and September 2009 reporting periods, resulting in 23.6 and 43.2 hours of event detection system unavailability, respectively. The Hurricane Ike windstorm caused the 2008 outage while the cause for the 2009 outage was unknown.

Finally, some periods of event detection system unavailability were due to CANARY restarts. After each restart, CANARY required between 1 and 3 days of data for initialization, depending on each monitoring location's configuration, before analysis of real-time data for anomalies could resume. CANARY initialization accounted for 25% of event detection system unavailability. This design flaw was fixed in the version of CANARY installed on March 9, 2010, which queried existing data in the database to obtain data for initializing the software.

The data collection design element was the second largest contributor to data unavailability. For this design element to be available, both the communication and SCADA systems must be working. Most communications outages were brief and localized to a single monitoring station, and thus did not result in component downtime. There were only two occurrences of prolonged data collection unavailability:

- **September 2008:** The SCADA system crashed during this reporting period, resulting in the component being unavailable for 40.9 hours. This outage was unrelated to the Hurricane Ike windstorm that occurred during this reporting period.
- **September 2009:** The communications provider experienced an internal issue during this reporting period that required multiple days to resolve. This caused the component to be unavailable for 51.1 hours.

The WQM station design element caused very little component data unavailability as most issues were localized to a single monitoring station. There were only three reporting periods during which the monitoring station design element was not available over the course of the evaluation period:

- **March 2008:** This reporting period had 8.3 hours of unavailability when four stations were concurrently unavailable: there were prolonged TOC and chlorine sensor issues at one monitoring station and three other stations were in calibration mode, either due to ongoing maintenance work or being inadvertently left in calibration mode after service was complete.
- **August 2008:** This reporting period had instances where five to six stations experienced concurrent power outages caused by the Hurricane Ike windstorm, leading to 7.9 hours of unavailability. Note that all of the monitoring station design element unavailability during this reporting period coincided with event detection system downtime.
- **September 2008:** This reporting period had instances where four to five monitoring stations experienced concurrent power outages caused by the Hurricane Ike windstorm, leading to 12.0 hours of unavailability. All of these hours coincided with unavailability of the event detection system.

Table 8-4 shows the amount of concurrent unavailability for one to six monitoring stations – both in terms of the percentage of the evaluation period and the actual number of hours the unavailability occurred. Overall, at least one monitoring station was unavailable for 26.6% of the evaluation period.

Table 8-4. Concurrent Unavailability of "X" Number of WQM Stations

Concurrent Unavailability	1 Monitoring Station	2 Monitoring Stations	3 Monitoring Stations	4 Monitoring Stations	5 Monitoring Stations	6 Monitoring Stations
Percent of time / hours for which "X" monitoring station(s) were concurrently unavailable	22.3% (4710 hours)	3.7% (777 hours)	0.5% (115 hours)	0.1% (12.3 hours)	0.1% (15.3 hours)	0.0% (0.6 hours)

Single monitoring station unavailability was fairly evenly distributed over the evaluation period, with only 54.4% of the hours where a single monitoring station was unavailable occurring within the first seven out of 29 total reporting periods. Stations placed in calibration mode for extended periods while technicians addressed issues with the Sievers TOC and U. S. Filter Chlorine sensors caused most of the occurrences of individual monitoring station unavailability. Maintenance errors that occurred when a technician inadvertently left a monitoring station in calibration mode after service were also a significant cause of single monitoring station unavailability.

Most instances where two or three stations were simultaneously unavailable occurred early in the evaluation period, with 98.2% of the hours where three stations were unavailable occurring within the first four reporting periods and 77.6% of the hours where two stations were unavailable occurring within the first seven reporting periods. Incomplete and inaccurate data was common during this period due to hardware, software, or maintenance issues, and thus it was not uncommon to have more than one station experiencing issues at the same time.

The incidents when four, five, or six monitoring stations were unavailable were analyzed in the previous discussion regarding unavailability of the monitoring station design element (i.e., if more than three monitoring stations are concurrently down, the WQM design element is considered unavailable). There were no instances where more than six monitoring stations were concurrently unavailable.

8.4 Summary

The availability of the WQM component to detect contamination incidents was evaluated by analyzing the performance of the four design elements: monitoring stations, data collection, event detection and component response procedures.

The availability of the monitoring station design element was characterized by the completeness and accuracy of the data generated by the monitoring stations. Data completeness measured the amount of usable data, (i.e. not missing or flagged as unusable), and accuracy measured the amount of data that was within a predetermined tolerance range. The monitoring station design element was considered available when at least 12 of the 15 monitoring stations in the distribution system were producing complete and accurate TOC or chlorine data, because these two parameters have been shown to be most effective for contaminant detection.

Out of a total of 1,768,763 data hours, there were 121,853 hours of incomplete data (6.9%) and 61,235 hours of complete but inaccurate data (3.5%). Incomplete data was mostly attributable to sensors being taken offline for extended periods due to recurring equipment malfunctions, sensor faults and data collection outages. Sensor malfunctions, mostly due to issues with TOC sensors, was the leading cause of inaccurate data. The vast majority of instances where data were not complete or accurate affected only a single monitoring station, and rarely more than 3 of the 15 stations. As such, the WQM component had 28.2 hours of unavailability attributable to the monitoring station design element.

The availability of the data collection design element depended on the of data transmission from the monitoring stations to the SCADA system. Similar to the criteria for the monitoring station design element, data collection was considered available when data was successfully transmitted by at least 12 of the 15 monitoring stations. System-wide communications outages and SCADA system downtime led to 110 hours of WQM component unavailability attributable to the data collection design element.

The event detection design element was considered available when both the EDDIES and CANARY applications were running properly. Issues with both applications and power outages to the computer that ran these applications led to 3,795 hours of WQM component unavailability attributable to the event detection system design element.

