Optimal Monitoring Location Selection for Water Quality Issues

Dominic L. Boccelli[1] and William E. Hart[2]

[1]National Homeland Security Research Center, U.S. Environmental Protection Agency, MS 163, 26 W. Martin Luther King Dr, Cincinnati, OH 45268; PH: 513-569-7654; FAX: 513-487-2555; e-mail: boccelli.dominic@epa.gov
[2]Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185-1318; PH: 505-844-2217; FAX: 505-845-7442; e-mail: wehart@sandia.gov

Abstract

Recently, extensive focus has been placed on determining the optimal locations of sensors within a distribution system to minimize the impact on public health from intentional intrusion events. Modified versions of these tools may have additional benefits for determining monitoring locations for other more common objectives associated with distribution systems. A modified Sensor Placement Optimization Tool (SPOT) is presented that can be used for satisfying more generic location problems such as determining monitoring locations for tracer tests or disinfectant byproduct sampling. The utility for the modified SPOT algorithm is discussed with respect to implementing a distribution system field-scale tracer study.

1 Introduction

In recent years, significant effort has been focused on developing optimal sensor placement tools for protecting public health against intentional contamination events [1, 2, 4, 6, 7, 8, 9, 10, 11]. These tools potentially offer additional benefits for designing optimal monitoring locations for objectives other than public health protection. For example, recent large-scale distribution tracer studies have used expert opinion and distribution system network models to determine monitoring locations that are spatially diverse and capture a wide range of expected hydraulic behavior within the distribution system [3] that could be solved by a modified sensor placement tool. Other applications include sampling associated with the Total Coliform Rule and the Stage 2 Disinfectant and Disinfection Byproducts Rule.

One recent sensor placement formulation that has been developed is SPOT, Sensor Placement Optimization Tool, for contaminant warning system design in water distribution systems [5]. Although SPOT has initially been developed to locate sensors for protecting public health, the sensor placement formulations incorporated into SPOT can be readily generalized for other domains or objectives. For this research, SPOT has been extended to allow for a generic performance objective that can be used to incorporate water quality issues. In particular, the modifications have been made to allow sensor placement that results in spatially diverse locations that better represent the water quality issues associated with time varying hydraulics.

This study presents a modified integer programming formulation for sensor placement within SPOT that allows the placement of sensors and/or monitoring locations that incorporate *spatial* coverage across the distribution system and surrogate measures for water quality issues. The modified SPOT formulation will be retroactively applied to sensor placement with respect to large-scale tracer studies, and used to investigate the potential benefits for determining the monitoring locations for more common water quality sampling, such as for the Stage 2 Disinfectant and Disinfection Byproducts Rule.

2 A Sensor Placement Formulation

The Sensor Placement Optimization Tool (SPOT) is capable of solving multiple objective sensor placement problems by minimizing a single objective function and incorporating additional objectives through side-constraint formulations. Thus, the current challenge for solving water quality related problems is in adequately specifying the appropriate *spatial* and water quality coverage metrics.

In general, SPOT places sensors to minimize public health impacts assuming an intrusion event could occur at locations within a distribution system. The "event" approach can also be applied to different objectives to allow monitoring locations to be selected. For example, a tracer study that uses a pulsed injection signal (e.g., see Boccelli et al. [3]) is equivalent to having multiple "events" occurring in the distribution system. While SPOT can determine the optimal monitoring locations for use in the field studies, the question is how to formulate the problem to achieve the desired objectives.

2.1 Spatial Coverage

One salient objective for water quality is *spatial* coverage. Given the discrete nature of distribution system network topology and the transport characteristics associated with the hydraulics, adequate spatial coverage cannot be measured simply by the Cartesian distance between two locations. Instead, a more appropriate notion of spatial coverage is to monitor the flow paths in an attempt to observe as many different flow paths as possible.

This latter notion of spatial coverage can be directly related to a common sensor placement objective: minimize the number of undetected events. In practice, we expect that there will be flows that cannot be covered by a given budget of sensors. Consequently, by minimizing the number of undetected events, we ensure that sensors are spaced out across the network. For example, Figure 1 shows a small portion of a distribution system where the arrows intend to illustrate the general direction of flow. If we assume an "event" can occur at any node within this portion of the distribution system, we can illustrate the general results associated with minimizing the number of undetected events. If water enters the portion of the system at location "A", then placing a sensor at location 1.a would not be appropriate as every "event" occurring downstream would not be detected. Placing a sensor at location 1.b would be preferable as this location will now "observe" every upstream event that terminates at this location. If we were to add a second sensor location, location 2.a would not be ideal as this location may observe similar upstream flow paths as location 1.b. Therefore, location 2.b would likely be a preferable location as the upstream flow paths of 1.b and 2.b would likely be more different. Thus, allowing a greater number of "events" to be observed. As this example suggests, when using this sensor placement objective a serious complication is that the optimal locations often lie at the edges of the distribution system, which would not provide adequate coverage in for use in, as an example, tracer studies.

