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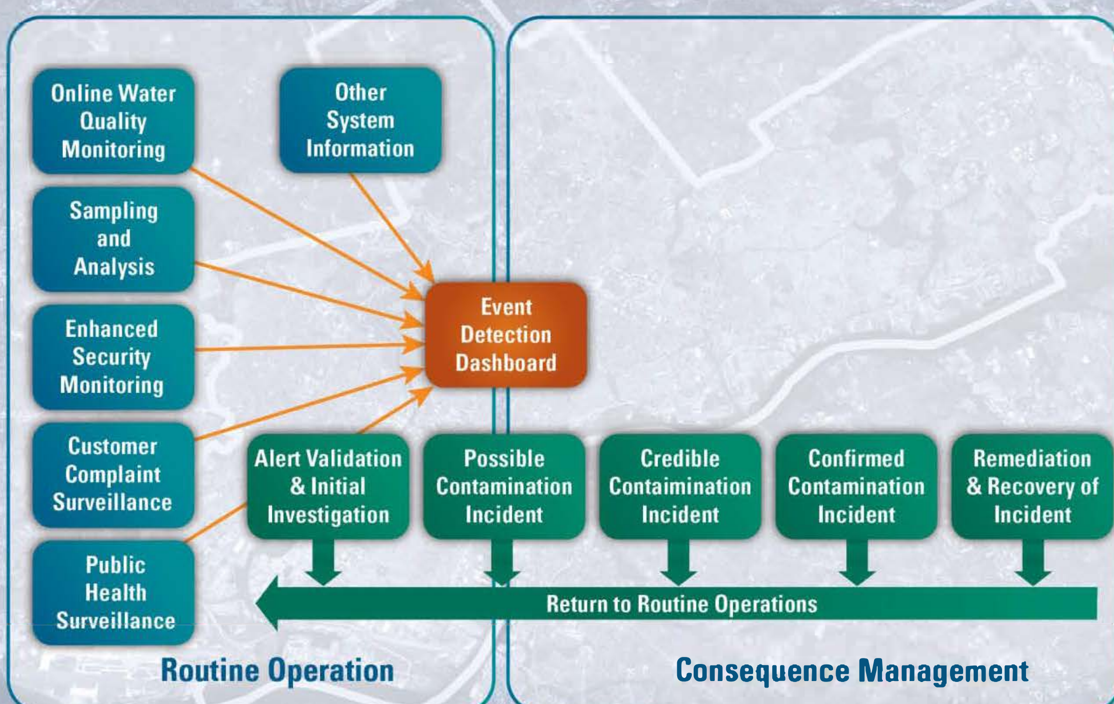
Philadelphia Water Department
Contamination Warning System Demonstration Pilot Project:

Locating Online Water Quality Monitoring Stations Using TEVA-SPOT



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This paper can also be downloaded from www.ch2mhill.com/iws.

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Abstract

The Philadelphia Water Department (PWD) developed a comprehensive drinking water contamination warning system (CWS) under a Water Security (WS) initiative grant from the U.S. Environmental Protection Agency (EPA). Water security is an increasing concern for utility managers, and protecting the water distribution system from contamination is a top priority of PWD. The CWS project included installation of Online Water Quality Monitoring (OWQM) stations throughout the water distribution service area to detect security concerns and to improve distribution system operation. This document provides an overview of project background, technical requirements, and analytical methods used to select the OWQM sites. In developing this document, the EPA resources cited herein and CH2M HILL's previous work on this and other CWS pilots were used.

Installation locations for the OWQM stations were selected using EPA's Threat Ensemble Vulnerability Assessment—Sensor Placement and Optimization Tool (TEVA-SPOT), as well as PWD's hydraulic models, operators' knowledge of the system, and on-site feasibility assessments. TEVA-SPOT is an analytical tool built upon a distribution system hydraulic model that uses probabilistic analysis and optimization to conduct a vulnerability assessment and determine optimized sensor placement.

The first step in developing the TEVA-SPOT analytical model was to define a design basis threat (contaminant, location of contamination, time of contamination, contaminant properties, size of affected population, sensor set size, and optimization objective) that would be used in the simulations. Due to computational limitations, the TEVA-SPOT ensemble was then applied in a two-step approach. PWD's transmission model was analyzed using contamination scenarios to identify the pressure districts that would be selected as locations for water quality sensors. The individual all-pipe, pressure district hydraulic models were then used to determine optimal sensor locations within the district.