The component response procedures design element was considered available when the WQM alert investigations procedures were in place and trained staff were available to execute those procedures. The Cincinnati pilot had personnel trained to investigate WQM alerts according to the component response procedures working 24/7 since the beginning of the evaluation period. Thus there was no WQM component unavailability attributable to this design element.

After accounting for the unavailability attributed to each design element and 69.2 hours when multiple design elements were not available, it was determined that the component was available for 81.7% of the evaluation period.

In addition to overall WQM component availability, the performance of individual sensors was characterized, as sensor-related issues were the most common cause of incomplete and inaccurate data. The amount of complete and accurate data from individual sensors ranged from 79.0% to 99.7% during the first year of the evaluation period, but the majority of sensor-related issues were resolved by the end of the second year of the evaluation period in 2009, resulting in nine out of the ten sensor types to have at least 95% complete and accurate data in 2010. The Hach Astro TOC was the only exception at 58.9% in 2010; several sensors were decommissioned due to ongoing sensor issues.

It should be noted that many of the issues associated with data unavailability were a result of using a variety of sensors and equipment in an effort to evaluate different monitoring options. Utilities deploying WQM should carefully evaluate sensors and other equipment before putting the units into service. This will result in reduced downtime and increase data accuracy.

Section 9.0: Design Objective: Sustainability

Sustainability is a key objective in the design of a CWS and each of its components, which for the purpose of this evaluation is defined in terms of the cost-benefit trade-off. Costs are estimated over the 20-year lifecycle of the CWS and include the capital cost to implement the CWS and the cost to operate and maintain the CWS. The benefits derived from the CWS are defined in terms of primary and dual-use benefits. 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 that provide value to routine utility operations are an important driver for sustainability. Ultimately, sustainability can be demonstrated through utility and partner compliance with the protocols and procedures necessary to operate and maintain the CWS. The three metrics that will be evaluated to assess how well the Cincinnati CWS met the design objective of sustainability are: costs, benefits and compliance. The following subsections define each metric, describe how it was evaluated and present the results.

9.1 Costs

Definition: Costs are evaluated over the 20-year lifecycle of the Cincinnati CWS and comprise costs incurred to design, deploy, operate and maintain the WQM component since its inception.

Analysis Methodology: Parameters used to quantify the implementation cost of the WQM component were extracted from the *Water Security Initiative: Cincinnati Pilot Post-Implementation System Status* (USEPA, 2008a). The cost of modifications to the WQM component made after the completion of implementation activities were tracked as they were incurred. O&M costs were tracked on a monthly basis over the duration of the evaluation period. Renewal and replacement costs, along with the salvage value at the end of the lifecycle were estimated using vendor supplied data, field experience, and expert judgment. Note that all costs reported in this section are rounded to the nearest dollar. Section 3.6 provides additional details regarding the methodology used to estimate each of these cost elements.

Results: The methodology described in Section 3.6 was applied to determine the value of the major cost elements used to calculate the total cost of the WQM component, which are presented in **Table 9-1**. It is important to note that the Cincinnati CWS was a research effort, and as such incurred higher costs than would be expected for a typical large utility installation. A similar WQM component implementation at another utility should be less expensive as it could benefit from lessons learned and would not incur research-related costs.

Table 9-1. Cost Elements used in the Calculation of Total Cost of the WQM Component

Parameter	Value
Implementation Costs	$4,229,333
Annual O&M Costs	$178,478
Renewal and Replacement Costs	$1,555,555
Salvage Value	($96,686)
Dual-use benefits	($4,410)

Table 9-2 below presents the implementation cost for each WQM design element, with labor costs presented separately from the cost of equipment, supplies and purchased services.

Table 9-2. Implementation Costs for the WQM Component

Design Element	Labor	Equipment, Supplies, Purchased Services	Component Modifications	Total Implementation Costs
Project Management[1]	$102,749	-	-	$102,749
Monitoring Stations	$1,719,703	$1,628,890	$10,000	$3,358,594
Data Collection	$233,578	$133,134	-	$366,712
Event Detection System	$271,245	$50,873	$2,752	$324,869
Response Procedures	$76,409	-	-	$76,409
TOTAL:	**$2,403,684**	**$1,812,897**	**$12,752**	**$4,229,333**

[1] Project management costs incurred during implementation were distributed evenly among the CWS components.

Project management includes overhead activities necessary to design and implement the component. The monitoring station design element includes the cost of the water quality sensors, the custom panels, and the modeling necessary to select a location for each monitoring station. The data collection design element includes the cost of a communications system to transmit data to the utility control center and the computer hardware and software to display and archive the data collected from the monitoring stations. Costs associated with the event detection system design element include installation and configuration of the software to analyze the data generated, as well as the computer hardware required to run the software. The final design element, response procedures, includes the cost of developing procedures that guide the routine operation of the component and alert investigations, along with training on those procedures.

Overall, the monitoring stations design element had the highest implementation cost (79%). The total implementation cost for data collection and the event detection system were substantially lower at 9% and 8%, respectively. Implementation costs for development of the procedures for routine operation and training on those procedures, as well as for project management were significantly lower at 2% each. The monitoring stations, with their water quality sensors, associated supplies, and mounting panels, accounted for 90% of the equipment costs. Costs for the other design elements were mostly labor costs associated with system design and setup; computers and servers to house these systems were the only equipment needed for those elements.

The component modification costs represent the labor, equipment, supplies and purchased services associated with enhancements to the WQM component after completion of major implementation activities at the end of December 2007. The single most costly modification was the relocation of one of the monitoring stations to a new location in order to obtain more representative data from the targeted area of the distribution system. The costs associated with event detection system modification were all labor costs, as the CANARY developers and EPA staff worked to make software updates requested by the utility, fix software bugs, and refine CANARY configurations to reduce the number of invalid alerts.

The annual O&M labor hours and costs for the WQM component, broken out by design element, are shown in **Table 9-3**.