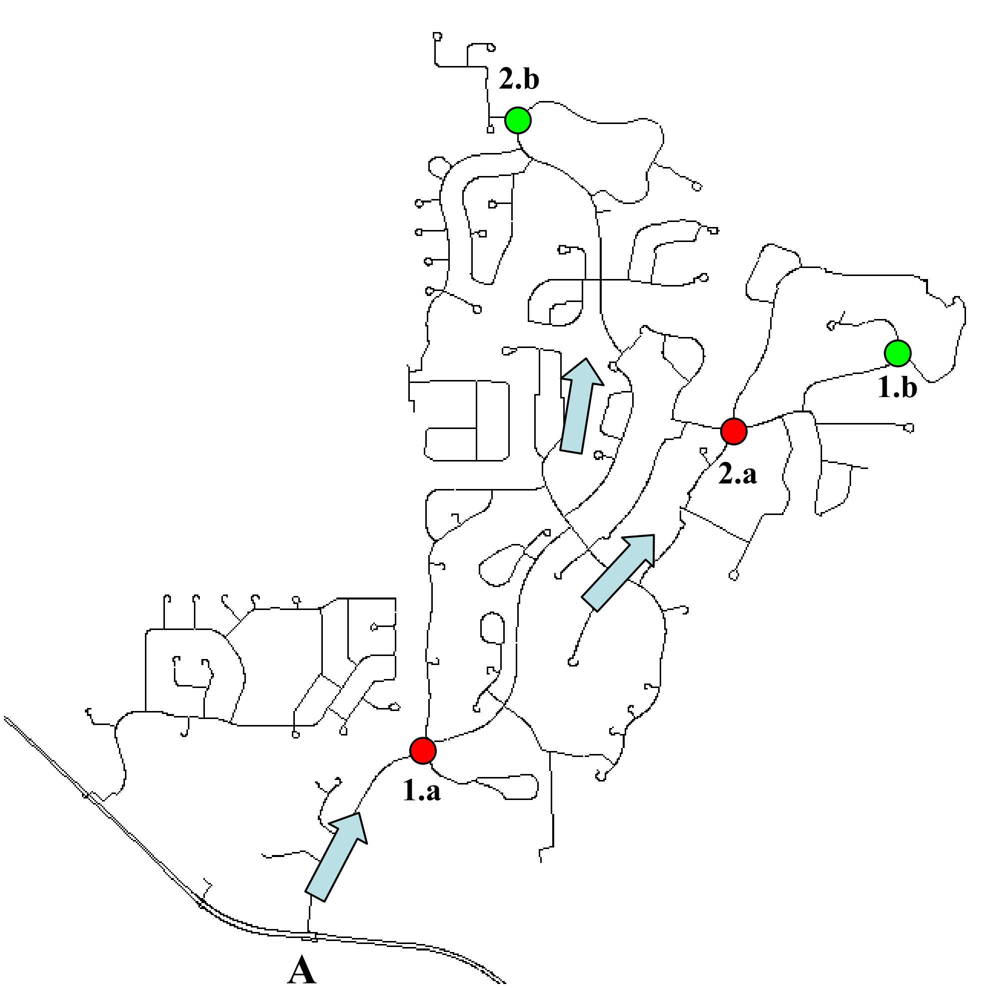

Figure 1. Example network illustrating the potential benefits and drawbacks of minimizing the number of undetected “events” using SPOT.

While this objective does provide a spatially diverse set of sensor locations, the resulting locations may not be adequate to ensure effective water quality monitoring. With respect to tracer tests, information from interior portions of the distribution system, not just the edges, is desirable. With respect to other water quality objectives, such as the monitoring of disinfection byproducts, those locations at the edges of the distribution system should also be coupled with ensuring the residence times of the system are also higher (assuming increased water age is an adequate surrogate for higher disinfectant byproduct concentrations). This drawback can be reduced through the use of an additional objective, as a side constraint, to provide adequate distribution system coverage with respect to additional hydraulic or water quality metrics.