Project Background

PWD developed a comprehensive CWS for its drinking water system under a WS initiative grant. The WS initiative is an EPA program developed in partnership with drinking water utilities and other key stakeholders in response to Homeland Security Presidential Directive 9. It involves designing, deploying, and evaluating a model CWS for drinking water security. A CWS is a systematic approach to the collection of information from various sources, including monitoring and surveillance programs, to detect contamination events in drinking water early enough that public health impacts and economic consequences may be minimized. The WS initiative goal is to develop water security CWS guidance that can be applied by drinking water utilities nationwide.

The project has six major components:

1. Online water quality monitoring
2. Sampling and analysis
3. Enhanced security monitoring
4. Consumer complaint surveillance
5. Public health surveillance
6. Consequence management

As part of the PWD CWS project, OWQM stations were installed throughout the service area to detect security concerns and improve distribution system operation. The EPA program Threat Ensemble Vulnerability Assessment—Sensor Placement and Optimization Tool (TEVA-SPOT) was used to determine optimal locations for OWQM sites within the distribution system. The requirements for this analysis include a calibrated hydraulic model and contaminant and simulation design parameters for TEVA-SPOT.

CH2M HILL served as the project contractor and supported PWD in development of its CWS, including the determination of optimized OWQM locations using TEVA-SPOT, review of site feasibility, and selection of final OWQM station locations.

Hydraulic Model

The backbone of the TEVA-SPOT analysis is an EPANET hydraulic model. The hydraulic analysis uses multiple objectives and contaminant parameters, and it is a computationally intensive process. It is important to optimize both the input hydraulic model and the multiple objectives to ensure efficient analysis. A well-calibrated, extended-period simulation hydraulic model is essential for accurate representation of system performance under average-day conditions.

TEVA-SPOT Design Parameters

TEVA-SPOT is a comprehensive tool that can be applied in the selection of OWQM sites. It uses probabilistic analysis and optimization to conduct a vulnerability assessment and determine optimized sensor placement. Several design parameters are required for each of the three modules that make up the TEVA-SPOT application. In the first module, the EPANET hydraulic model simulation, the simulation duration, start time of the contamination incident, location of the contamination incident, duration of contamination, and rate of contaminant injection are all required to define the hydraulic analysis.

In the second module, Health Impact Analysis, the population density, dose calculation, and response methods frame the probabilistic consequence analysis.

In the third module, Optimized Sensor Placement, the following design parameters are required: solver method, number of sensors, utility response time, locations for sensor selection, detection limit of sensors, and performance measure or objective function.

Sensor Location Selection

TEVA-SPOT can be used to identify optimal sensor locations, but those sites may not always be practical. Several considerations factor into the feasibility of OWQM sites, such as available space, water sample supply and drainage, power, data communications, accessibility, and safety. Therefore, several methods for identifying OWQM sites were used. First, optimal locations were selected anywhere in the distribution network. Then feasible parcels were identified based on geographic information system (GIS) data. These feasible parcels were then optimized by TEVA-SPOT to develop alternative optimal locations, and each location was visited to assess the practical feasibility of installing a station there before final site selections were made.

Analysis and Implementation

Analysis and implementation of OWQM stations involves knowledge of the hydraulic model requirements, design basis, sensor placement analysis, site selection, and field verification.

Hydraulic Model Requirements

To capture a contamination injection incident, a hydraulic model must be able to represent the spread of the contaminant throughout the distribution system. Therefore, a calibrated extended period simulation model is required. TEVA-SPOT's analysis of a contamination scenario for selected injection nodes, ideally every node in the hydraulic model, is a computationally intensive analysis, and the hydraulic model should first be optimized for quick and efficient performance. PWD's hydraulic model was converted to EPANET since it was originally developed using an alternative software package (many commercially available packages have the ability to export the hydraulic model to EPANET). A verification of correct conversion of the PWD hydraulic model was performed.

PWD Water Distribution System and Model Overview

PWD draws source water from the Schuylkill and Delaware rivers. Treated water is then discharged into the distribution system from three conventional water treatment plants at an average flow of 250 million gallons per day, serving a population of 1.6 million. The distribution system is divided into 13 pressure districts and consists of 11 reservoirs, 5 tanks, 12 pump stations, and more than 3,000 miles of pipe.