Table 9-3. Annual O&M Costs for the WQM Component

Design Element[1]	Total Labor (hours/year)	Total Labor Cost ($/year)	Supplies and Purchased Services ($/year)	Total O&M Cost ($/year)
WQM Stations	615	$27,898	$105,480	$133,378
Data Collection[2]	96	$3,743	$15,840	$19,583
Event Detection System	170	$10,003	$0	$10,003
Procedures	317	$15,513	$0	$15,513
TOTAL:	**1198**	**$57,158**	**$121,320**	**$178,478**

[1] Overarching project management costs were only incurred during implementation of the WQM component and are not applicable for annual O&M costs.
[2] Reoccurring communication cost is split between WQM and ESM.

The most labor-intensive aspect of the component involves routine maintenance, calibration, and repair of the sensors on the monitoring stations. O&M for the data collection and event detection systems requires a low-level of monitoring and troubleshooting of the IT infrastructure, as well as periodic software updates. In addition, the database used to store the component data requires updates when sensors are changed or moved to another location, and the event detection system occasionally needs to be reconfigured to accommodate shifts in the water quality baseline.

Most of the O&M labor hours reported under procedures were spent on the routine investigation of alerts. On average, investigation of an alert took 5.1 minutes. As the number of CANARY alerts is reduced, the number of hours required for procedures should decrease.

The renewal and replacement costs and salvage value were based on costs associated with major pieces of equipment. The useful life of these items was estimated as either five or seven years based on field experience, manufacturer-provided data, and input from subject matter experts. For the items with a useful life of seven years, it was assumed that the equipment would need to be replaced twice during the 20-year lifecycle of the CWS, and items with a useful life of five years were assumed to be replaced three times. These items and their total costs are presented in **Table 9-4**.

Table 9-4. Equipment Costs for the WQM Component

Equipment Item	Useful Life (years)	Unit Capital Costs	Quantity (# of Units)	Total Cost
GE-Sievers 900, TOC Instrument	7	$24,950	14	$349,300
Hach Astro 1950, TOC Instrument	7	$22,450	3	$67,350
S::can Carbo::lyser, Spectral Instrument (TOC)	7	$8,200	2	$16,400
YSI 6920 DW Sonde, Chlorine, pH, Conductivity, ORP	7	$10,700	5	$53,500
Hach WDMPsc, Chlorine, pH, Conductivity, ORP	7	$14,950	9	$134,550
Hach WDMP, Chlorine, pH, Conductivity	7	$12,400	3	$37,200
Siemens (US Filter) Depolox 3+, Chlorine, pH	7	$3,700	5	$18,500
SCADA License	5	$13,200	3	$39,600
SCADA System I Primary Server	5	$5,126	1	$5,126
SCADA System II: Secondary and Thin Client Server	5	$5,097	2	$10,193
SCADA Tape Drive	5	$2,224	1	$2,224
SCADA UPS	5	$4,611	1	$4,611
EDDIES Computer	5	$5,565	1	$5,565
			TOTAL:	**$744,118**

While many dual-use benefits were realized over the course of the evaluation period, as discussed in Section 9.2, only one could be monetized and used to offset the cost of the WQM component; a savings of $4,410 per year in the cost of chlorine feed solution. This benefit was realized through the additional water quality data provided by the WQM component which allowed utility operators to more accurately adjust the amount of chlorine added at the treatment plants while maintaining the target disinfectant residual in the distribution system.

To calculate the total cost of the WQM component, all costs and monetized benefits were adjusted to 2007 dollars using the change in the Consumer Price Index (CPI) between 2007 and the year that the cost or benefit was realized. Subsequently, the implementation costs, renewal and replacement costs, and annual O&M costs were combined, and the monetized dual-use benefits and salvage value were subtracted to determine the total cost:

WQM Total Cost: **$8,202,994**

In this calculation, the implementation costs and salvage value were treated as one-time balance adjustments, the O&M costs and dual-use benefits recurred annually and the renewal and replacement costs for major equipment items were incurred at regular intervals based on the useful life of each item.

9.2 Benefits

Definition: The benefits of CWS deployment can be considered in two broad categories: primary and dual-use. Primary benefits relate to the application of the CWS to detect contamination incidents and can be quantified in terms of a reduction in consequences. Primary benefits are evaluated at the system-level and are thus discussed in the report titled *Water Security Initiative: Evaluation of the Cincinnati Contamination Warning System Pilot* (USEPA, 2013). Dual-use benefits are derived through application of the CWS to any purpose other than detection of intentional and unintentional drinking water contamination incidents. Dual-use benefits realized by the WQM component are presented in this section.

Analysis Methodology: Information collected from forums such as data review meetings, lessons learned workshops and interviews were used to identify dual-use applications of the WQM component of the Cincinnati CWS.

Results: Operation of the WQM component of the CWS has resulted in benefits beyond the detection of intentional and unintentional contamination incidents. These key dual-use benefits and examples identified by the utility include:

- **Backup monitoring capabilities:**
    - WQM data can be used to support and enhance existing distribution system monitoring. Additionally, monitoring station data can be used to confirm water quality trends observed in other monitoring programs.
- **Information to optimize distribution system water quality and operations:**
    - By providing continuous readings, WQM provides a better understanding of water quality variability in the distribution system. This variability can be related to activities such as changes in source water quality and treatment chemical dosing rates. Continuous WQM data enables the utility to quickly identify and respond to water quality changes, resulting in optimized operations.

  - GCWW has recently agreed to participate in the Partnership for Safe Water Distribution program. The development of the program included input from representatives of utilities, state and federal regulators, consultants and subject matter experts. The program is divided into various phases including goal setting, data collection and self-assessment. Areas covered by the program include maintaining chlorine residual and pressure and minimizing main breaks. In support of these areas, goals including optimizing water quality are established by the utility and then evaluated during the self-assessment phase. The WQM data will be used in this evaluation. Additionally, the role of the WQM component as part of an overall water security system would likely be identified as a goal.