2.2 Water Age

A single metric that would provide additional information for placing monitoring locations for field-scale tracer studies and other water quality objectives is water age. With respect to tracer studies, the transport of the signal through the distribution system directly measures residence time. Therefore, one would want to place monitoring stations in such a way as to test network model predictions regarding hydraulic residence time, which is represented by water age. For most water quality metrics, water age can also act as a surrogate. For example, disinfectant concentrations and byproduct formation are generally correlated with water age. That is, the greater the water age the lower (higher) the disinfectant residual (byproduct concentration). Therefore, for sensor placement we are considering the second objective to collect a representative sample of water ages in the network. Such a sample will enable effective evaluation of water quality by ensuring that various water ages are regularly sampled.

The additional objective included in the SPOT minimizes the absolute difference between a target water age distribution and the distribution of water ages from the sub-set of locations where sensors are placed. Water quality simulations can be used to predict the target water age distributions at junctions in the network where sensors may be placed.

Ultimately, the goal of this objective is to locate sensors that together sample the same distribution of water ages as are found in the overall network. If this performance objective is treated as a constraint, it forces sensors to *not* be placed at the edges of the distribution system to ensure that the distribution of water ages is satisfied. Thus, the overall sensor design *observes* maximally different flow paths (from the first objective) while representing the targeted distribution of water age.

2.3 A Revised Sensor Placement Formulation

To compute a target age distribution, we sort the computed water ages into a fixed number of bins. Suppose there are k bins and let f_k be the frequency of ages occurring in the k-th bin. Similarly, for each feasible sensor location we need to compute the distribution of water ages that would be observed at that location. Using the same binning scheme, let f_{kl} be the frequency of ages occurring in the k-th bin at location l. Finally, let $\mathcal{F}$ be the set of bin indices.

The canonical sensor placement formulation used in SPOT can be easily revised to integrate the water age objective as a constraint. The following integer program minimizes the mean number of failed detections with the added constraint that the summed absolute deviation from the target age distribution is constrained below a user-specified tolerance, Δ:

$$
\begin{array}{lll}
\min & \sum_{a\in\mathcal{A}} \alpha_a \sum_{i\in\mathcal{L}_a} d_{ai} x_{ai} & \\
\text{s.t.} & \sum_{i\in\mathcal{L}_a} x_{ai} = 1 & \forall a \in \mathcal{A} \\
& x_{ai} \le s_i & \forall a \in \mathcal{A}, i \in \mathcal{L}_a \\
& \sum_{i\in L} s_i \le p & \\
& s_i \in \{0,1\} & \forall i \in L \\
& f_k - \frac{1}{p}\sum_{l\in L} f_{kl} s_i \le \delta_k & \forall k \in \mathcal{F} \\
& \frac{1}{p}\sum_{l\in L} f_{kl} s_i - f_k \le \delta_k & \forall k \in \mathcal{F} \\
& \sum_{k\in\mathcal{F}} \delta_k \le \Delta & \\
& 0 \le x_{ai} \le 1 & \forall a \in \mathcal{A}, i \in \mathcal{L}_a
\end{array}
$$

This formulation models the placement of p sensors on a set L vertices, with the objective of minimizing the expected impact of a set $\mathcal{A}$ of flow events. The binary decision variable s_i for each potential sensor location $i \in L$ equals 1 if a sensor is placed at location i and 0 otherwise. Each flow event $a \in \mathcal{A}$ has a likelihood α_a such that $\sum_{a\in A} \alpha_a = 1$. Let $\mathcal{L}_a$ be the subset of locations that could possibly observe flow event a. For all locations $i \in \mathcal{L}_a$, the impact of the event a is $d_{ai}x_{ai}$, where d_{ai} is a the precomputed impact for this event, when detected at location i, and x_{ai} indicates whether the event has been detected at location i. This integer program is adapted from the model described by Berry et al. [2], and details needed to make the solution of this integer program tractable are the same in both models.

The use of precomputed impact values, d_{ai}, enables the application of this sensor placement formulation to a wide range of performance objectives, since different objectives simply translate into different impact values (e.g. see Watson et al. [12]). Specifically, the d_{ai} impact values used in this study represent the number of failed detections for a flow scenario if detected at location *i*. These values are zero for each location in the network, but one for a *dummy* location that represents a failed detection.

3 Using SPOT

The capabilities of the modified SPOT will be illustrated through application to three problems: a) selection of 14 sensor locations from approximately 4000 network nodes for a retroactive analysis from a previously performed field-scale tracer test; b) selection of 45 sensor locations from approximately 2000 network model nodes for implementing a large field-scale tracer test; and c) selection of monitoring locations to assist with the Stage 2 Disinfectant and Disinfection Byproduct Rule. The necessary input files to the SPOT will be generated using the EPANET Programmer's Toolkit, and network simulations will be of sufficient duration to reduce the impacts of the initial model conditions and utilize the last 24-hours of simulated data to test the modified SPOT.