Before the CWS project was undertaken, calibrated hydraulic models for each of the pressure zones and a system transmission main hydraulic model were developed for the PWD system. The all-pipe pressure zone hydraulic models were combined into a system-wide model with more than 100,000 pipes. The large size of the model made it unusable in the TEVA-SPOT analysis. Therefore, a combination of the transmission system model and individual pressure zone all-pipe models was used. The hydraulic models were reviewed, and minor adjustments were made to increase model efficiency and to reduce run times.

The process for locating sensors was achieved in two steps. First, the full system transmission model was analyzed using TEVA-SPOT to determine in which of the 11 pressure districts the sensors should be installed. The all-pipe models for each identified pressure district were then individually analyzed, and locations for the recommended number of sensors were determined. This two-step process reduced the computational effort and provided a more efficient analysis.

Design Basis for TEVA-SPOT Analysis

To determine the optimal sensor locations, it was necessary to define a distribution system design basis threat against which the water utility wants to protect. The design basis threat considers, among other properties, type, location, and time of contamination.

The TEVA-SPOT simulations include three analyses: EPANET Simulation, Health Impact Analysis, and Sensor Placement. The parameters used in each of these components and the rationale for the design basis parameters are described in the following sections.

Design Basis Threat Contaminant Selection

To analyze a range of impacts, two contaminants with different characteristics were selected for analysis. Information provided by EPA was used to determine high-impact and low-impact contaminants and the required contaminant doses. The hydraulic model flow rates were used to determine an appropriate release duration based on the contaminant mass. Calculation of appropriate contaminant dosing rates is important as both insufficient dosing or overdosing can affect the accuracy of the analysis.

EPANET Simulation Parameters

After determining the contaminant parameters, the EPANET simulation was used to define the following parameters: time and duration of contaminant release, mass released, and the locations of contaminant release.

Simulation Time. An analysis of the hydraulic model was used to determine the average water age in the distribution system and the oldest water age under average-day demand conditions. A simulation time of maximum water age was used for the TEVA-SPOT analysis so that the full extents of the system were captured appropriately.

Contaminant Release Duration. The duration of contaminant release and the mass released are related parameters. For a low-impact contaminant, a larger mass is required if injected over a short duration, and a smaller mass is required if injected for longer durations. For a high-impact contaminant, less mass is required to produce significant impacts; therefore, a longer release duration can be used. Substantial benefits may be gained from a sensor network design that can detect a small mass of a high-impact contaminant released over a long duration (up to 24 hours). Release durations greater than 24 hours are not realistic and therefore were not considered.

For a low-impact contaminant, injection durations of 1, 20, and 24 hours were used. For the high-impact contaminant, a duration of 24 hours was used.

Contaminant Release Timing. The contaminant release timing used in the analysis is based on the peak demand time of the system, which is a function of the diurnal usage patterns and demands in the hydraulic model. The peak demand time maximizes the probability that the contaminant will be consumed, resulting in higher impacts. The release time of the contaminant injection is less important with longer contaminant release durations. For example, release duration of 24 hours or more includes the peak demand time without regard to the release start time.

Contaminant Release Rate. The contaminant property information provided by the EPA and the hydraulic model pipe flow rates were used to calculate mass release rates for the selected low-impact and high-impact contaminant durations.

Contaminant Release Locations. Because of the computationally intensive nature of a TEVA-SPOT analysis, it is important to consider the size of the hydraulic model when determining the contaminant release locations. The all-node injection in which every node in the model was considered to be a potential contaminant release location was used for the PWD system analysis, as it provided the most comprehensive coverage. However, depending on the size of the hydraulic model, this may not be feasible in all cases. In those instances, a reasonable number of injection nodes with maximum geographic distribution should be used.

Within the EPANET simulation component of TEVA-SPOT, a separate simulation is conducted for each contaminant release location with the contaminant properties listed above. The result is a collection of extended period simulation results that are stored in the Health Impact Simulation component.

Health Impact Simulation Parameters

For the health impact simulation, the previous EPANET results were used to determine the health impact to the population based on the specific contaminant properties. The parameters defined in this component include the population, the dose calculation, and dose response method.

Dose Calculation Method. The dose calculation depends on the contaminant concentration in the water and the amount of water consumed. The average water consumption was assumed to be 1 liter/person/day based on an EPA study.[1] The ingestion method used assumes five equal amounts of water consumed throughout the day, i.e., three meal times and between meals.