- **Information to augment compliance monitoring:**
  - GCWW developed a model for trihalomethane (THM) formation in the distribution system. The chlorine residual and pH data from the monitoring stations can be entered into this model to predict THM concentrations. Results from the THM model can inform treatment and/or operational changes to maintain compliance with disinfection and disinfection byproduct regulations.
  - Continuous data from the monitoring stations can be used to ensure that more consistent and stable water quality (e.g., pH) is maintained for optimal corrosion control.

- **Improved knowledge of distribution system hydraulics:**
  - Data from the monitoring stations can be used to follow a change in water quality leaving the treatment plant and traveling through the distribution system. This data allows for estimation of hydraulic travel times which can be used to verify the accuracy of the distribution system model and evaluate the impact of operational actions on water quality and hydraulics. This provides the utility with greater confidence in the model, which is important for all model applications.
  - GCWW uses both ground water and surface water, and the interface zone between these two sources in the distribution system can change depending on operations and water demand. GCWW can use pH and conductivity data from the WQM stations to monitor the water type in the interface zone in real-time. This information also has potential regulatory implications. Specifically, a plan was submitted to and approved by the Ohio Environmental Protection Agency to use this data to meet the Groundwater Rule requirement to define the location of ground water in the distribution system.

- **Detection of unusual water quality not resulting from contamination:**
  - Turbidity readings can be used to identify or confirm distribution system activities such as flow reversals, hydrant operation and main breaks.
  - A slow decrease in chlorine residual in an isolated part of the distribution system may be an indication of possible microbiological activity (i.e., regrowth).
  - While not a benefit realized at the Cincinnati pilot, utilities that use chloramines for secondary disinfection can use data from the WQM stations to identify onset of nitrification.

- **Optimize the application of treatment chemicals:**
  - By establishing the relationship between the chlorine residual leaving the plant and the residual at various points in the distribution system, the applied chlorine dose can be optimized resulting in a more efficient use of chlorine. For utilities that boost the

chlorine in the distribution system, the same approach can be used to optimize booster disinfectant application. This can minimize the total amount of chlorine applied, resulting in chemical savings.

  - By monitoring the pH in the distribution system, the application of chemicals to adjust pH of the water leaving the plant can be optimized.

- **Optimize pumping and storage:**
  - Chlorine sensors showing a low reading can be used to identify a need for an operational change related to tank turnover and pumping. Early identification of the potential for unacceptably low chlorine residual at storage facilities allows greater flexibility in balancing the objectives of maintaining acceptable water quality and minimizing energy costs.
  - Chlorine readings from locations at or near a storage tank can be used to provide an indication of the effectiveness of tank mixing.

The listed dual-use benefits are illustrated in the case studies presented below. These case studies were developed from experiences occurring at the Cincinnati pilot during the evaluation period.

Case Study 1a: Backup monitoring capabilities.

On September 14-15, 2008 the utility experienced a windstorm caused by Hurricane Ike, resulting in a combination of power outages and flooding in a treatment plant building. This disabled the primary sensors used to monitor the plant effluent water quality. The utility boosted chlorine levels at the treatment plant to ensure safe drinking water in the distribution system, then used sensors installed as part of the CWS (relying on UPS backup power) to monitor chlorine levels water quality in the system.

Case Study 1b: Determining compliance with the Groundwater Rule.

GCWW is evaluating the potential of complying with the Groundwater Rule by achieving four-log virus inactivation at its ground water plant. This requires online chlorine residual data, which is used to determine compliance. In order to ensure that the required data is available, the utility's standard practice is to install two sensors with one serving as the primary and the other as a backup. Rather than install another sensor at the ground water plant, the utility is utilizing the WQM chlorine sensors installed as part of the CWS to provide backup chlorine readings.

Case Study 2: Minimizing main breaks during cold weather.

Data collected by the WQM stations in the distribution system was used to monitor operational changes in an attempt to minimize the number of water main breaks during the winter months. GCWW's largest treatment plant uses a surface water source. The second plant uses groundwater as its source, which has a more consistent temperature that is significantly warmer than the surface water in the winter. The groundwater also has higher pH and a different conductivity profile compared with the surface water. In an effort to minimize main breaks caused by the colder surface water, the utility has been conducting a study to determine if increasing the area of the distribution system served by the ground water plant during the winter months would decrease the number of main breaks. The warmer water is moved farther into the system by changing system valving and increasing pumping from the groundwater plant. Several WQM stations are located at critical points in the interface zone between the two water sources. The utility uses pH, conductivity, and temperature data from these stations to monitor the distribution of groundwater in the system.

Case Study 3a: Assisting with investigations required by the Groundwater Rule.

If a positive total coliform sample result is found in a groundwater distribution system, the Groundwater Rule requires Triggered Source Water monitoring of all wells serving the area at the time that the positive sample was collected. A request for waiver of this sampling requirement may be approved if it can be shown that the positive sample was due to an issue in the distribution system and not the source. As part of an investigation, GCWW can use data from the WQM stations to check water quality in the portion of the service area supplied by the groundwater plant and evaluate the data to show that the distribution system was the cause of the positive sample.

Case Study 3b: Assisting with investigations of positive sample results collected for the Total Coliform Rule.

The Total Coliform Rule requires implementation of the utility sampling plan in response to a positive total coliform result. While currently not required, the utility performs an assessment of operational and water quality information in the area of the positive result. This assessment includes evaluating recent water quality data for any abnormalities. As such, GCWW has used data collected from the WQM stations for performing this assessment. A recent positive total coliform result was obtained at a location downstream from one of the monitoring stations. The data from the station was evaluated and found to show no unusual water quality.

The proposed revisions to the Total Coliform Rule have requirements for performing Triggered Investigations. While the specifics of what constitutes a Triggered Investigation are still being finalized, they will most likely include an assessment of available water quality data from the area.

Case Study 4: Providing an increased knowledge of distribution system hydraulics, which can be applied to the distribution system model.