4 Discussion

The first application – the retroactive analysis of a previous field-scale tracer study – will be used to illustrate the implementation of the modified SPOT. The tracer studies were performed in conjunction with a southeastern United States utility. The basis of the tracer study was to inject a concentrated sodium chloride solution into the treated water to increase the background conductivity. Portable conductivity monitors, equipped with data loggers, were used to monitor the conductivity signal throughout the distribution system. Figure 2 illustrates the conductivity signal injected into the system. The intent was to send six conductivity pulses through the distribution system in order to monitor the transport of a 24-hour window of treated water (each pulse provides an additional piece of information).

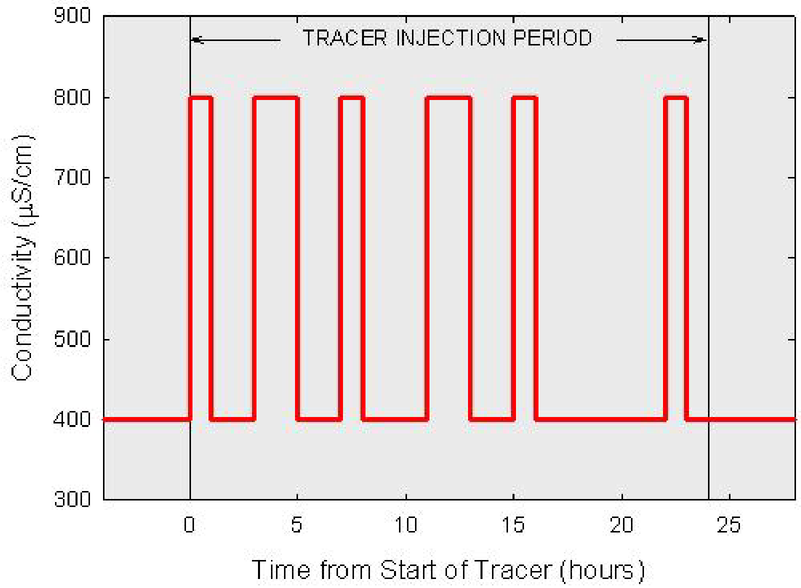

Figure 2. Injected conductivity signal for use in the field-scale distribution system tracer studies.

The placement of the monitoring stations was intended to achieve two objectives: spatial coverage of the distribution system and monitoring of water representative of the water age within the distribution system. The latter objective was intended to evaluate how well the network model matched the observed hydraulic residence times. The former objective was intended to provide coverage of the system and to try and minimize the any commonality among flow paths.

Figure 3 shows one of the areas studied during the field study along with the locations of the conductivity monitors. One monitor was placed at each of the two treatment plants, the one storage facility, and at a location just upstream of the storage facility. The other ten monitoring locations were placed using an iterative process with the existing network model and expert opinion to evaluate spatial coverage. The fitness of the monitoring locations with respect to matching the water age distribution was performed using the existing network model. Figure 4 shows the distribution of water age for all of the nodes in the study area [solid line] and the ten manually placed monitoring locations [symbols]. The objective was to minimize the differences between these two curves while maintaining a spatial diverse set of locations.

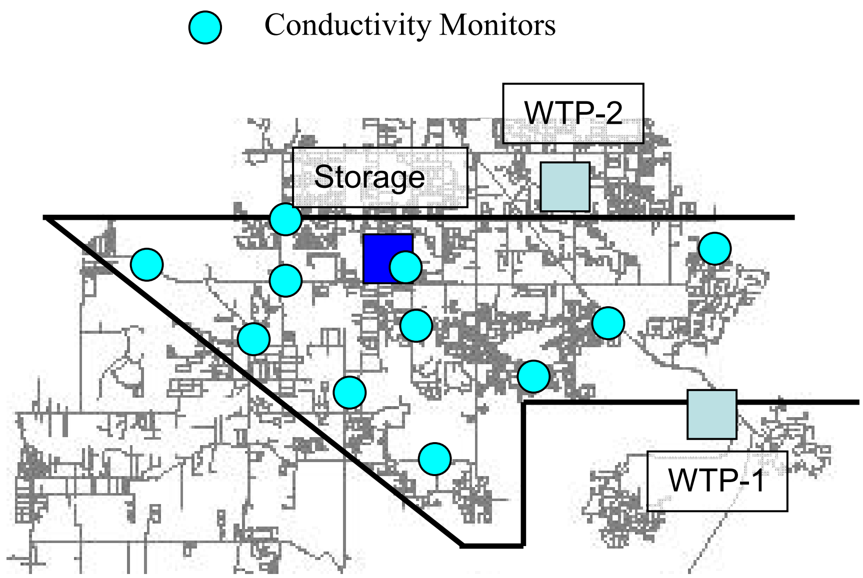

Figure 3. Field study region where a portion of the tracer study was implemented; the conductivity monitoring stations were placed at the two treatment plants, one storage facility, and eleven other locations within the distribution system.