Population Estimate. TEVA-SPOT calculates population using either a demand-based or census-based approach. For the demand-based model, an average per capita demand is used to calculate the corresponding population at each non-zero demand node. This approach does not distinguish between variations in water usage (that is, there is no differentiation for industrial and commercial usage). PWD’s high-usage customers were evaluated and determined to be primarily industrial users; therefore, this demand was disregarded in the population estimate. A per capita usage of 96 gallons per person per day was determined based on historic usage records and was applied to the remaining demands in the model to develop a population estimate.

The alternative approach for population data is the census-based model, which uses census data and a geographic information system to allocate population to non-zero demand nodes. The census data do not account for the nonresidential population (i.e., diurnal fluctuations of population) and census tract information has a coarse resolution. To effectively capture population using this method, finer resolution data would be required.

Dose Response Method. The median lethal dose (LD_{50}) is the dose required to kill half the exposed population. The two contaminants selected in this analysis have different LD_{50} toxicity values. The high-impact contaminant results in a large number of deaths and is more lethal than the low-impact contaminant.

The dose-response calculation method, Probit, was used for both contaminants. The latency time, fatality time, and fatality rate are additional parameters relating to the characteristics of the contaminants. These parameters dictate how the disease progresses and they are not related to the LD_{50} value for the contaminant. For example, a contaminant may have a longer delay in onset of symptoms and therefore delay death, but it could have a higher LD_{50} and so result in fatalities of many more people. Definitions of these parameters are given below:

- LD_{50}—Median lethal dose, relates to toxicity and the dose that will kill half of the exposed population
- Latency time—Time from contaminant exposure until symptoms appear
- Fatality time—Time from the start of symptoms until death occurs
- Fatality rate—Fraction of exposed population that results in death

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[1] EPA. 2004. *Estimated Per Capita Water Ingestion and Body Weight in the United States—An Update*. EPA-822-R-00-001.

Sensor Placement Simulation Parameters

The third component of the TEVA-SPOT simulation is the sensor placement analysis. In this component, the optimal locations for sensors are determined from among allowable nodes. The parameters defined here are solver type, sensor set size, performance measure used in conjunction with the health impact analysis results, the utility's response time, sensor properties, and feasible nodes for sensor locations.

Solver Type. The computational requirements for running the TEVA-SPOT analysis on the PWD hydraulic models required a robust solver that can handle very large and complex optimizations; therefore, a Grasp Heuristic algorithm was used.

Sensor Set Size. A range of sensor set sizes, or the number of sensors to be located, were analyzed using a "knee of the curve" analysis. This allows for determination of an appropriate sensor set that provides the optimal reduction in mean population exposed. Larger sensor sets are not always beneficial, as there is a point of diminishing return beyond which the reduction in health impact is incrementally smaller. A zero-sensor set size was used to provide a comparison baseline with other sensor set sizes. More details are presented in the "Determination of Optimal Sensor Set Size" section of this report.

Performance Measure. The performance measure, objective, or objective function used was the reduction of mean population exposure. This measure uses the mean statistic and, therefore, considers all release locations as equally likely. Additional options for performance measures, specifically worst case, are computationally intensive and thus were not used due to computational limitations. The objective function used, reduction of mean population exposed, has reasonable computation times and allows for a sufficient comparison between scenarios in this analysis.

Response Time. Response time represents the interval from contaminant detection at an OWQM station until all contaminated water has been consumed. Practically, this represents the amount of time from when a potential threat is detected until PWD issues a "Do Not Use" notice to the public. Various response delay times were used in the analyses to quantify the range of impacts. The zero-hour response time, i.e., consumption of contaminated water ceases as soon as it is detected by the OWQM, provides a baseline value for comparison against the desired design response time specified by PWD.

Sensor Locations. All nodes in the hydraulic model were used to identify recommended sensor locations and determine the number of sensors to be installed in each pressure district. For the all-pipe models, specific lists of feasible nodes were developed based on conversations with PWD.

Detection Limit. The EPA provided information on contaminant properties, including typical detection limits from water quality sensors. This information is consistent with PWD's deployment of ultraviolet (UV)-based sensors, with a similar approximate range of detection limits.

Design Basis Contamination Scenarios

Four contamination scenarios were chosen for analysis to provide a meaningful range of results: three with low impact contaminant at varying release durations, and one with the high impact contaminant using the simulation, health impact, and sensor placement parameters identified above.