Data collected from the WQM stations was used to verify and improve the accuracy of the existing GCWW distribution system model. When water leaving the treatment plant changed, the utility was able to track the slug through the distribution system, just as the injection of a chemical tracer is tracked during a tracer study. In one specific instance, there was a temporary failure of a chemical feed system at one of the treatment plants that produced a slightly abnormal slug of water entering the distribution system. The SCADA system recorded the timing of this event, so the utility knew precisely when this slug of water entered the system. The time that this slug reached each WQM location was apparent from the sudden change in water quality at the location, which provided an estimated travel time from the plant to that location in the system. These data were then compared with the predictions made by the GCWW distribution system model. At many locations, the observed travel times agreed reasonably well with the model predications. However, the slug flowed into an area that was not predicted by the hydraulic model. After an investigation, it was determined that a model parameter was inaccurate and required an update. GCWW has also decided to perform similar checks in the future.

Additionally, GCWW was in the process of developing an all-pipes distribution system model. An evaluation of the accuracy of this model using all data, including that from the WQM stations, was conducted. This evaluation enabled verification and appropriate adjustment to the all-pipes distribution system model resulting in a more accurate model. A more accurate model will produce results that better reflect the distribution system performance for all modeling applications.

Case Study 5: Detecting benign water quality anomalies.

Data collected from WQM stations can be used to respond to changes in water quality resulting from verified water quality anomalies. GCWW has discovered that most WQM alerts, unrelated to sensor malfunction, are associated with operational changes. For example, maintenance on the granular activated carbon beds has caused alerts due to changes in TOC concentrations in the distribution system. While these changes in water quality are neither problematic nor unanticipated, it does demonstrate the ability of the system to detect changes in water quality. Early knowledge of unanticipated changes in water quality can provide time for intervention through operational changes at the treatment plant or in the distribution system.

9.3 Compliance

Definition: The degree to which utility staff fulfill their responsibilities to operate and maintain the WQM component of the CWS. The component response procedures for the Cincinnati CWS required utility staff to investigate all alerts and document those investigations in checklists.

Analysis Methodology: The percentage of WQM alerts that were investigated by utility staff is used as a proxy for compliance with the component response procedures for the component. All WQM alerts and investigations were entered into a database. The database was queried to determine the number and percentage of alerts that were investigated.

Results: Figure 9-1 shows the percentage of WQM alerts that were investigated during each reporting period over the course of the evaluation. The number of alerts received each month is also shown to give a sense of how many investigations were performed.

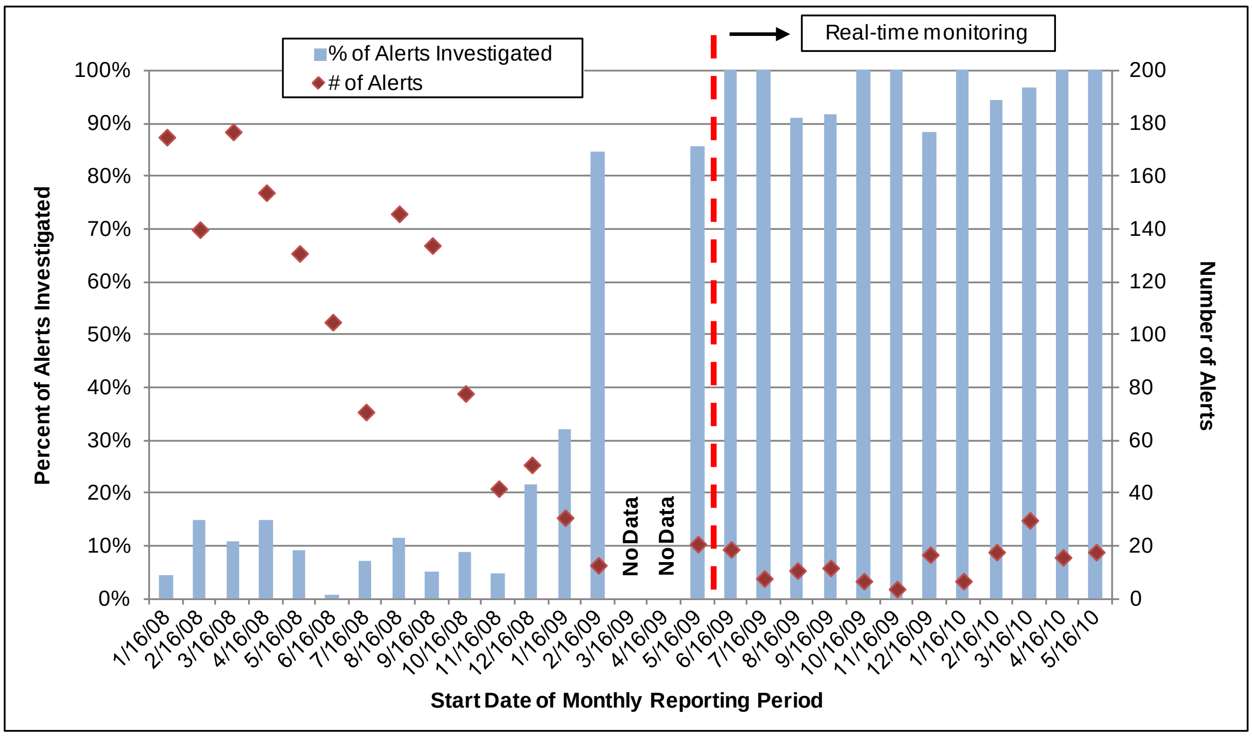


Figure 9-1. Percentage of WQM Alerts Investigated and Number of Alerts Received

From the beginning of the evaluation period until the December 2008 reporting period, the WQM component was undergoing significant modifications to address performance issues, most notably sensor malfunctions and event detection software bugs. During this period, utility staff were not expected to investigate all alerts. Instead, investigations were conducted on a representative sample of the alerts generated by the 15 stations in the distribution system to provide utility staff with an opportunity to become familiar with the investigation procedures and to learn the typical water quality patterns associated with each monitoring location. The resulting compliance rate during this period was approximately 10%.