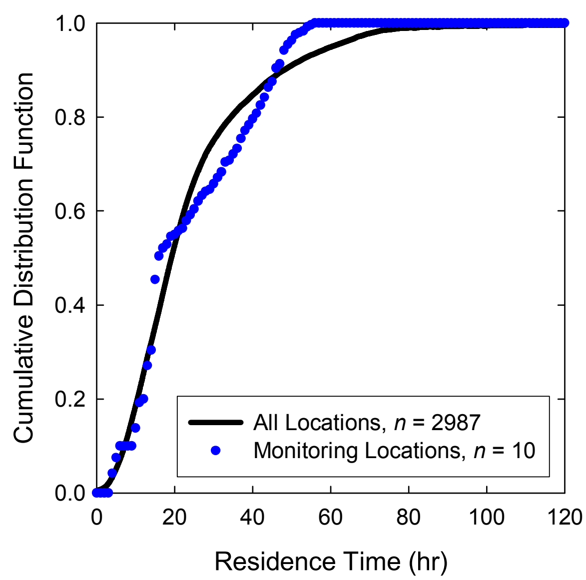

Figure 4. Illustration of the target distribution of water age in the region of the tracer study [solid line] and the distribution of water age from the selected monitoring locations [symbols].

The manual process of selecting monitoring locations that are spatially diverse and representative of a target water age distribution is time consuming and, at times, difficult given the complex nature of the flow paths within a distribution system. The modified SPOT will automate the selection of monitoring locations and provide a more efficient search approach.

Acknowledgements

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Bibliography

[1] J. Berry, L. Fleischer, W. E. Hart, C. A. Phillips and J.-P. Watson, *Sensor Placement in Municipal Water Networks*, J. Water Planning and Resources Management, 131 (2005), pp. 237-243.

[2] J. Berry, W. E. Hart, C. E. Phillips, J. G. Uber and J.-P. Watson, *Sensor placement in municipal water networks with temporal integer programming models*, J. Water Resources Planning and Management, 132 (2006), pp. 218-224.

[3] D. L. Boccelli, *Case Study: Hillsborough County Water Department*, *Water Distribution Systems Analysis Symposium Workshop on Distribution System Tracer Studies - Design, Implementation, and Case Studies*, 2006.

[4] R. A. Deininger, *The Survival of Father Rhine*, Journal of the American Water Works Association, 70 (1987), pp. 78-84.

[5] W. E. Hart, J. Berry, L. A. Riesen, R. Murray, C. A. Phillips and J.-P. Watson, *SPOT: A sensor placement optimization toolkit for drinking water contaminant warning system design*, *Proc. World Water and Environmental Resources Conference*, American Society of Civil Engineers, 2007.

[6] A. Kessler, A. Ostfeld and G. Sinai, *Detecting Accidental Contaminations in Municipal Water Networks*, Journal of Water Resources Planning and Management, 124 (1998), pp. 192-198.

[7] A. Kumar, M. L. Kansal and G. Arora, *Discussion of `Detecting Accidental Contaminations in Municipal Water Networks'*, Journal of Water Resources Planning and Management, 125 (1999), pp. 308-310.

[8] B. H. Lee and R. A. Deininger, *Optimal Locations of Monitoring Stations in Water Distribution System*, Journal of Environmental Engineering, 118 (1992), pp. 4-16.

[9] B. H. Lee, R. A. Deininger and R. M. Clark, *Locating Monitoring Stations in Water Distribution Systems*, Journal, Am. Water Works Assoc. (1991), pp. 60-66.

[10] A. Ostfeld and E. Salomons, *Optimal Layout of Early Warning Detection Stations for Water Distribution Systems Security*, Journal of Water Resources Planning and Management, 130 (2004), pp. 377-385.

[11] M. Propato, O. Piller and J. Uber, *A Sensor Location Model to Detect Contaminations in Water Distribution Networks*, *Proc. World Water and Environmental Resources Congress*, American Society of Civil Engineers, 2005.

[12] J.-P. Watson, H. J. Greenberg and W. E. Hart, *A multiple-objective analysis of sensor placement optimization in water networks*, *Proc. World Water and Environment Resources Conference*, 2004.