Sensor Placement Analysis

This section describes the basic procedures and objectives of the sensor placement analysis and discusses the variability between sensor designs. A two-step approach to locating sensors was employed, as described below.

Overview and Method

The TEVA-SPOT sensor placement analyses determine the optimal sensor network for the specified design basis contamination scenario. The objective of the analysis is to minimize the mean population exposed to the contamination scenario.

For the project, the sensor placement analysis component was conducted in two steps. First, the TEVA-SPOT analysis was run on the transmission model for all four contaminant scenarios, and a regret analysis was conducted to determine the optimal sensor network design and design basis contamination scenario. A regret analysis is a comparison analysis that allows the user to compare performance across scenarios. In this case, an optimal sensor set design is defined for a specific design basis scenario and this optimal design is then run within a different design basis scenario for performance evaluation. The analysis conducted compares every optimal sensor set design's performance across all design basis scenarios. This analysis enables determination of the sensor set design that performs best in all cases.

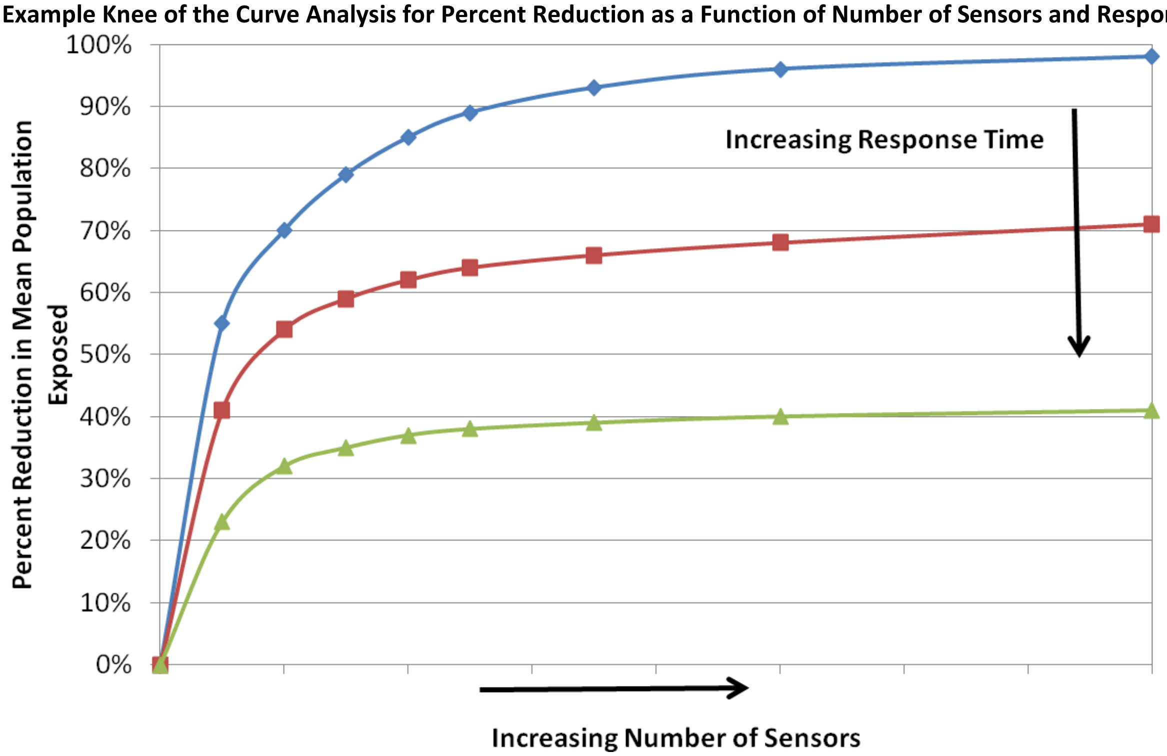
The goal of the analysis was to determine the number of sensors to be located in each pressure district. Following this determination, TEVA-SPOT analyses were conducted on the individual all-pipe models to determine specific locations within each pressure district for the OWQM sites. PWD and CH2M HILL staff then conducted field surveys to evaluate each site for feasibility as installed sensor locations.

Determination of Optimal Sensor Set Size

Before optimizing sensor locations, the number of sensors to be installed in the system must be determined. The optimal sensor set size is determined based on the knee of the curve, where additional sensors beyond an optimal number provides diminishing incremental reduction in mean population exposed to the simulated contaminants. Response time is also seen to have a substantial impact on population exposed. As response time increases, monitoring becomes less effective even with a large sensor set size.