During the January 2009 reporting period, five monitoring stations that had achieved acceptable performance were transitioned to real-time monitoring, and utility staff were instructed to investigate alerts from these stations as soon as they were received. Beginning in January 2009, the compliance rate was based only on the stations monitored in real-time. The compliance rate was only 32% during the January 2009 reporting period because the monitoring started in the middle of the reporting period

Five more monitoring stations transitioned to real-time monitoring during the March 2009 reporting period, and the final five stations transitioned to real-time monitoring during the May 2009 reporting period. As each group of stations transitioned to real-time monitoring, the basis for calculating the compliance rate for alert investigations was increased accordingly. Data was not available for the March and April 2009 reporting periods, but by May 2009 the investigation rate increased to 85%. Minor issues with the sensors, event detection system, and communications system during the subsequent periods prevented compliance from reaching 100% because the utility staff learned to recognize alerts that were due to such issues and thus did not investigate them.

By the June 2009 reporting period, most problems with the sensors and CANARY event detection system had been resolved and all 15 stations were monitored in real-time. After May 2009, compliance averaged 97%, reaching 100% in 7 out of 12 reporting periods, indicating a high level of utility compliance with the WQM component response procedures. During the real-time monitoring period, which spanned 12 months, 220 alerts were investigated and a total of 25.9 labor hours were spent on investigations, resulting in an average of 0.12 labor hours (7.2 minutes) per investigation.

9.4 Summary

The sustainability of the WQM component of a CWS is dependent upon the relative costs and benefits of the component. The total cost to deploy the WQM component of the Cincinnati CWS was $4,109,686, and the annual cost to operate and maintain the component was $862,674. The monitoring stations were responsible for the majority of these costs. Note that the fact that this was a pilot project significantly inflated costs, as described in Section 10.2.

While this component is expensive, it greatly enhances the ability of the integrated CWS to detect contamination incidents and reduce consequences from such incidents (USEPA, 2013). WQM also provides numerous dual-use benefits which can enhance day-to-day water quality management at a utility. Numerous dual-use benefits were observed during the evaluation period of the Cincinnati pilot, including: backup monitoring capabilities, information to optimize distribution system water quality and operations, information to augment compliance monitoring, improved knowledge of distribution system hydraulics, detection of water quality anomalies not related to contamination, optimization of treatment chemical usage and optimization of pumping and storage.

The sustainability of the WQM component can be verified through continued O&M of the component. This includes compliance with component response procedures that guide the routine investigation of alerts. By the end of the pilot evaluation period, the rate of alert investigations reached an average of 97%. Furthermore, the component is still in operation at the time of publication of this report. This indicates that the Cincinnati CWS is sustainable and will likely continue to operate into the foreseeable future. In this case, the benefits derived from the component would appear to justify the costs.

Section 10.0: Summary and Conclusions

The evaluation of the WQM component of the Cincinnati CWS involved analysis of empirical data, observations from drills and exercises, results from the simulation study, qualitative observations gleaned from participants during forums and a cost and benefit analysis from the benefit-cost analysis. A set of performance metrics was defined for each of six design objectives, and results were presented showing how well the WQM component 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 WQM component produced a comprehensive assessment of a robust WQM system deployed as part of the first CWS pilot deployed under WSI. Notably, it was shown that a variety of water quality incidents can be detected by monitoring standard water quality parameters in the distribution system. During real-time operation, valid alerts were produced for a variety of incidents including main breaks, treatment process upsets, and unusual system operations. Furthermore, bench-scale testing showed that standard water quality parameters change in the presence of a variety of contaminants at concentrations well below those that would cause harm to utility infrastructure or the public. Results from the simulation study confirmed the broad detection capabilities of the WQM component, with scenarios involving 16 of the 17 test contaminants being detected. The simulation study results also demonstrated the value of monitoring multiple parameters, as three WQM stations that were missing one or two parameters had lower detection percentages compared with the stations equipped with the full suite of sensors. Finally, the variability of baseline water quality was observed to impact detection capabilities. Monitoring stations with more variable baselines generally had lower detection percentages compared to those with stable water quality. However, detection percentages were still above 64% for all WQM stations with a full set of parameters, demonstrating that monitoring can be performed effectively even at locations with highly variable water quality.

The WQM network deployed in Cincinnati also achieved a high degree of spatial coverage: 72% of the area and 84% of the population. While spatial coverage was high, the network was limited with respect to scenario coverage under the conditions and assumptions of the simulation study. Of the 2,015 simulation study scenarios, a practically detectable contaminant concentration with the potential to generate an alert reached a WQM location in only 737 (36.6%) scenarios. However, most of these potentially detectable scenarios were detected 643 (87.3%). Scenarios that were not potentially detectable because no WQM stations were impacted in the scenario tended to be localized with limited contaminant spread.

Not all alerts generated during real-time operation were valid; the majority of the alerts (95%) were not due to unusual water quality. The most common causes of invalid alerts were sensor issues (40%) and monitoring location water quality variability (40%). The number of invalid alerts decreased significantly over the evaluation period. This was largely due to updated CANARY configuration settings and improved water quality data as sensor hardware issues were resolved. By the end of the evaluation period, the utility found the frequency of alerts received was sustainable as the average alert investigation was under 15 minutes

Overall, the WQM component had 81.7% availability. The CANARY event detection system was the biggest contributor to unavailability (96%), largely caused by maintenance and troubleshooting. Taking equipment offline for repair caused the majority of data incompleteness during the evaluation period, accounting for 62% of the incomplete data hours.