An analysis was conducted to determine the number of sensors beyond which additional sensors provide diminishing returns. Figure 2 shows an example of the way in which the percent reduction in the mean population exposed varies as a function of the sensor set sizes and response times. The figure indicates that only a small number of sensors are needed to provide most of the available reduction of mean population exposed.

FIGURE 2
Example Knee of the Curve Analysis for Percent Reduction as a Function of Number of Sensors and Response Time



Development of Transmission Model Sensor Network

To develop the transmission model sensor network, TEVA-SPOT analyses were conducted for each of the four contaminant injection scenarios. Optimized sensor network designs were developed to minimize the mean population exposed. The TEVA-SPOT regret analysis was then conducted to determine how each sensor design performed compared to the other three. Through this regret analysis, the most effective sensor network design was determined.

Regret Analysis. For the regret analysis, two methods were used by TEVA-SPOT to evaluate the effectiveness of a design. The *preferred overall design* was determined by minimizing the square root of the sum of the squared deviations in the objective for a sensor design from the best case sensor design across all scenarios. The *preferred design to minimize maximum deviation* was determined by minimizing the maximum deviation from the best case for a particular sensor design across all scenarios. That is, the regret analysis evaluates the performance a particular sensor design in the reduction of mean population exposed for all contamination scenarios. The results of this particular sensor design are then compared against the results of the best case sensor design which was developed for each individual contamination scenario. The preferred design can then be determined from the two statistics described above that minimize the deviation (either overall deviation or maximum deviation) from the best individual sensor designs to develop a single sensor design for all contamination scenarios. After the best and second best sensor design networks were identified, the sensor locations in each individual pressure districts were summarized.

Recommendation for Transmission Model Sensor Network. A detailed analysis was performed to determine the number of the sensors in each pressure district in the PWD water distribution system. As described above, the analysis included determining contaminant scenarios that will be used to design the OWQM sensor network, conducting a regret analysis to compare different sensor networks designed for high- and low-impact contaminant scenarios, and evaluating these designs with PWD's response time to determine the preferred sensor designs among these scenarios. The regret analysis results showed the most effective sensor network design across all contamination scenarios and were the basis for selecting the number of sensors in each pressure zone.

Development of All-Pipe Models Specific Sensor Potential Locations

To develop specific sensor locations, optimal locations were first selected from among all possible nodes using TEVA-SPOT and the all-pipe models. Potential sensor locations were then limited to feasible locations including PWD-owned facilities, fire stations, police stations, and hospitals. Two different methods of selecting sensor site locations were used. The TEVA-SPOT optimal locations originally selected from the all-pipe models were compared to nearby available parcels to determine the closest feasible parcel. Alternately, the TEVA-SPOT analysis was limited to only the feasible parcels to select those parcels with the highest percent reduction in mean population exposed.

Method 1: Select Nearest Feasible Parcel by Distance from TEVA-SPOT Optimal All-Pipe Model Selections. This method used the optimal locations selected by TEVA-SPOT from the all-pipe models and determined the nearest feasible parcel by linear distance. When an optimal TEVA-SPOT selected location was not adjacent to a feasible parcel, the closest parcel by linear distance was evaluated. Because of the limited number of feasible parcels, linear distance was used for parcel evaluation rather than hydraulic connectivity. In most cases, only one or two parcels were near the TEVA-SPOT selected location. In cases where multiple parcels were found to be at a similar distance from the TEVA-SPOT optimal selection, all parcels were analyzed for effectiveness in reducing mean population exposed.

Method 2: Limit TEVA-SPOT Site Selection to Feasible Parcels Only. For this method, a list of feasible parcels including all fire stations, police stations, hospitals, and PWD-owned facilities was generated. TEVA-SPOT was used to analyze only these parcels and determine the parcel that provides the highest percent reduction in mean population exposed in the selected pressure districts.

Results and Recommendations for Preliminary Sensor Site Selection. Sensor designs were created in TEVA-SPOT for each method and the analysis was performed to determine their effectiveness at reducing the mean population exposed. The original results in reduction of mean population exposed from the TEVA-SPOT selected optimal locations were compared to results from the two sensor location evaluation methods.