10.2 Limitations of the Analysis

The fact that the CWS deployed in Cincinnati was the first of its type had several consequences that impacted the evaluation. A few of the more important considerations included:

- This was a pilot project and thus a variety of solutions were implemented. Several sensor types were installed, some of which were unreliable and required an unsustainable amount of maintenance. This also required service contracts with multiple vendors. Significant trial and error was necessary to produce a viable, functioning system. A utility implementing their own WQM system would likely not do this.
- Improved products are now available. In many cases, the Cincinnati pilot was the first time hardware and software products were installed in real-time. Thus, many issues were encountered and resolved, and these improvements are included in the currently available products. In addition, the increased awareness of this application has motivated vendors of hardware and software products to make their solutions more effective and reasonable to implement.
- The planning and implementation approach, in which EPA took the lead role, was inefficient. If all relevant utility experts had been involved in the planning, several pitfalls could have been avoided and existing systems could likely have been leveraged more fully.

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 communication system was down. Also, there were some instances in which alert investigation checklists were incomplete or missing.

As explained in Section 6.2.2, no 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 of reality. Thus the results of the simulation study should only be considered in the context of the design and assumptions intrinsic to the study.

It is also important to consider that the WQM component of the Cincinnati CWS was being updated and modified during most of the evaluation period. As discussed in Section 2.5, major system changes were made through February 2010, which is 86% of the evaluation period. The evolving nature of the system during the evaluation period skewed the following metrics.

- Operational reliability metrics were inconsistent because elements of the system were taken down for long periods of time for maintenance and replacement, and data streams were added and removed from service. It is expected that operational reliability will be higher and more consistent in the post-evaluation period after modifications were completed and the system was operating consistently.
- Metrics relating to alert occurrence were inconsistent due to modifications made to CANARY over the course of the evaluation period. As discussed in Section 6.1, the data from the evaluation period was reprocessed with the final CANARY settings to estimate alert occurrence under the optimal CANARY configuration. However this analysis was still impacted by periods of inaccurate and missing data.
- Real-time monitoring accounted for only 40% of the evaluation period. This was the only time during which alerts were consistently investigated and documented using alert checklists. No investigation checklists were completed in real-time during the first year of the evaluation period.

In addition to causing low alert investigation numbers, this impacted alert classification. Researchers had to retrospectively analyze water quality data at the time of the alert to identify the possible cause of the alert. These retrospective alert investigations were performed without the benefit of ancillary data from system operations or maintenance that would have been available during an investigation conducted in real-time.

While the system changes did illustrate the impact of improvements on system performance for some metrics, they did not provide an extended period of stable operations that could have provided the evaluators with a basis for estimating long-term performance.

10.3 Potential Applications of the WQM Component

The WQM component of the Cincinnati CWS was tailored to the capabilities and structure of GCWW; therefore, the evaluation described in this report is specific to Cincinnati and interpretation should be treated as such. However, the Cincinnati CWS revealed numerous applications and lessons that can be applicable to other CWSs.

During the pilot, a variety of equipment was evaluated. While some of the water quality sensors performed below acceptable levels, a set of sensors were identified that could effectively monitor each of the parameters considered during the pilot. Furthermore, GCWW has identified a suite of sensors and technologies that they plan to incorporate into a standard monitoring station design. This standard design includes all of the parameters piloted with the exception of TOC. Experience during the pilot showed that the online TOC instrumentation tested was expensive and difficult to maintain. As a result, TOC units will only be deployed at more critical locations. GCWW decided to replace existing TOC instrumentation at some sites with spectral instruments which they find easier and less expensive to maintain. In addition, GCWW has replaced some of the existing chlorine monitors with reagent-less models to further reduce costs and upkeep time.

With the deployment of 17 new WQM stations, each with six or more sensors, a greater demand has been placed on instrument technicians to keep the system running and producing quality data. As noted above, some sensor types exerted a greater demand on staff than others. But after the down-selection process in which poor performing equipment was decommissioned and after technicians received adequate training, GCWW was able to keep the sensors performing at acceptable levels with a sustainable level of effort.

At the start of the pilot, there was concern that the WQM component would generate too many alerts and that eventually these alerts would be largely ignored. In the early stages of the pilot, this was indeed the case. However, most of these invalid alerts were caused by instrument malfunction which produced noisy and inaccurate data, and bugs in the developmental CANARY event detection system software. After these problems were remedied, alert rates fell to acceptable levels and GCWW reports getting eight to ten alerts in a typical month. Furthermore, through training and practice, GCWW was able to reduce the average time for completing the investigation of an alert to less than 15 minutes. In addition, staff has reported that the investigations are interesting and useful for maintaining confidence in water quality. At the time of publication, GCWW staff continues to investigate and document WQM alerts in real-time. This demonstrates that real-time water quality data, monitored by an automated event detection system, can produce an acceptable rate of alerts and provide valuable information for everyday operation.

While the WQM component is expensive to operate and maintain at over $178,000 per year, GCWW has realized many day-to-day benefits of the component. Real-time knowledge of distribution system water quality has provided a deeper understanding of the impact of system operations on distribution system water quality, which has lead to increased confidence in the quality of the water provided to the customer.

In addition, water quality anomalies not caused by contamination have been detected, including treatment process disruptions and main breaks.

Most importantly, the component has been incorporated into GCWW's broader water quality management strategy. It appears that the component will be maintained and potentially expanded in the future.

The overarching goal of the WQM component is to improve real-time awareness of water quality throughout the distribution system in order to optimize system operation and allow for detection of unusual water quality. The overall success of WQM depends not only on reliable data, but also requires commitment by utility staff in maintaining the system and using the data generated.

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 WQM component at a much smaller cost than was incurred for the Cincinnati CWS. For example, if a utility has existing chlorine sensors used for compliance monitoring, a valuable step towards integrating those sensors into a WQM component is to develop procedures for regularly reviewing the data produced by the sensors and investigating any unusual water quality conditions.