Some of the optimal locations selected by method 1 were also selected by method 2; however, for all selected sites there was seen to be equal or improved exposure reduction performance with the locations selected by method 2. Therefore the parcels selected by method 2 were recommended for further onsite investigation as to their feasibility as installed sensor sites.

Selection of Preliminary Sensor Sites and Field Verification

This section details the process for preliminary sensor site selection in each pressure district and the onsite feasibility assessment procedure. As noted, the sensor network design from the TEVA-SPOT analysis using method 2 (limiting feasible nodes in the sensor placement simulation to PWD-determined feasible parcels) was used to develop the recommended list of sensor locations for further investigation. Alternate locations were also identified for several sites, and TEVA-SPOT analyses and field visits were conducted.

Additional feasibility considerations included space availability, ease of access by PWD, presence of other utilities including water sample supply, drain to the sanitary sewer, electric power, and data communications. Safety of employees and location of service connections were also important considerations. At some sites, multiple buildings on the same property were evaluated. In some instances, the building that had the best space and accessibility for the OWQM station had a separate service connection from a different water main than the optimal modeled location. Depending on system hydraulics, the location of the service connection can make a site less effective despite its proximity to the optimal location. If space within the building was unavailable, an outdoor installation of an enclosure to house the equipment was evaluated. In some case, multiple visits to the selected sites were conducted to measure the space and ensure that the instrument cabinet could be transported into the space allocated or to determine whether an outdoor enclosure would be required. The percent reduction of mean population exposed does not take into account the additional travel time to the service connection.

Sites were recommended based on their reduction in mean population exposed and on the physical feasibility of using the facility space. Negotiations with facility managers along with other practical factors were considered by PWD when making final site selections.

A comparison between the recommended sites' reduction in mean population exposed to the optimal sites determined by TEVA-SPOT showed only a small decrease in effectiveness of a total reduction.

Lessons Learned

Lessons learned with regard to applying TEVA-SPOT analysis to OWQM selection involve the design basis and sensor placement.

Design Basis

The design basis for this analysis consisted of parameters that affected the simulation, consequence, and optimization of the vulnerability assessment and sensor placement. The sensitivity of these parameters was evaluated to provide a comprehensive analysis. In the CWS pilot project, two contaminants (one high impact, one low impact) with different properties were analyzed under a total of four contamination scenarios. This provided a bracket of results, and a detailed regret analysis was conducted to determine the effectiveness of each optimal sensor set design in the other contamination scenarios.

As the hydraulic model is the foundation of this analysis, it was critical to have a well-calibrated model that represented the average-day operations in the system over an extended period of time. It was important to have an efficient hydraulic model with short run times to minimize analysis times as much as possible. Due to the computationally intensive nature of the TEVA-SPOT analyses, a two-step approach using multiple hydraulic models was used to provide preliminary recommendations for OWQM sites.

Two key parameters have a significant influence on the reduction of mean population exposed: sensor set size and response time. In determining the optimal sensor set size, the "knee of the curve" analysis highlighted the diminishing returns of additional sensors beyond an optimal number. A small number of sensors account for most of the benefit in reducing mean population exposed. Response time also has a significant influence and is generally more critical than the number of sensors, as shown in the example in Figure 2. If response time is long (i.e., slow utility response to the contamination event), there is a significant reduction in the effectiveness of the sensors regardless of the number of sensors. Increased benefits of OWQM sensors can be achieved by reducing utility response time and locating an optimized number of sensors.

Sensor Placement

The optimal locations from the sensor placement analysis were reviewed against the limited feasible sites. It was found that there was improved performance when the limited sites were run in the TEVA-SPOT analysis compared to merely selecting the closest feasible site to the optimal sites. The selected feasible sites were taken into consideration, and field visits were conducted to make final site selections based on various practical concerns, including geographic location, physical space for the equipment, site utilities, ease of access, and effectiveness of locations as provided from the TEVA-SPOT analyses.

PWD was able to establish nearly optimal sensor placement for OWQM stations that will not only protect against contamination events, but also provide a dual benefit by generating valuable information about daily system performance.

Acronyms and Abbreviations

CWS	Contamination warning system
EPA	U.S. Environmental Protection Agency
GIS	Geographic Information System
LD_{50}	Median lethal dose
OWQM	Online water quality monitoring
PWD	Philadelphia Water Department
TEVA-SPOT	Threat Ensemble Vulnerability Assessment–Sensor Placement and Optimization Tool
WS	Water Security
UV	Ultraviolet

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