Section 11.0: References

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Section 12.0: Abbreviations

CWS	Contamination Warning System
DMZ	Demilitarized Zone
EDDIES	Event Detection Deployment, Integration, and Evaluation System
EPA	Environmental Protection Agency
ESM	Enhanced Security Monitoring
GCWW	Greater Cincinnati Water Works
HMI	Human Machine Interface
IT	Information Technology
O&M	Operations and Maintenance
ORP	Oxidation Reduction Potential
PLC	Programmable Logic Controller
SCADA	Supervisory Control and Data Acquisition
TEVA-SPOT	Threat Ensemble Vulnerability Assessment and Sensor Placement Optimization Tool
THM	Trihalomethane
TOC	Total Organic Carbon
UPS	Uninterruptible Power Supply
UV	Ultraviolet
WQM	Water Quality Monitoring
WSI	Water Security Initiative

Section 13.0: Glossary

Accurate data. A measured data value within an acceptable range of the true value obtained through an independent method.

Alert. Information from a monitoring and surveillance component indicating an anomaly in the system, which warrants further investigation to determine if the alert is valid.

Alert investigation. A systematic process, documented in a component response procedure, for determining whether an alert is valid, and identifying the cause of the alert. If a benign 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 are classified as either primary or dual-use.

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 10^{th} and 90^{th} percentiles of the ranked data, respectively. The bottom and top of the box represent the 25^{th} and 75^{th} percentiles of the ranked data, respectively. The line inside the box represents the 50^{th} percentile, or median of the ranked data. Note that some data sets have the same values for the percentiles presented in box-and-whisker plots, in which case not all lines will be visible.

Component response procedures. Documentation of roles and responsibilities, process flows, and procedural activities for a specified component of the contamination warning system, including the investigation of alerts from the component. Standard operating procedures for each monitoring and surveillance component are integrated into an operational strategy for the contamination warning system.

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 impacts, 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.

Contaminant detection potential. The capability of the contamination warning system to detect specific contaminants or contaminant classes. In order for the WQM component to have the potential to detect a specific contaminant, at least one of the measured water quality parameters must produce a statistically significant change from the baseline in the presence of the contaminant at a concentration capable of producing significant consequences.

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, life cycle. The total cost of a system, component, or equipment over its useful or practical life. Life cycle 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 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, etc.) 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 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.

Critical concentration. The concentration of a specific contaminant capable of producing significant consequences, either with adverse impacts to the exposed population or utility infrastructure.

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 QC failures, data transmission errors, and faulty equipment among other causes.

Data stream. The output signal for a single instrument (e.g. Hach chlorine sensor at a specific monitoring station).

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 when data was actively collected for the evaluation of the Cincinnati contamination warning system pilot.

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

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

Impacted WQM location. A monitoring location that receives a practically detectable concentration of contaminant in a simulation study scenario.

Incomplete data. Data that is missing or unusable. This occurs when a sensor's data is not delivered to the SCADA system or if the data is flagged to indicate suspect quality.

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.

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.

Metric. A standard or statistic for measuring or quantifying an attribute 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, potentially including contamination incidents. The four monitoring & surveillance components of a contamination warning system include: 1) online 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 location 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 thus generally do not pose an immediate threat to public health. However, contamination with these chemicals can make the drinking water supply unusable.

Observed water quality anomaly. Period of unusual water quality in utility data, where data does not match expected values or variability.

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 alerts are not being acted upon in real-time. 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).

Parameter sensitivity value. For a specific water quality parameter, the smallest change that can be reliably discriminated from normal instrument noise. Practically, this represents the true change in the parameter value that could potentially generate an alert.

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

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.

Potential data hours. For a monitoring and surveillance component, the total number of hours in the evaluation period multiplied by that component’s total number of data streams.

Potential data hours for a sensor. The total hours that data is expected to be collected from an individual sensor during the evaluation period. This excludes times when external factors limit data collection, such as during station calibration or a system-wide communication outage.

Potential data hours for the component. The total number of hours in the evaluation period multiplied by the total number of data streams.

Practically detectable contaminant concentration. The minimum concentration of a contaminant which produces a change in at least one water quality parameter greater than or equal to the parameter's sensitivity value.

Practically detectable scenario. A simulation study scenario in which at least one monitoring location receives a practically detectable concentration of contaminant.

Primary benefits. Benefits that are derived from the reduction in consequences associated with a contamination incident due to deployment of a contamination warning system.

Priority contaminant. A contaminant that has been identified by the EPA for monitoring 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.

Process flow. The central element of a component response procedure that guides routine monitoring and surveillance activities in a contamination warning system. The process flow is represented in a flow diagram that shows the step-by-step process for investigation of alerts - identifying the potential cause of the alert and determining whether contamination is possible.

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.

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 producing actionable alerts. Utility staff and partners now respond to alerts in real-time and in full accordance with component response procedures. Optimization of the system still occurs as part of a continuous improvement process, however the system is no longer considered to be developmental.

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.

Simulation study. A study designed to systematically characterize the detection capabilities of the Cincinnati drinking water contamination warning system. In this study, a computer model of the contamination warning system was challenged with an ensemble of 2,023 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 a site of interest to support the investigation of a possible contamination incident during consequence management.

Target in-pipe concentration. A simulation study scenario variable that defines the target concentration of a contaminant in the distribution system at the injection location.

Threat level. The results of the threat level determination process, indicating whether contamination is possible, credible or confirmed.

Timeliness of 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.).

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

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

Trigger parameter. Event detection system output during alerting timesteps that indicates the water quality parameters whose changes triggered the alert.

Usable data. Data that is *usable* for event detection or most other applications. It must be complete *and* accurate.

Valid alert. Alerts due to water contamination, system events (i.e., work in the distribution system for customer complaint surveillance or WQM) or public health incidents (for public health surveillance).

WQM location. A single location of monitoring where sensors measuring multiple water quality parameters are installed.

Water Utility Emergency Response Manager. A role within the Cincinnati contamination warning system filled by a mid-level manager from the drinking water utility. 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. In the early stages of responding to possible contamination, the Water Utility Emergency Response Manager may serve as Incident Commander.